

National Transportation Library

Section 508 and Accessibility Compliance

The National Transportation Library (NTL) both links to and collects electronic documents in a variety of formats from a variety of sources. The NTL makes every effort to ensure that the documents it collects are accessible to all persons in accordance with Section 508 of the Rehabilitation Act Amendments of 1998 (29 USC 794d), however, the NTL, as a library and digital repository, collects documents it does not create, and is not responsible for the content or form of documents created by third parties. Since June 21, 2001, all electronic documents developed, procured, maintained or used by the federal government are required to comply with the requirements of Section 508.

If you encounter problems when accessing our collection, please let us know by writing to librarian@bts.gov or by contacting us at (800) 853-1351. Telephone assistance is available 9AM to 6:30PM Eastern Time, 5 days a week (except Federal holidays). We will attempt to provide the information you need or, if possible, to help you obtain the information in an alternate format. Additionally, the NTL staff can provide assistance by reading documents, facilitate access to specialists with further technical information, and when requested, submit the documents or parts of documents for further conversion.

Document Transcriptions

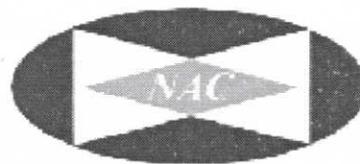
In an effort to preserve and provide access to older documents, the NTL has chosen to selectively transcribe printed documents into electronic format. This has been achieved by making an OCR (optical character recognition) scan of a printed copy. Transcriptions have been proofed and compared to the originals, but these are NOT exact copies of the official, final documents. Variations in fonts, line spacing, and other typographical elements will differ from the original. All transcribed documents are noted as "Not a True Copy."

The NTL Web site provides access to a graphical representation of certain documents. Thus, if you have any questions or comments regarding our transcription of a document's text, please contact the NTL at librarian@bts.gov. If you have any comment regarding the content of a document, please contact the author and/or the original publisher.

Hydrogen Fuel Cell Engines and Related Technologies

XCELLSiS
The Fuel Cell Engine Company

BALLARD



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2001		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE Hydrogen Fuel Cell Engines and Related Technologies				5. FUNDING NUMBERS
6. AUTHOR(S) FTA Project Manager, Shang Hsiung				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) College of the Desert, Energy Technology Training Center 43-500 Monterey Avenue, Palm Desert, CA 92260				8. PERFORMING ORGANIZATION REPORT NUMBER FTA-CA-26-7022-01.1
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Federal Transit Administration U.S. Department of Transportation Washington, DC 20590 Website URL [http://www.fta.dot.gov]				10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. DISCLAIMER-- This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. The United States Government does not endorse products of manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Available From: National Technical Information Service/NTIS, Springfield, Virginia, 22161. Phone 703.605.6000, Fax 703.605.6900, Email [orders@ntis.fedworld.gov]				12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) <i>The Hydrogen Fuel Cell Engines and Related Technologies</i> report documents the first training course ever developed and made available to the transportation community and general public on the use of hydrogen fuel cells in transportation. The course is designed to train a new generation of technicians in gaining a more complete understanding of the concepts, procedures, and technologies involved with hydrogen fuel cell use in transportation. This manual is one of the primary reference books for the study of renewable energies and the use of hydrogen as a fuel for transportation purposes. The manual contains 11 modules (chapters). The first eight modules cover (1) hydrogen properties, use and safety; and (2) fuel cell technology and its systems, fuel cell engine design and safety, and design and maintenance of a heavy duty fuel cell bus engine. The different types of fuel cells and hybrid electric vehicles are presented, however, the system descriptions and maintenance procedures focus on proton-exchange-membrane (PEM) fuel cells with respect to heavy duty transit applications. The PEM fuel cell engine was chosen because it is the most promising for automotive applications, and its transit application is currently the most advanced. Modules 9 and 10 are intended to provide a better understanding of the acts, codes, regulations and guidelines concerning the use of hydrogen, as well as the safety guidelines for both hydrogen maintenance and fueling facilities. Module 11 presents a glossary and conversions. Specific fuel cell system descriptions and maintenance are based on Phases 3 and 4 fuel cell buses (XCELLSIS), representing the most complete description of fuel cell bus maintenance currently available. This course is part of an emerging curriculum under development by the College of the Desert in support of a "Tech Prep Associate Degree" in Advanced Transportation Technologies. The program starts at the high school level and progresses through a rigorous program that includes instructions in electronics, engine performance, alternative fuels, and advanced power train technologies.				
14. SUBJECT TERMS Hydrogen fuel cells Hydrogen Properties Use and Safety Training Course Manual Fuel cell technology and systems Proton-exchange-membrane (PEM) fuel cells Renewable energies				15. NUMBER OF PAGES
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

This course is a joint project of College of the Desert and SunLine Transit Agency.

Funding for this project was made possible by the United States Federal Transit Administration (FTA).

Hydrogen Fuel Cell Engines and Related Technologies
Revision 0, December 2001

Published by:

College of the Desert, Palm Desert, CA, USA
Energy Technology Training Center
College of the Desert
43-500 Monterey Avenue
Palm Desert, CA 92260

COPYRIGHT ©2001
ALL RIGHTS RESERVED

Printed in the United States of America

Copies and information regarding training courses based on this curriculum is available from:

Jack Dempsey, Director
jdempsey@dccd.cc.ca.us
(760) 773-2596

Course Preparation

Principal Author:

- Andre Lanz, P. Eng., WriteRight Technical Communications, Vancouver, BC, Canada

Andre Lanz is a mechanical engineer with a specialty in fuel cell systems and the hydrogen economy. He has many years' experience designing and documenting fuel cell systems for Ballard Power Systems, XCELLSiS Fuel Cell Engines and other fuel cell related companies.

Contributing Authors:

- James Heffel, Principal Research Engineer, Advanced Vehicle Engineering, University of California Center for Environmental Research and Technology (CE-CERT), Riverside, CA, USA

James Heffel is a mechanical engineer and MBA with many years' experience providing testing and engineering support to both the aerospace and alternative energy industries. His interest in hydrogen as a propulsive fuel for surface transportation have led to numerous technical publications and two pending patents.

- Colin Messer, Alternative Fuels Project Instructor, College of the Desert – Energy Technology Training Center, Palm Desert, CA, USA

Colin Messer has a B.A. in Professional Writing from the University of New Mexico and 18 years of experience working as an instructor and consultant in the gaseous fuels industry. He has served as the principal author for several compressed natural gas manuals published by College of the Desert and the National Alternative Fuels Training Consortium at West Virginia University.

Review Team Members:

- | | |
|------------------|--|
| • Andre Lanz | WriteRight Technical Communications |
| • Bill Clapper | SunLine Transit |
| • Byron Anderson | City College of San Francisco |
| • Colin Messer | College of the Desert |
| • Douglas Byrne | A. C. Transit |
| • Henry Bustillo | A. C. Transit |
| • Jack Dempsey | Energy Technology |
| • James Heffel | University of California Riverside CE-CERT |
| • John Williams | SunLine Transit |
| • Keith Adams | College of the Desert |
| • Peter Davis | ATTI Director |
| • Ron Anderson | Santa Clara Valley Transit Agency |
| • Tommy Edwards | SunLine Transit |

Acknowledgments

This project would not have been possible without the generous cooperation of the following organizations:

College of the Desert in Palm Desert, CA, is a two-year California State community college with an enrollment of approximately 8,400 students per semester. Associate degrees and certificate programs are offered in over 70 areas of study. The Energy Technology Training Center at College of the Desert was formed in 1993 and is recognized nationally as one of the leading sources of information, training and curriculum development in the area of advanced transportation technologies. ETTC is the lead college in the California Advanced Transportation Technology Initiative and has been designated as National Training Center for alternative fuels/clean energy.

SunLine Transit Agency in Thousand Palms, CA, is an internationally respected leader and advocate of clean fuels and clean energy. In 1994, SunLine became the first public transit agency in the country to park all its diesel buses and switch overnight to a fleet powered 100% by compressed natural gas. The conversion, though extremely successful, was always deemed an interim step toward a zero-emission future powered by hydrogen fuel cells. In April 2000, SunLine opened the world's first hydrogen generation, storage and dispensing facility built by a transit agency where hydrogen is generated from renewable solar power and reformed from natural gas. SunLine has more than a year's experience operating fuel cell and blended fuel vehicles (hydrogen and natural gas) and as an Associate Member of the California Fuel Cell Partnership, looks toward a gradual replacement of its fleet with fuel cell buses.

XCELLSiS Fuel Cell Engines, Inc., in Burnaby, BC, Canada, is a joint venture between Daimler- Chrysler, the Ford Motor Company and Ballard Power Systems that specializes in the design of fuel cell engines for use in heavy, medium and light duty transportation applications. The XCELLSiS Phase 5 fuel cell bus is the first production fuel cell bus in the world.

Ballard Power Systems, Inc., in Burnaby, BC, Canada, is the world leader in proton exchange membrane fuel cell technology. Ballard fuel cells have been used in fuel cell engines, stationary powerplants, submarines, portable power sources, robotics and other applications around the world.

AC Transit in Oakland, CA, is the public bus system serving the thirteen cities and adjacent unincorporated communities in 390 square miles along the eastern shores of San Francisco and San Pablo Bays. AC Transit has 230,000 daily riders and a fleet of 800 buses that run over 25 million annual revenue service miles. In 1999, AC Transit started road testing a hybrid electric bus.

The Santa Clara Valley Transportation Authority (VTA) in San Jose, CA, is an independent special district responsible for bus, light rail and paratransit operations, congestion management, specific highway improvement projects, and countywide transportation planning. The VTA is a member of the California Fuel Cell Partnership (CaFCP), with plans to test zero-emission buses starting in 2003.

WriteRight Technical Communications in Vancouver, BC, Canada, is an independent technical communication business specializing in engineering documentation.

The Advanced Transportation Technology Initiative [ATT], with centers throughout California, provides leadership, guidance and coordination in the development of curricula and technical training programs related to alternative fueled vehicles and other emerging transportation technologies. ATT initiative programs result in consistent, replicable curricula, services and programs tailored to unique regional needs while training technicians to meet the challenges of tomorrow's rapidly developing, technologically driven transportation technologies.

National Automotive Center (NAC), in Detroit, Michigan, is the Nation's unique laboratory for the development and execution of collaborative research to achieve military ground - vehicle superiority for the U.S. Army. The NAC identifies dual needs of the Department of Defense and the commercial automotive sector and then initiates joint government, industry and academic programs to develop and insert new technology into current and future fleets of military vehicles.

Course Contents

- MODULE 1 HYDROGEN P**ROPERTIES
- MODULE 2 HYDROGEN U**SE
- MODULE 3 HYDROGEN U**SE IN **I**NTERNAL **C**OMBUSTION **E**NGINES
- MODULE 4 FUEL C**ELL **T**ECHNOLOGY
- MODULE 5 FUEL C**ELL **S**YSTEMS
- MODULE 6 FUEL C**ELL **E**NGINE **S**AFETY
- MODULE 7 FUEL C**ELL **B**US **M**AINTENANCE
- MODULE 8 FUEL C**ELL **H**YBRID **E**LECTRIC **V**EHICLES
- MODULE 9 A**CTS, **C**ODES, **R**EGULATIONS AND **G**UIDELINES
- MODULE 10 M**AINTENANCE AND **F**UELING **F**ACILITY **R**EQUIREMENTS
- MODULE 11 G**LOSSARY AND **C**ONVERSIONS

Scope

This course covers hydrogen properties, use and safety, fuel cell technology and its systems, fuel cell engine design and safety, and design and maintenance of a heavy duty fuel cell bus engine. The different types of fuel cells and hybrid electric vehicles are presented, however, the system descriptions and maintenance procedures focus on proton-exchange-membrane (PEM) fuel cells with respect to heavy duty transit applications. The PEM fuel cell engine was chosen as it is the most promising for automotive applications, and its transit application is currently the most advanced.

Specific fuel cell system descriptions and their maintenance is based on the Phase 3 and 4 fuel cell buses designed and built by XCELLSiS Fuel Cell Engines, Inc. This information represents the most complete description of fuel cell bus maintenance currently available, although it cannot cover all hardware configurations and variations or anticipate future developments.

Fuel cell technology is proprietary to those organizations developing it, and subject to patents, confidentiality agreements and copyright. Consequently, the details of fuel cell stack design, their construction methods and fuel cell engine control systems cannot be presented in detail.

The various methods of procuring, storing and transporting hydrogen are presented, but the practical material only covers hydrogen stored on a vehicle as a high-pressure gas. This course does *not* include hydrogen produced by means of an on-board reformer, or stored as a cryogenic liquid on a vehicle.

This course is part of an emerging curriculum under development by the College of the Desert in support of a "Tech Prep Associate Degree" in Advanced Transportation Technologies. This program starts at the high school level with basic automotive technologies and progresses through a rigorous program that includes instruction in electronics, engine performance, alternative fuels and advanced power train technologies. This manual is one of the primary reference books for the study of renewable energies and the use of hydrogen as a fuel for transportation purposes.

Completion of this course does not qualify the student for high-pressure cylinder certification or for any other form of high-pressure gas certification. The College of the Desert offers the following related courses pertaining to CNG high-pressure gas training and cylinder safety and certification training:

- CNG Cylinder Safety and Certification Course (12 Hour Course)
- Medium & Heavy-Duty Gaseous Fuel Engines and Fuel Systems (40 Hour Course)

Bibliography

Appleby, A. J., and F. R. Foulkes, *Fuel Cell Handbook*, New York, NY: Van Nostrand Reinhold, 1989.

Asimov, Isaac, *Understanding Physics, Vol. I: Motion, Sound and Heat*, New York, NY: Barnes and Noble Books, 1966.

Ballard Power Systems, *The Ballard Fuel Cell: An Overview*, Burnaby, BC, n.d., Doc. No. 710.740.003.

Brady, James E., and Gerard E. Humiston, *General Chemistry: Principles and Structure, 2 ed.*, New York, NY: John Wiley and Sons, 1978.

Canadian Hydrogen Association and National Hydrogen Association, *The Sourcebook for Hydrogen Applications*, for the Department of Natural Resources Canada and the U.S. Department of Energy, Montreal, QC: TISEC Inc., 1998.

Cognizant Media Production, *Hydrogen: A Matter of Safety Video* and Companion Guide, Studio City, CA: Hydrogen 2000, Inc., n.d.

College of the Desert, *Medium & Heavy Duty Gaseous Fuel Engines & Fuel Systems*, Palm Desert, CA: College of the Desert, 2001.

CylTek Labs Inc., *Natural Gas Vehicle Cylinder Care and Maintenance Handbook*, for the Gas Research Institute, Natural Gas Vehicle Coalition, Chicago, IL, 1997, Doc. No. GRI-97/0250.

EDO Canada Limited, *EDO Literider NGV Cylinder, All Composite Natural Gas Cylinder* Video, 1993.

Ford Motor Company, *Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System For Transportation Applications: Hydrogen Vehicle Safety Report*, for the U.S. Department of Energy, Office of Transportation Technologies, Dearborn, MI, 1997, Doc. No. DOE/CE/50389-502.

Haile, Sossina M. et al., *Solid Acids as Fuel Cell Electrolytes*, Materials Science, California Institute of Technology, Pasadena, CA, *Nature* Vol. 410 pp. 910-913, April 19, 2001.

Hansel, James G., *Safety Considerations for Handling Hydrogen: A Seminar for Presentation to Ford Motor Company*, Allentown, PA, June 12, 1998

National Aeronautics and Space Administration, Office of Mission Assurance, *Safety Standards for Hydrogen and Hydrogen Systems*, Washington, DC, 1997, Doc. No. NSS 1740.16.

Norbeck, Joseph M. et al, *Hydrogen Fuel for Surface Transportation*, Warrendale, PA: Society of Automotive Engineers, Inc., 1996

Public Works Canada, *Metric Conversion Handbook for Mechanical Engineers in the Building Industry*, Ottawa, ON: Public Relations and Information Services, 1984, Doc. No. W31-34/1984E.

Technology and Management Systems, Inc., *Design Guidelines for Transit Systems Using Hydrogen as an Alternative Fuel: Final Report*, for the South Coast Air Quality Management District, Burlington, MA, 1996.

Van Wylen, Gordon J., and Richard E. Sonntag, *Fundamentals of Classical Thermodynamics SI Version 2e* Revised Printing, New York, NY: John Wiley & Sons, Inc., 1978.

Westinghouse Savannah River Company, *Regulations, Codes, and Standards for Hydrogen Fueled Vehicles*, Aiken, SC, 1995.

XCELLSiS Fuel Cell Engines, Inc., *Fuel Cell Bus Maintenance Manual - Phase 4*, Burnaby, BC, 2000.

XCELLSiS Fuel Cell Engines, Inc., *Fuel Cell Powered Bus Maintenance Manual - Phase 3*, Burnaby, BC, 1998.

XCELLSiS Fuel Cell Engines, Inc., *Safety Considerations for Hydrogen Capable Fueling and Maintenance Facilities*, Burnaby, BC, 2000.

MODULE 1:

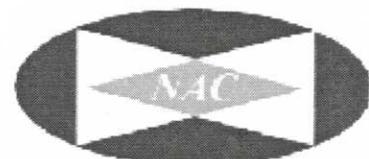
Hydrogen Properties

College of the Desert

Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

1.1	A TOMIC S TSTRUCTURE	1-1
1.2	P HYSICAL P ROPERTIES	1-4
1.2.1	S TATE	1-4
1.2.2	O DOR, C OLOR AND T ASTE	1-5
1.2.3	T OXICITY	1-5
1.2.4	D ENSITY AND R ELATED M EASURES	1-7
1.2.5	L EAKAGE	1-9
1.3	C HEMICAL P ROPERTIES	1-12
1.3.1	R EACTIVITY	1-12
1.3.2	E NERGY	1-14
1.3.3	F LAMMABILITY	1-17
1.3.4	H YDROGEN E MBRITTLEMENT	1-25
1.4	G AS L AWS	1-26
1.5	K EY E NGINEERING P ARAMETERS AND T HEIR M EASUREMENT	1-31
1.5.1	P RESSURE	1-31
1.5.2	T EMPERATURE	1-34
1.5.3	V OLUME AND C APACITY	1-36
1.5.4	M ASS AND W EIGHT	1-38
1.5.5	M ASS F LOW	1-39

OBJECTIVES

At the completion of this module, the technician will understand:

- the atomic structure of hydrogen
- the physical and chemical properties of hydrogen
- how hydrogen compares to hydrocarbon fuels in terms of energy, flammability and safety
- the fundamental gas laws
- how pressure, temperature and mass flow are measured
- the units of pressure, temperature, volume, mass and mass flow as they relate to gases

1.1 Atomic Structure

Key Points & Notes

Hydrogen is by far the most plentiful element in the universe, making up 75% of the mass of all visible matter in stars and galaxies.

Hydrogen is the simplest of all elements. You can visualize a hydrogen atom as a dense central nucleus with a single orbiting electron, much like a single planet in orbit around the sun. Scientists prefer to describe the electron as occupying a “probability cloud” that surrounds the nucleus somewhat like a fuzzy, spherical shell.

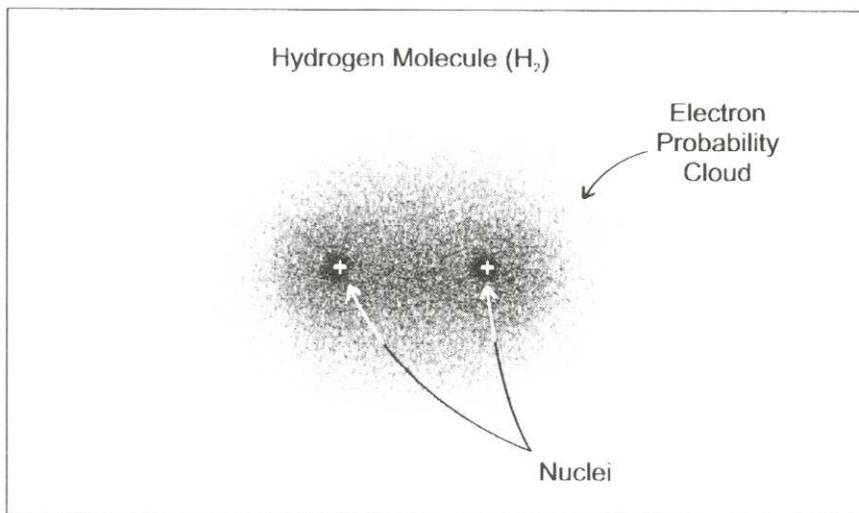


Figure 1-1 Atomic Structure of a Hydrogen Molecule

In most hydrogen atoms, the nucleus consists of a single proton, although a rare form (or “isotope”) of hydrogen contains both a proton and a neutron. This form of hydrogen is called deuterium or heavy hydrogen. Other isotopes of hydrogen also exist, such as tritium with two neutrons and one proton, but these isotopes are unstable and decay radioactively.

Most of the mass of a hydrogen atom is concentrated in its nucleus. In fact, the proton is more than 1800 times more massive than the electron. Neutrons have almost the same mass as protons. However, the radius of the electron’s orbit, which defines the size of the atom, is approximately 100,000 times as large as the radius of the nucleus! Clearly, hydrogen atoms consist largely of empty space. Atoms of all elements consist largely of empty space, although all others are heavier and have more electrons.

A proton has a positive electrical charge, and an electron has a negative electrical charge. Neutrons do not carry a charge.

Together, the charges associated with the proton and electron of each hydrogen atom cancel each other out, so that individual hydrogen atoms are electrically neutral.

Chemically, the atomic arrangement of a single electron orbiting a nucleus is highly reactive. For this reason, hydrogen atoms naturally combine into molecular pairs (H_2 instead of H). To further complicate things, each proton in a hydrogen pair has a field associated with it that can be visualized and described mathematically as a “spin”. Molecules in which both protons have the same spin are known as “orthohydrogen”. Molecules in which the protons have opposite spins are known as “parahydrogen”.

Over 75% of normal hydrogen at room temperature is orthohydrogen. This difference becomes important at very low temperatures since orthohydrogen becomes unstable and changes to the more stable parahydrogen arrangement, releasing heat in the process. This heat can complicate low temperature hydrogen processes, particularly liquefaction.

Composition of Other Fuels

It is natural for us to compare hydrogen to other hydrocarbon fuels with which we are more familiar. All hydrocarbon fuels are molecular combinations of carbon and hydrogen atoms. There are thousands of types of hydrocarbon compounds, each with a specific combination of carbon and hydrogen atoms in a unique geometry.

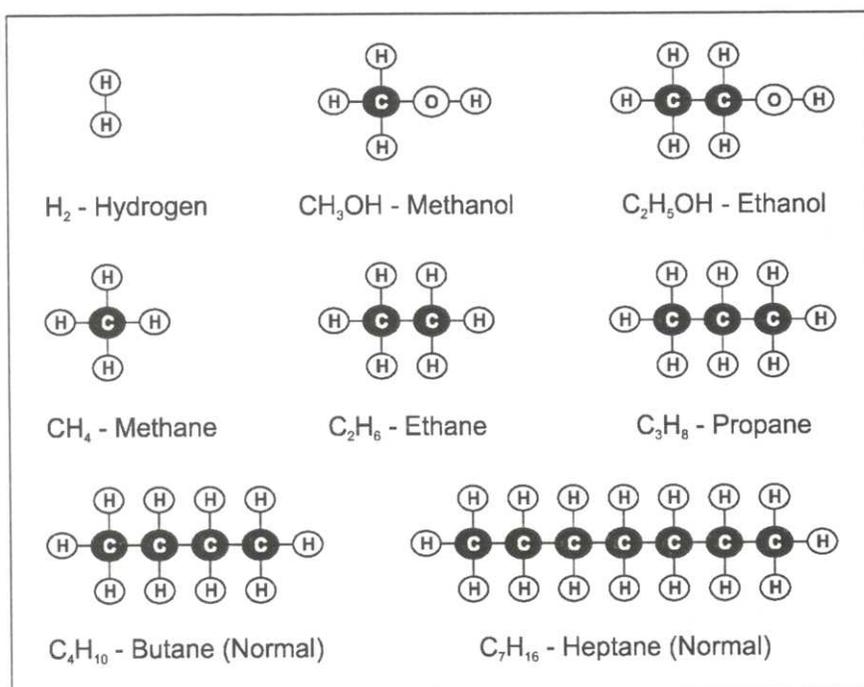
The simplest of all hydrocarbons is methane, which is the principal constituent of natural gas. (Other components of natural gas include ethane, propane, butane and pentane as well as impurities.) Methane has the chemical formula CH_4 , which means that each molecule has four hydrogen atoms and one carbon atom.

Other common hydrocarbons are ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). These are all considered light hydrocarbons since they contain less than five carbon atoms per molecule and therefore have low molecular weight (a carbon atom is almost 12 times as heavy as a hydrogen atom).

Gasoline is composed of a mixture of many different hydrocarbons, but an important constituent is heptane (C_7H_{16}). Gasoline, diesel, kerosene, and compounds found in asphalt, heavy oils and waxes, are considered heavy hydrocarbons as they contain many carbon atoms per molecule, and therefore have high molecular weight.

The lightest hydrocarbons are gases at normal atmospheric pressure and temperature. Heavier hydrocarbons, with 5 to 18 carbon atoms per compound, are liquid at ambient conditions and have increasing viscosity with molecular weight.

Other chemical fuels include alcohols whose molecules combine an oxygen/hydrogen atom pair (OH) with one or more hydrocarbon groups. Common alcohol fuels are methanol (CH_3OH) and ethanol ($\text{C}_2\text{H}_5\text{OH}$). These may be blended with hydrocarbons for use in internal combustion engines.



Key Points & Notes

Figure 1-2 Chemical Structure of Common Fuels

1.2 Physical Properties

Key Points & Notes

1.2.1 State

All substances exist on earth as either a gas, liquid or solid. Most substances will change from one of these states to another depending on the temperature and pressure of their surroundings. In general, a gas can be changed into a liquid by reducing its temperature, and a liquid to a solid by reducing its temperature further. To some extent, an increase in pressure will cause a substance to liquefy and solidify at higher temperature than would otherwise be required.

The transition from liquid to gas is known as boiling and the transition from liquid to solid as freezing. Accordingly, each substance has a characteristic boiling temperature and freezing temperature (at a given pressure). The opposite transitions, from gas to liquid and solid to liquid, are known as condensation and melting respectively. The condensation temperature is the same as the boiling temperature and the melting temperature is the same as the freezing temperature. The process of condensation is also known as liquefaction and the process of freezing is also known as solidification.

Boiling and freezing temperatures are most meaningfully compared relative to “absolute zero”. Absolute zero (0 °R; 0 K; -459.69 °F; -273.15°C) is the lowest temperature in the universe at which all molecular motion stops.

Hydrogen has the second lowest boiling point and melting points of all substances, second only to helium. Hydrogen is liquid below its boiling point of 20 K (-423 °F; -253 °C) and solid below its melting point of 14 K (-434 °F; -259 °C) and atmospheric pressure.

Obviously, these temperatures are extremely low. Temperatures below -100 °F (200 K; -73 °C) are collectively known as cryogenic temperatures, and liquids at these temperatures are known as cryogenic liquids.

The boiling point of a fuel is a critical parameter since it defines the temperature to which it must be cooled in order to store and use it as a liquid. Liquid fuels take up less storage space than gaseous fuels, and are generally easier to transport and handle. For this reason, fuels that are liquid at atmospheric conditions (such as gasoline, diesel, methanol and ethanol) are particularly convenient. Conversely, fuels that are gases at atmospheric conditions (such as hydrogen and natural gas) are less convenient as they must be stored as a pressurized gas or as a cryogenic liquid.

The boiling point of a pure substance increases with applied pressure—up to a point. Propane, with a boiling point of -44°F (-42°C), can be stored as a liquid under moderate pressure, although it is a gas at atmospheric pressure. (At temperatures of 70°F (21°C) a minimum pressure of 111 psig (7.7 barg) is required for liquefaction). Unfortunately, hydrogen's boiling point can only be increased to a maximum of -400°F (-240°C) through the application of approximately 195 psig (13 barg), beyond which additional pressure has no beneficial effect.

Hydrogen as a vehicle fuel can be stored either as a high-pressure gas or as a cryogenic liquid (Section 2.2).

1.2.2 Odor, Color and Taste

Pure hydrogen is odorless, colorless and tasteless. A stream of hydrogen from a leak is almost invisible in daylight. Compounds such as mercaptans and thiophanes that are used to scent natural gas may not be added to hydrogen for fuel cell use as they contain sulfur that would poison the fuel cells.

Hydrogen that derives from reforming other fossil fuels (Section 2.1.2) is typically accompanied by nitrogen, carbon dioxide, carbon monoxide and other trace gases. In general, all of these gases are also odorless, colorless and tasteless.

1.2.3 Toxicity

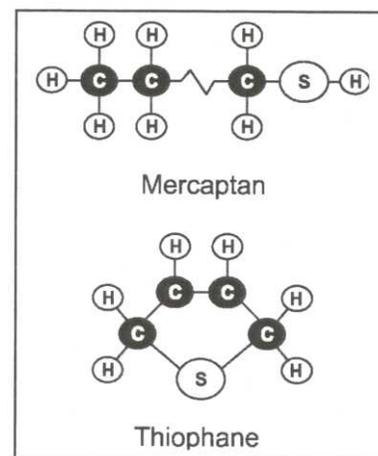
Hydrogen is non-toxic but can act as a simple asphyxiant by displacing the oxygen in the air.

Asphyxiation

Oxygen levels below 19.5% are biologically inactive for humans. Effects of oxygen deficiency may include rapid breathing, diminished mental alertness, impaired muscular coordination, faulty judgement, depression of all sensations, emotional instability and fatigue. As asphyxiation progresses, dizziness, nausea, vomiting, prostration and loss of consciousness may result, eventually leading to convulsions, coma and death. At concentrations below 12%, immediate unconsciousness may occur with no prior warning symptoms.

In an enclosed area, small leaks pose little danger of asphyxiation whereas large leaks can be a serious problem since the hydrogen diffuses quickly to fill the volume. The potential for asphyxiation in unconfined areas is almost negligible due to the high buoyancy and diffusivity of hydrogen.

Key Points & Notes



Inhaled hydrogen can result in a flammable mixture within the body. Inhaling hydrogen can lead to unconsciousness and asphyxiation.

Key Points & Notes

Other Gases Accompanying Hydrogen

Gases that accompany hydrogen when reforming other fossil fuels, such as nitrogen, carbon dioxide, carbon monoxide and other trace gases, can also act as asphyxiants by displacing oxygen. In addition, carbon monoxide is a poisonous gas that is a severe health hazard.

*Carbon Monoxide*

The affinity of hemoglobin (in the blood) for carbon monoxide is 200–300 times greater than its affinity for oxygen. As a result, inhalation of carbon monoxide quickly restricts the amount of oxygen in the bloodstream and asphyxiation ensues. Asphyxiation can continue for some time after a victim is moved to fresh air.

Depending on levels and duration of exposure, the symptoms may include headache, dizziness, heart palpitations, weakness, confusion, or nausea, leading to convulsions, eventual unconsciousness and death. With repeated long-term overexposures, carbon monoxide can damage the central nervous system and possibly lead to hardening of arteries. Since carbon monoxide is odorless, colorless and tasteless, there is no warning of its presence other than the symptoms it causes.

Published exposure limits vary somewhat depending on the regulating body. Typical values state that exposure to carbon monoxide becomes a health hazard when it exceeds the time weighted average of 25 molar ppm over 8 hours, or 100 molar ppm over 15 minutes. An exposure of 1200 ppm poses immediate danger without warning symptoms.

Carbon monoxide is poisonous.

Carbon monoxide is flammable over a very wide range of concentrations in air (12.5 – 74%). As a result, even small leaks of carbon monoxide have the potential to burn or explode. Leaked carbon monoxide can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion. The autoignition temperature of carbon monoxide is 609 °C (1128 °F). Carbon monoxide has almost the same density as air and will therefore not diffuse by rising. Carbon monoxide burns with a characteristic blue flame.



A mixture of carbon monoxide and air is potentially flammable and explosive, and can be ignited by a spark or hot surface!

Key Points & Notes

1.2.4 Density and Related Measures

Hydrogen has lowest atomic weight of any substance and therefore has very low density both as a gas and a liquid.

*Density*

Density is measured as the amount of mass contained per unit volume. Density values only have meaning at a specified temperature and pressure since both of these parameters affect the compactness of the molecular arrangement, especially in a gas. The density of a gas is called its vapor density, and the density of a liquid is called its liquid density.

Substance	Vapor Density (at 68 °F; 20 °C, 1 atm)	Liquid Density (at normal boiling point, 1 atm)
Hydrogen	0.005229 lb/ft ³ (0.08376 kg/m ³)	4.432 lb/ft ³ (70.8 kg/m ³)
Methane	0.0406 lb/ft ³ (0.65 kg/m ³)	26.4 lb/ft ³ (422.8 kg/m ³)
Gasoline	0.275 lb/ft ³ (4.4 kg/m ³)	43.7 lb/ft ³ (700 kg/m ³)

Table 1-2 Vapor and Liquid Densities of Comparative Substances

Specific Volume

Specific volume is the inverse of density and expresses the amount of volume per unit mass. Thus, the specific volume of hydrogen gas is 191.3 ft³/lb (11.9 m³/kg) at 68 °F (20 °C) and 1 atm, and the specific volume of liquid hydrogen is 0.226 ft³/lb (0.014 m³/kg) at -423 °F (-253 °C) and 1 atm.

Specific Gravity

A common way of expressing *relative* density is as specific gravity. Specific gravity is the ratio of the density of one substance to that of a reference substance, both at the same temperature and pressure.

For vapors, air (with a density of 0.0751 lb/ft³; 1.203 kg/m³) is used as the reference substance and therefore has a specific gravity of 1.0 relative to itself. The density of other vapors are then expressed as a number greater or less than 1.0 in proportion to its density relative to air. Gases with a specific gravity greater than 1.0 are heavier than air; those with a specific gravity less than 1.0 are lighter than air.

Gaseous hydrogen, with a density of 0.00523 lb/ft³, has a specific gravity of 0.0696 and is thus approximately 7% the density of air.

For liquids, water (with a density of 62.4 lb/ft³; 1000 kg/m³) is used as the reference substance, so has a specific gravity of 1.0 relative to itself. As with gases, liquids with a specific gravity greater than 1.0 are heavier than water; those with a specific gravity less than 1.0 are lighter than water.

Liquid hydrogen, with a density of 4.432 lb/ft³, has a specific gravity of 0.0708 and is thus approximately (and coincidentally) 7% the density of water.

Expansion Ratio

The difference in volume between liquid and gaseous hydrogen can easily be appreciated by considering its expansion ratio. Expansion ratio is the ratio of the volume at which a gas or liquid is stored compared to the volume of the gas or liquid at atmospheric pressure and temperature.

When hydrogen is stored as a liquid, it vaporizes upon expansion to atmospheric conditions with a corresponding increase in volume. Hydrogen's expansion ratio of 1:848 means that hydrogen in its gaseous state at atmospheric conditions occupies 848 times more volume than it does in its liquid state.

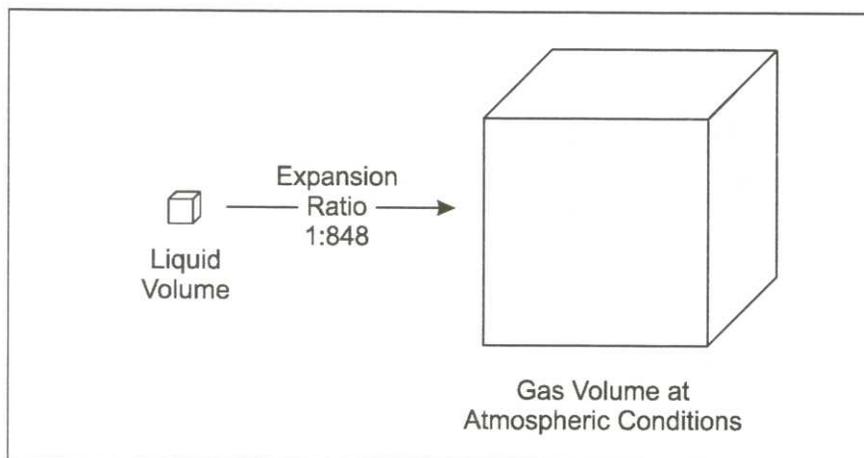


Figure 1-3 Hydrogen Liquid to Gas Expansion Ratio

When hydrogen is stored as a high-pressure gas at 3600 psig (250 barg) and atmospheric temperature, its expansion ratio to atmospheric pressure is 1:240. While a higher storage pressure increases the expansion ratio somewhat, gaseous hydrogen under any conditions cannot approach the expansion ratio of liquid hydrogen.

Hydrogen Content

Key Points & Notes

Even as a liquid, hydrogen is not very dense. Ironically, every cubic meter of water (made up of hydrogen and oxygen) contains 111 kg of hydrogen whereas a cubic meter of liquid hydrogen contains only 71 kg of hydrogen. Thus, water packs more mass of hydrogen per unit volume, because of its tight molecular structure, than hydrogen itself. This is true of most other liquid hydrogen-containing compounds as well; a cubic meter of methanol contains 100 kg of hydrogen and a cubic meter of heptane contains 113 kg. Hydrocarbons are compact hydrogen carriers with the added advantage of having higher energy density than pure hydrogen (Section 1.3.1.2).

When used as vehicle fuel, the low density of hydrogen necessitates that a large volume of hydrogen be carried to provide an adequate driving range.

1.2.5 Leakage

The molecules of hydrogen gas are smaller than all other gases, and it can diffuse through many materials considered airtight or impermeable to other gases. This property makes hydrogen more difficult to contain than other gases.

Leaks of liquid hydrogen evaporate very quickly since the boiling point of liquid hydrogen is so extremely low.

Hydrogen leaks are dangerous in that they pose a risk of fire where they mix with air (Section 1.3.1). However, the small molecule size that increases the likelihood of a leak also results in very high buoyancy and diffusivity, so leaked hydrogen rises and becomes diluted quickly, especially outdoors. This results in a very localized region of flammability that disperses quickly. As the hydrogen dilutes with distance from the leakage site, the buoyancy declines and the tendency for the hydrogen to continue to rise decreases. Very cold hydrogen, resulting from a liquid hydrogen leak, becomes buoyant soon after it evaporates.

In contrast, leaking gasoline or diesel spreads laterally and evaporates slowly resulting in a widespread, lingering fire hazard. Propane gas is denser than air so it accumulates in low spots and disperses slowly, resulting in a protracted fire or explosion hazard. Heavy vapors can also form vapor clouds or plumes that travel as they are pushed by breezes. Methane gas is lighter than air, but not nearly as buoyant as hydrogen, so it disperses rapidly, but not as rapidly as hydrogen.

For small hydrogen leaks, buoyancy and diffusion effects in air are often overshadowed by the presence of air currents from a slight ambient wind, very slow vehicle motion or the radiator fan. In general, these currents serve to disperse leaked hydrogen even more quickly with a further reduction of any associated fire hazard.

When used as vehicle fuel, the propensity for hydrogen to leak necessitates special care in the design of the fuel system to ensure that any leaks can disperse with minimum hindrance, and the use of dedicated leak detection equipment on the vehicle and within the maintenance facility.

Hydrogen leaks pose a potential fire hazard.

Key Points & Notes



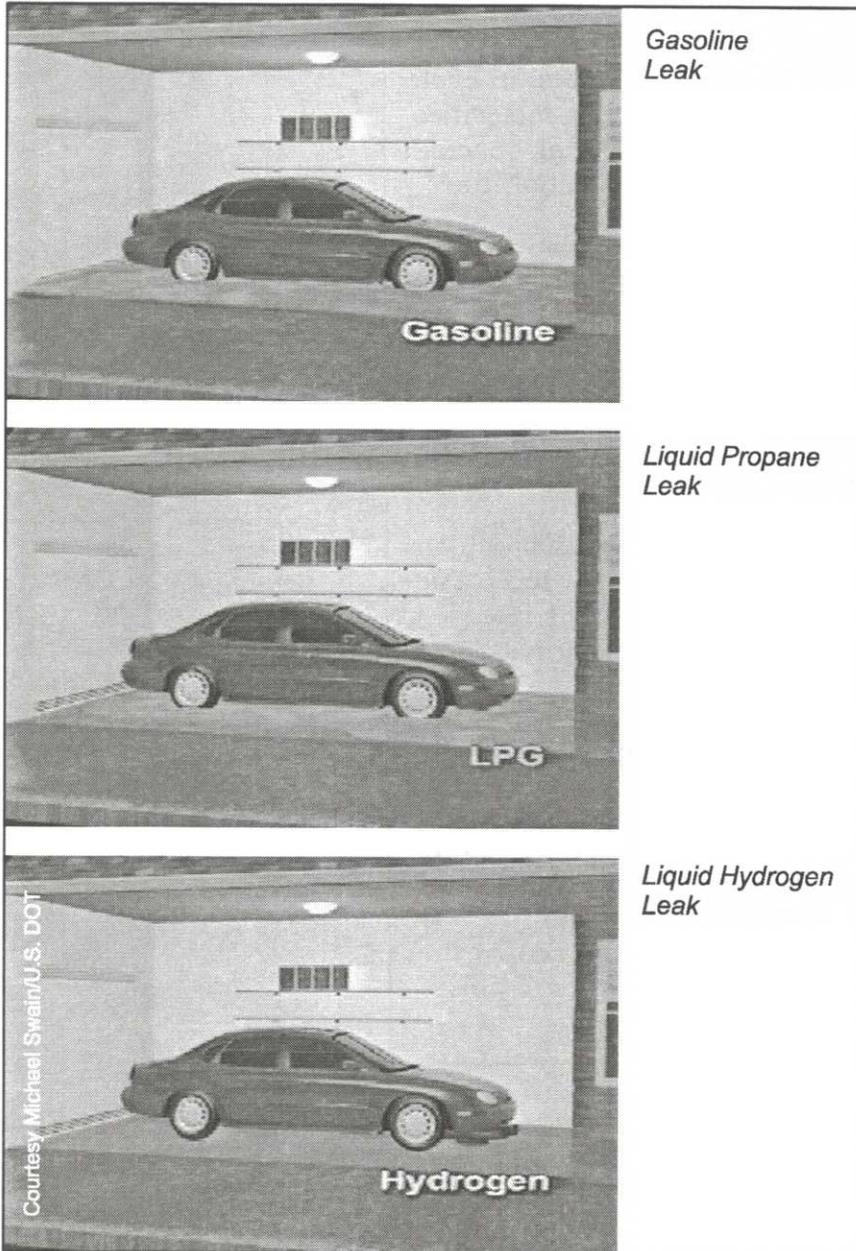


Figure 1-4 Fuel Leak Simulations

Key Points & Notes

1.3 Chemical Properties

Key Points & Notes

1.3.1 Reactivity

High reactivity is characteristic of all chemical fuels. In each case, a chemical reaction occurs when the fuel molecules form bonds with oxygen (from air) so that the final, reacted molecules are at a lower energy state than the initial, unreacted molecules.

As the molecules react, the change in chemical energy state is accompanied by a corresponding release of energy that we can exploit to do useful work. This is true in both a combusive reaction (as in an internal combustion engine where the energy is released explosively as heat) or in an electrochemical reaction (as in a battery or fuel cell where the energy is released as an electrical potential and heat).

This chemical energy release is analogous to that which occurs when water flows from a high level to a low level. The water at the high level has potential energy that is released as it falls to the low level. This energy can be harnessed to do useful work, such as turning a turbine.

Once at the low level, the energy is spent and it cannot do further work at that level. In order to do further work, it must either fall to an even lower level, or be raised back to the high level through some external agency that inputs energy. The natural cycle of evaporation, condensation, and precipitation that returns water to a higher level is driven by solar and wind energy. Alternatively, a pump can return the water to a higher level, but the pump consumes a corresponding amount of energy.

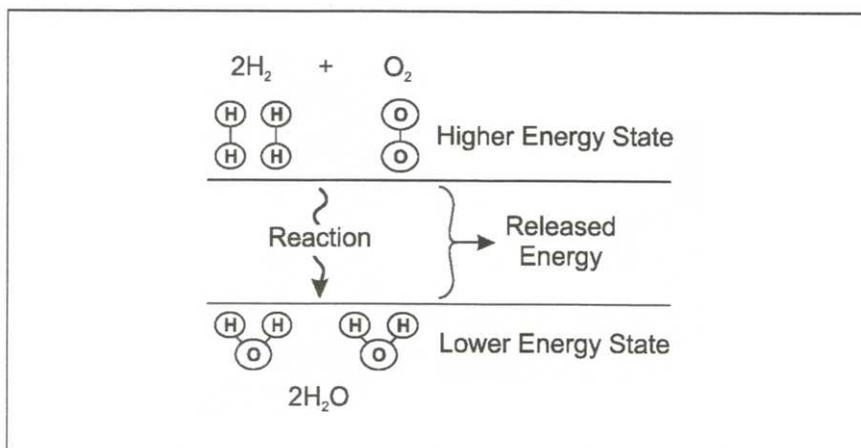


Figure 1-5 Chemical Energy States

Chemical reactions of this type often require a small amount of activation energy to get started, but then the energy re-

leased by the reaction feeds further reaction in a domino effect. Thus, when a small amount of activation energy in the form of a spark is provided to a mixture of hydrogen and oxygen, the molecules react vigorously, releasing a substantial amount of heat, with water as the final product. We experience this reaction as a fire or explosion, and the resulting water vaporizes and is invisible to us since it is a superheated vapor. (This water vapor can condense and become visible as it cools; this is the cloud we see when the space shuttle takes off.)

The water-forming reaction of hydrogen and oxygen is reversible. Thus, it is possible to convert water, at a low energy state, to hydrogen and oxygen, at a higher energy state, by adding energy slightly greater than that which was previously released (the extra to cover losses). This is the principle behind hydrogen production through electrolysis (Section 2.1.1).

Chemical By-Products of Fuel Reactions

All of the atoms present at the start of a reaction are present at the end of the reaction although they may be reorganized into different molecules. Hydrocarbon fuels, in addition to hydrogen and carbon, may contain other impurities such as sulfur. Air, in addition to being a ready source of oxygen, also consists of 78% nitrogen and 1% trace gases.

The presence of carbon, nitrogen and sulfur (as well as unreacted hydrocarbons) result in chemical compounds during combustion that cause smog with serious health and environmental consequences:

- Oxygen reacts with carbon to form carbon monoxide (CO) and carbon dioxide (CO₂). CO₂ is benign to human beings and does not produce smog, but is a greenhouse gas and contributes to global warming. CO, on the other hand, is poisonous to humans and severely limits the blood's ability to transport oxygen to body tissues resulting in dizziness, headaches, impaired coordination and death. The formation of CO is favored by lack of air during combustion and therefore leaner running engines emit less CO. Any reduction in CO formation is accompanied by a proportional increase in CO₂ formation.
- Oxygen reacts with nitrogen to form oxides of nitrogen (NO_x). Oxides of nitrogen damage lung tissue and act as a precursor to ozone, which irritates the respiratory tract and eyes, decreases the lungs' ability to work, and causes both cough and chest pain. The formation of NO_x is favored by high combustion temperatures (2700 °F; 1480

"In the United States, emissions from 190 million cars, trucks and buses account for half of all air pollution – more than 80% in major cities – and one-third of carbon dioxide emissions"

— American Methanol Institute, 1998

°C) thus, advanced ignition and increased pressure ratios tend to increase NO_x emissions since these increase the combustion temperature. Lean burning engines typically reduce NO_x emissions. Diesel engines, however, generate high NO_x emissions when operating lean under low load conditions.

- Oxygen reacts with sulfur to form oxides of sulfur (SO_x). Sulfur also forms the basis for soot, which is a form of particulate matter. Large soot particles are visible and can be filtered out of the air, or coughed out of the respiratory system. Very small soot particles (<2.5 microns) are not visible and can lodge in the lungs and cause cancer.
- Hydrocarbon emissions pass into the atmosphere through incomplete combustion and evaporation. Hydrocarbons are either volatile organic compounds (VOC's) or reactive hydrocarbons (RHC). The RHC's, such as gasoline, produce photochemical smog (visual pollution). VOC's, such as natural gas, do not produce smog. Unburned hydrocarbons act as precursor to ozone just like NO_x emissions.

The type of fuel and the use of post-combustion catalytic converters affect the amount and type of smog pollution. Light hydrocarbons are relatively rich in hydrogen and therefore provide less carbon atoms for CO and CO₂ formation. Non-sulfur containing fuels eliminate SO_x and soot.

Hydrogen is a nearly ideal fuel in terms of smog reduction when combusted. Hydrogen contains no carbon or sulfur, so no CO, CO₂ or SO_x or soot is produced during combustion (although the combustion of lubricating oil may result in trace amounts). Hydrogen allows for leaner combustion, resulting in lower combustion temperatures and very low NO_x emissions. Hydrogen is non-toxic so uncombusted hydrogen does not pose a direct health risk.

Hydrogen is an ideal fuel in terms of smog reduction when used electrochemically in a fuel cell, rather than combusted. Hydrogen in a fuel cell produces zero harmful emissions. Oxides of nitrogen are completely eliminated due to the low operating temperature (175 °F; 80 °C) of the cells. Lubricating oil is not present and is therefore not reacted.

1.3.2 Energy

Energy Content

Every fuel can liberate a fixed amount of energy when it reacts completely with oxygen to form water. This energy

Key Points & Notes

Use of hydrogen in the U.S. transportation sector alone could reduce 70% of CO emissions, 41% of NO_x emissions, 38% of hydrocarbon emissions, and 30% of human-generated CO₂ emissions.

content is measured experimentally and is quantified by a fuel's higher heating value (HHV) and lower heating value (LHV). The difference between the HHV and the LHV is the "heat of vaporization" and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam.

The higher and lower heating values of comparative fuels are indicated in Table 1-3. Although the terms HHV and LHV do not apply to batteries, the energy density of a lead acid battery is approximately 46 Btu/lb (0.108 kJ/g).

Fuel	Higher Heating Value (at 25 °C and 1 atm)	Lower Heating Value (at 25 °C and 1 atm)
Hydrogen	61,000 Btu/lb (141.86 kJ/g)	51,500 Btu/lb (119.93 kJ/g)
Methane	24,000 Btu/lb (55.53 kJ/g)	21,500 Btu/lb (50.02 kJ/g)
Propane	21,650 Btu/lb (50.36 kJ/g)	19,600 Btu/lb (45.6 kJ/g)
Gasoline	20,360 Btu/lb (47.5 kJ/g)	19,000 Btu/lb (44.5 kJ/g)
Diesel	19,240 Btu/lb (44.8 kJ/g)	18,250 Btu/lb (42.5 kJ/g)
Methanol	8,580 Btu/lb (19.96 kJ/g)	7,760 Btu/lb (18.05 kJ/g)

Table 1-3 Heating Values of Comparative Fuels

Gaseous fuels are already vaporized so no energy is required to convert them to a gas. The water that results from both a combustive reaction and the electrochemical reaction within a fuel cell occurs as steam, therefore the lower heating value represents the amount of energy available to do external work.

Both the higher and lower heating values denote the amount of energy (in Btu's or Joules) for a given *weight* of fuel (in pounds or kilograms). Hydrogen has the highest energy-to-weight ratio of any fuel since hydrogen is the lightest element and has no heavy carbon atoms. It is for this reason that hydrogen has been used extensively in the space program where weight is crucial.

Specifically, the amount of energy liberated during the reaction of hydrogen, on a mass basis, is about 2.5 times the heat of combustion of common hydrocarbon fuels (gasoline, diesel, methane, propane, etc.) Therefore, for a given load duty, the mass of hydrogen required is only about a third of the mass of hydrocarbon fuel needed.

The high energy content of hydrogen also implies that the energy of a hydrogen gas explosion is about 2.5 times that of common hydrocarbon fuels. Thus, on an equal mass basis,

Key Points & Notes



Hydrogen Explosion

hydrogen gas explosions are more destructive and carry further. However, the duration of a conflagration tends to be inversely proportional to the combustive energy, so that hydrogen fires subside much more quickly than hydrocarbon fires.

Key Points & Notes

Energy Density

Whereas the energy content denotes the amount of energy for a given *weight* of fuel, the energy density denotes the amount of energy (in Btu's or Joules) for a given *volume* (in ft³ or m³) of fuel. Thus, energy density is the product of the energy content (LHV in our case) and the density of a given fuel.

The energy density is really a measure of how compactly hydrogen atoms are packed in a fuel. It follows that hydrocarbons of increasing complexity (with more and more hydrogen atoms per molecule) have increasing energy density. At the same time, hydrocarbons of increasing complexity have more and more carbon atoms in each molecule so that these fuels are heavier and heavier in absolute terms.

On this basis, hydrogen's energy density is poor (since it has such low density) although its energy to *weight* ratio is the best of all fuels (because it is so light). The energy density of comparative fuels, based on the LHV, is indicated in Table 1-4. The energy density of a lead acid battery is approximately 8700 Btu/ft³ (324,000 kJ/m³).

Fuel	Energy Density (LHV)
Hydrogen	270 Btu/ft ³ (10,050 kJ/m ³); gas at 1 atm and 60 °F (15 °C)
	48,900 Btu/ft ³ (1,825,000 kJ/m ³); gas at 3,000 psig (200 barg) and 60 °F (15 °C)
	121,000 Btu/ft ³ (4,500,000 kJ/m ³); gas at 10,000 psig (690 barg) and 60 °F (15 °C)
	227,850 Btu/ft ³ (8,491,000 kJ/m ³); liquid
Methane	875 Btu/ft ³ (32,560 kJ/m ³); gas at 1 atm and 60 °F (15 °C)
	184,100 Btu/ft ³ (6,860,300 kJ/m ³); gas at 3,000 psig (200 barg) and 60 °F (15 °C)
	561,500 Btu/ft ³ (20,920,400 kJ/m ³); liquid
Propane	2,325 Btu/ft ³ (86,670 kJ/m ³); gas at 1 atm and 60 °F (15 °C)
	630,400 Btu/ft ³ (23,488,800 kJ/m ³); liquid
Gasoline	836,000 Btu/ft ³ (31,150,000 kJ/m ³); liquid
Diesel	843,700 Btu/ft ³ (31,435,800 kJ/m ³); minimum; liquid
Methanol	424,100 Btu/ft ³ (15,800,100 kJ/m ³); liquid

Table 1-4 Energy Densities of Comparative Fuels

The energy density of a fuel is also affected by whether the fuel is stored as a liquid or as a gas, and if a gas, at what pressure. To put it into perspective:

- A 132-gal (500-L) diesel tank containing 880 lb (400 kg) of fuel is equivalent on an energy basis to a 2110 gal (8000 L) volume of hydrogen gas at 3600 psi (250 barg). This is a 16 times increase in volume, although the weight of the hydrogen is only 330 lb (150 kg), representing a decrease in fuel weight by a factor of about 2.8.
- The same diesel tank is equivalent to a 550-gal (2100-L) tank of liquid hydrogen. This is a 4.2 times increase in volume.
- If hydrogen is stored as a metal hydride, every kilogram of diesel fuel is replaced by approximately 4.5 kg of metal hydride to maintain the same hydrogen/diesel energy equivalence. Thus the same 132 gal (500 L) diesel tank containing 880 lb (400 kg) of fuel would have to be replaced with a hydride tank containing 3800 lb (1725 kg) of “fuel” mass.

1.3.3 Flammability

Three things are needed for a fire or explosion to occur: a fuel, oxygen (mixed with the fuel in appropriate quantities) and a source of ignition. Hydrogen, as a flammable fuel, mixes with oxygen whenever air is allowed to enter a hydrogen vessel, or when hydrogen leaks from any vessel into the air. Ignition sources take the form of sparks, flames, or high heat.

Flashpoint

All fuels burn only in a gaseous or vapor state. Fuels like hydrogen and methane are already gases at atmospheric conditions, whereas other fuels like gasoline or diesel that are liquids must convert to a vapor before they will burn. The characteristic that describes how easily these fuels can be converted to a vapor is the flashpoint. The flashpoint is defined as the temperature at which the fuel produces enough vapors to form an ignitable mixture with air at its surface.

If the temperature of the fuel is below its flashpoint, it cannot produce enough vapors to burn since its evaporation rate is too slow. Whenever a fuel is at or above its flashpoint, vapors are present. The flashpoint is not the temperature at which the fuel bursts into flames; that is the autoignition temperature.

The flashpoint is always lower than the boiling point. For fuels that are gases at atmospheric conditions (like hydrogen, methane and propane), the flashpoint is far below ambient temperature and has little relevance since the fuel is already fully vaporized. For fuels that are liquids at atmospheric conditions (such as gasoline or methanol), the flashpoint acts as a lower flammability temperature limit.

Key Points & Notes

Fuel	Flashpoint
Hydrogen	< -423 °F (< -253 °C; 20 K)
Methane	-306 °F (-188 °C; 85 K)
Propane	-156 °F (-104 °C; 169 K)
Gasoline	Approximately -45 °F (-43 °C; 230 K)
Methanol	52 °F (11 °C; 284 K)

Table 1-5 Flashpoint of Comparative Fuels

Flammability Range

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion; the fuel/air mixture is too lean.

The UFL of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the UFL, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich. Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited.

A stoichiometric mixture occurs when oxygen and hydrogen molecules are present in the exact ratio needed to complete the combustion reaction. If more hydrogen is available than oxygen, the mixture is rich so that some of the fuel will remain unreacted although all of the oxygen will be consumed. If less hydrogen is available than oxygen, the mixture is lean so that all the fuel will be consumed but some oxygen will remain. Practical internal combustion and fuel cell systems typically operate lean since this situation promotes the complete reaction of all available fuel.

One consequence of the UFL is that stored hydrogen (whether gaseous or liquid) is not flammable while stored due to the absence of oxygen in the cylinders. The fuel only

becomes flammable in the peripheral areas of a leak where the fuel mixes with the air in sufficient proportions.

Two related concepts are the lower explosive limit (LEL) and the upper explosive limit (UEL). These terms are often used interchangeably with LFL and UFL, although they are not the same. The LEL is the lowest gas concentration that will support an *explosion* when mixed with air, *contained* and ignited. Similarly, the UEL is the highest gas concentration that will support an explosion when mixed with air, contained and ignited.

An explosion is different from a fire in that for an explosion, the combustion must be contained, allowing the pressure and temperature to rise to levels sufficient to violently destroy the containment. For this reason, it is far more dangerous to release hydrogen into an enclosed area (such as a building) than to release it directly outdoors.

Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive over a wide range of concentrations (15 – 59%) at standard atmospheric temperature. The flammability limits increase with temperature as illustrated in Figure 1-6. As a result, even small leaks of hydrogen have the potential to burn or explode. Leaked hydrogen can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion. The flammability limits of comparative fuels are illustrated in Figure 1-7.

Mixtures of hydrogen and air are potentially flammable or explosive.

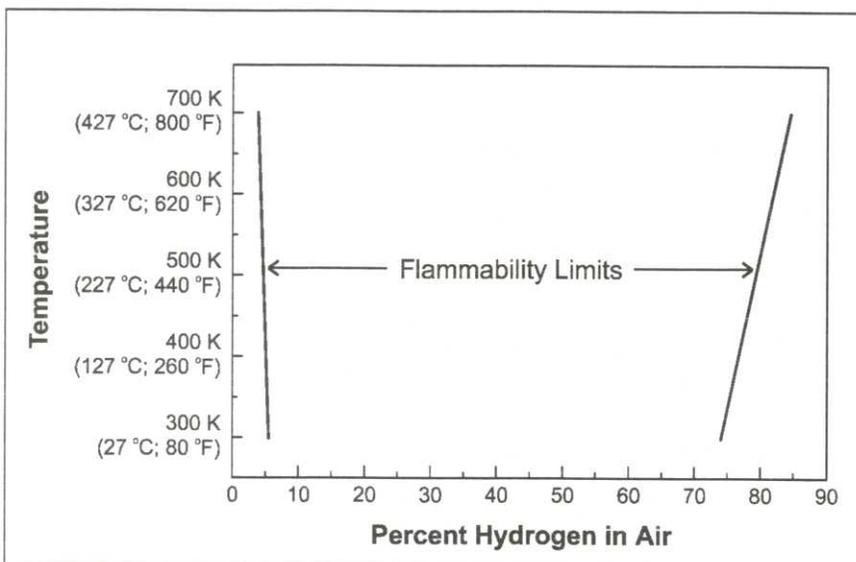


Figure 1-6 Variation of Hydrogen Flammability Limits with Temperature

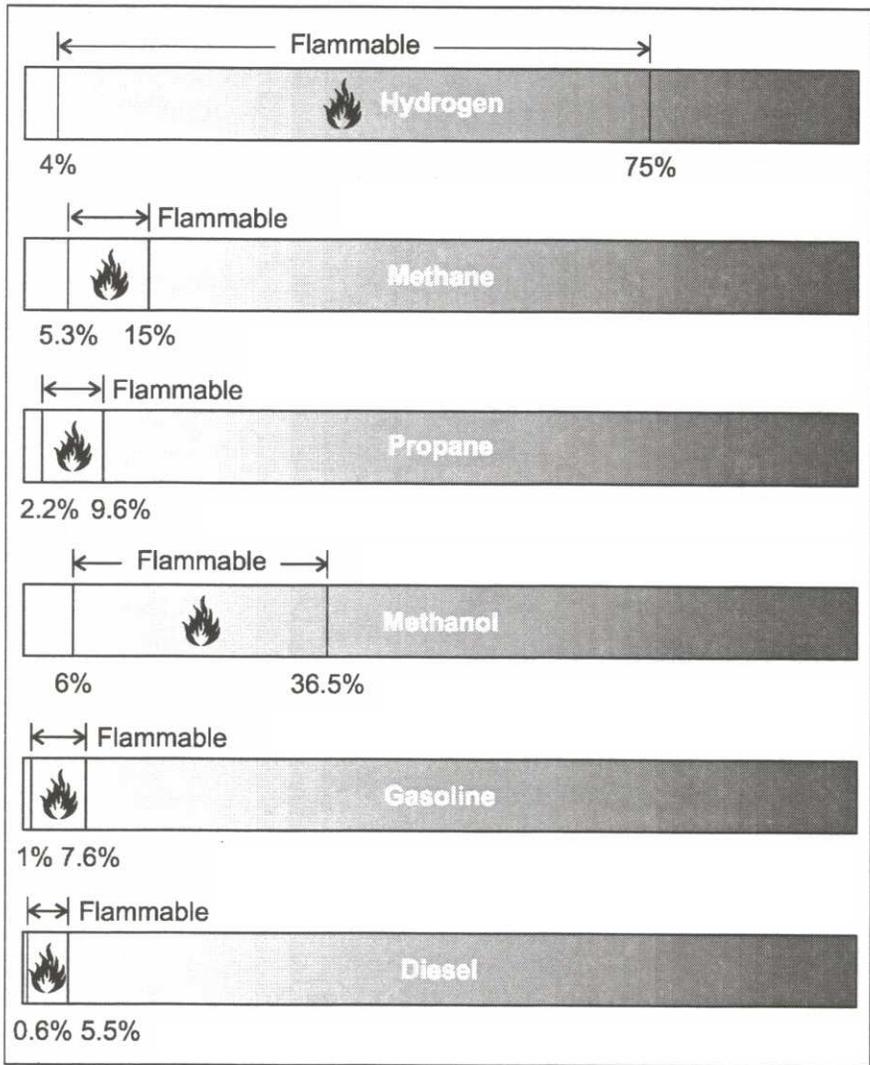


Figure 1-7 Flammability Ranges of Comparative Fuels at Atmospheric Temperature

Key Points & Notes

Autoignition Temperature

The autoignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of a source of ignition. In other words, the fuel is heated until it bursts into flame.

Each fuel has a unique ignition temperature. For hydrogen, the autoignition temperature is relatively high at 1085 °F (585 °C). This makes it difficult to ignite a hydrogen/air mixture on the basis of heat alone without some additional ignition source. The autoignition temperatures of comparative fuels are indicated in Table 1-6.

Fuel	Autoignition Temperature
Hydrogen	1085 °F (585 °C)
Methane	1003 °F (540 °C)
Propane	914 °F (490 °C)
Methanol	725 °F (385 °C)
Gasoline	450 to 900 °F (230 to 480 °C)

Key Points & Notes

Table 1-6 Autoignition Temperature of Comparative Fuels*Octane Number*

The octane number describes the anti-knock properties of a fuel when used in an internal combustion engine. Knock is a secondary detonation that occurs after fuel ignition due to heat buildup in some other part of the combustion chamber. When the local temperature exceeds the autoignition temperature, knock occurs.

The performance of the hydrocarbon octane is used as a standard to measure resistance to knock, and is assigned a relative octane rating of 100. Fuels with an octane number over 100 have more resistance to auto-ignition than octane itself. Hydrogen has a very high research octane number and is therefore resistant to knock even when combusted under very lean conditions. The octane number of comparative fuels are indicated in Table 1-7. The octane number has no specific relevance for use with fuel cells.

Fuel	Octane Number
Hydrogen	130+ (lean burn)
Methane	125
Propane	105
Octane	100
Gasoline	87
Diesel	30

Table 1-7 Octane Numbers of Comparative Fuels*Ignition Energy*

Ignition energy is the amount of external energy that must be applied in order to ignite a combustible fuel mixture. Energy from an external source must be higher than the autoignition temperature and be of sufficient duration to heat the fuel vapor to its ignition temperature. Common ignition sources are flames and sparks.

Although hydrogen has a higher autoignition temperature than methane, propane or gasoline, its ignition energy at 1.9×10^{-8} Btu (0.02 mJ) is about an order of magnitude lower and is therefore more easily ignitable. Even an invisible spark or static electricity discharge from a human body (in dry conditions) may have enough energy to cause ignition. Nonetheless, it is important to realize that the ignition energy for all of these fuels is very low so that conditions that will ignite one fuel will generally ignite any of the others.

Hydrogen has the added property of low electro-conductivity so that the flow or agitation of hydrogen gas or liquid may generate electrostatic charges that result in sparks. For this reason, all hydrogen conveying equipment must be thoroughly grounded.

Flammable mixtures of hydrogen and air can be easily ignited.

Burning Speed

Burning speed is the speed at which a flame travels through a combustible gas mixture.

Burning speed is different from flame speed. The burning speed indicates the severity of an explosion since high burning velocities have a greater tendency to support the transition from deflagration to detonation in long tunnels or pipes. Flame speed is the sum of burning speed and displacement velocity of the unburned gas mixture.

Burning speed varies with gas concentration and drops off at both ends of the flammability range. Below the LFL and above the UFL the burning speed is zero.

The burning speed of hydrogen at 8.7–10.7 ft/s (2.65–3.25 m/s) is nearly an order of magnitude higher than that of methane or gasoline (at stoichiometric conditions). Thus hydrogen fires burn quickly and, as a result, tend to be relatively short-lived.

Quenching Gap

The quenching gap (or quenching distance) describes the flame extinguishing properties of a fuel when used in an internal combustion engine. Specifically, the quenching gap relates to the distance from the cylinder wall that the flame extinguishes due to heat losses. The quenching gap has no specific relevance for use with fuel cells.

The quenching gap of hydrogen (at 0.025 in; 0.064 cm) is approximately 3 times less than that of other fuels, such as

Key Points & Notes

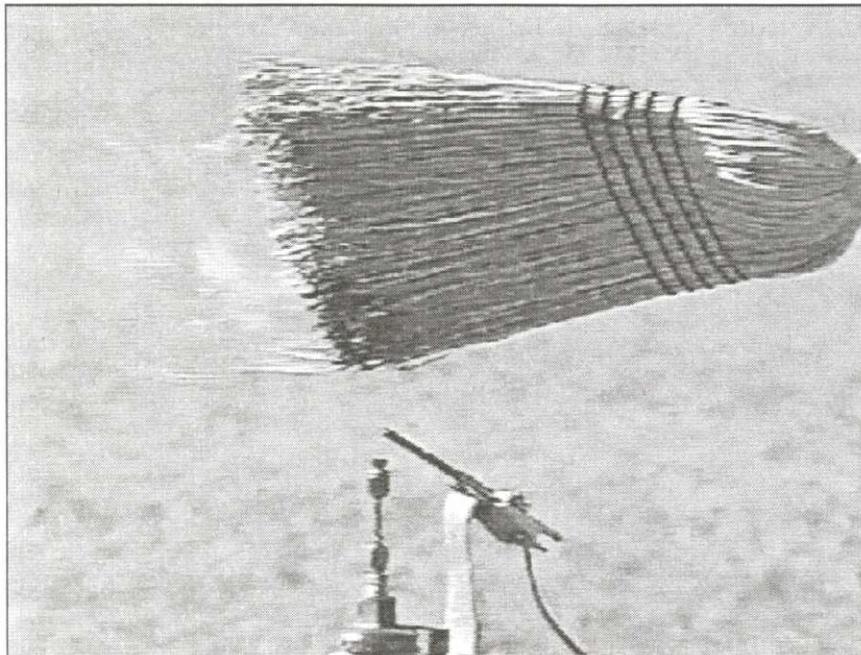


gasoline. Thus, hydrogen flames travel closer to the cylinder wall before they are extinguished making them more difficult to quench than gasoline flames. This smaller quenching distance can also increase the tendency for backfire since the flame from a hydrogen-air mixture can more readily get past a nearly closed intake valve than the flame from a hydrocarbon-air mixture.

Flame Characteristics

Hydrogen flames are very pale blue and are almost invisible in daylight due to the absence of soot. Visibility is enhanced by the presence of moisture or impurities (such as sulfur) in the air. Hydrogen flames are readily visible in the dark or subdued light. A hydrogen fire can be indirectly visible by way of emanating “heat ripples” and thermal radiation, particularly from large fires. In many instances, flames from a hydrogen fire may ignite surrounding materials that do produce smoke and soot during combustion.

Hydrogen flames are almost invisible in daylight.



Corn brooms are sometimes used by emergency response personnel to detect hydrogen flames.

Figure 1-8 Invisible Hydrogen Flame Igniting Broom

Hydrogen fires can only exist in the region of a leak where pure hydrogen mixes with air at sufficient concentrations. For turbulent leaks, air reaches the centerline of the leakage jet within about five diameters of a leakage hole, and the hydrogen is diluted to nearly the composition of air within roughly 500 to 1000 diameters. This rapid dilution implies that if the turbulent leak were into open air, the flammability

zone would exist relatively close to the leak. Therefore, when the jet is ignited, the flame length is less than 500 diameters from the hole (for example, for a 0.039 in/1 mm diameter leak, the flame length will be less than 19.7 in/0.5 m).

In many respects, hydrogen fires are safer than gasoline fires. Hydrogen gas rises quickly due to its high buoyancy and diffusivity. Consequently hydrogen fires are vertical and highly localized. When a car hydrogen cylinder ruptures and is ignited, the fire burns away from the car and the interior typically does not get very hot.

Gasoline forms a pool, spreads laterally, and the vapors form a lingering cloud, so that gasoline fires are broad and encompass a wide area. When a car gasoline tank ruptures and is ignited, the fire engulfs the car within a matter of seconds (not minutes) and causes the temperature of the entire vehicle to rise dramatically. In some instances, the high heat can cause flammable compounds to off-gas from the vehicle upholstery leading to a secondary explosion.

Key Points & Notes

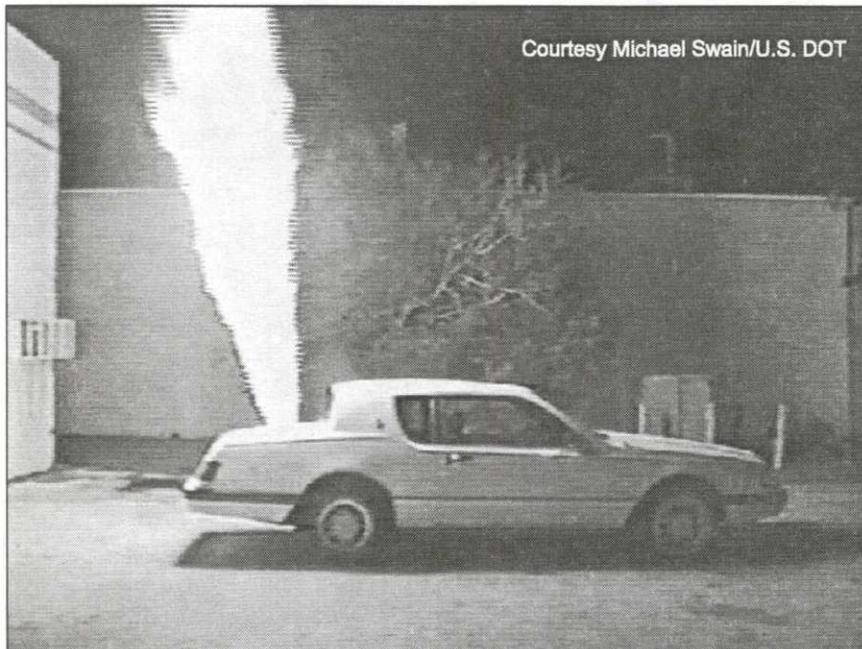


Figure 1-9 Hydrogen Flame from Ruptured Fuel Cylinder

Hydrogen burns with greater vigor than gasoline, but for a shorter time. Pools of liquid hydrogen burn very rapidly at 0.098 to 0.197 ft/min (3 to 6 cm/min) compared to 0.0098 to 0.00656 ft/min (0.3 to 1.2 cm/min) for liquid methane, and 0.00656 to 0.0295 ft/min (0.2 to 0.9 cm/min) for gasoline pools.

Hydrogen emits non-toxic combustion products when burned. Gasoline fires generate toxic smoke.

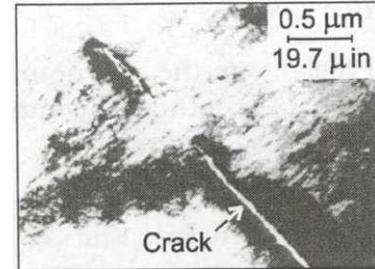
Key Points & Notes

1.3.4 Hydrogen Embrittlement

Constant exposure to hydrogen causes a phenomenon known as hydrogen embrittlement in many materials. Hydrogen embrittlement can lead to leakage or catastrophic failures in metal and non-metallic components.

The mechanisms that cause hydrogen embrittlement effects are not well defined. Factors known to influence the rate and severity of hydrogen embrittlement include hydrogen concentration, hydrogen pressure, temperature, hydrogen purity, type of impurity, stress level, stress rate, metal composition, metal tensile strength, grain size, microstructure and heat treatment history. Moisture content in the hydrogen gas may lead to metal embrittlement through the acceleration of the formation of fatigue cracks.

Materials in contact with hydrogen are subject to hydrogen embrittlement.



Hydrogen Embrittlement



1.4 Gas Laws

Key Points & Notes

Gas laws deal with how gases behave in response to changes in pressure, temperature or volume.

Pressure

Pressure is the exertion of continuous force on or against a body by another in contact with it. Pressure is expressed as force per unit area.

Since pressure is force per area (F/A), and force is mass times acceleration ($m \cdot a$), pressure can also be understood as mass times acceleration per area ($m \cdot a/A$). The atmosphere has mass and gravity accelerates this mass towards the earth, so there is atmospheric pressure on every area of earth. Atmospheric pressure is also known as air pressure or barometric pressure.

We do not feel air pressure because it is exerted in all directions, not just downward. It also acts within our bodies — this serves to balance the pressure outside our bodies so that we do not notice its presence.

Although gravity holds the atmosphere to the earth, it is unable to draw all of the air molecules to the surface of the earth. This is because the forces associated with the gas molecules' movements (as they jostle each other) are much stronger than gravity and resist being drawn together.

All gases are compressible, that is, they can be compressed into a smaller volume with pressure. The pressure of the atmosphere itself causes stratification of the air, with the densest levels near the earth's surface. The density of the atmosphere continues to decrease as we look far above the earth's surface to where the sparse air molecules are no longer different than those in interplanetary space.

Air pressure at sea level is defined as one atmosphere (1 atm), which is about 15 psia or 1 bara or 100 kPa. Air pressure varies with altitude and weather changes. At 7000 ft (2134 m) altitude, the air pressure is only 11.5 psia (0.79 bara). The weight of the air is correspondingly less at higher elevations, reducing by about 3% for every 1000 ft (305 m). The lower the pressure, the lower the boiling point of liquids, such that on the top of Mt. Everest, boiling water is little more than tepid. We notice this change in air pressure when our ears pop as we change altitude.

Pressure greater than air pressure is called positive pressure, while negative pressure is that below air pressure.

A carbureted internal combustion engine that is finely tuned at sea level, runs lean at a higher altitude.

Volume

Key Points & Notes

When we study gas within a container — a fixed volume — we find that the gas pressure is still equal in all directions (Pascal's Law). The pressure of a contained gas is the force exerted by its molecules against the walls of the container. The pressure is determined by the number of molecules within the container. The more molecules, the greater the pressure, as more molecules are colliding with the walls.

When we press more gas into a container, we move it from its lower-pressure higher-volume source to the higher-pressure lower-volume container. As we force more gas into the container (such as during fueling), the volume of the gas is reduced, while the pressure is increased.

Pressure also increases when the volume of the container is reduced, such as during the compression stroke of an internal combustion engine.

Boyle's Law: Pressure vs Volume

The relationship between pressure and volume was first shown by Boyle in 1662, who demonstrated that:

The pressure of a given mass of gas is inversely proportional to its volume at a constant temperature.

Expressed mathematically, Boyle's Law (or the first gas law) is:

$$P_1V_1 = P_2V_2$$

where:

P = absolute pressure
V = volume

Charles' Law: Temperature vs Volume

Whereas Boyle studied pressure, later scientists observed that temperature also had an effect on volume. Charles quantified the temperature change (1787), and his law (the second gas law) states that:

The volume of an ideal gas at constant pressure is directly proportional to the absolute temperature.

Charles was the first to realize that temperature had to be measured in absolute terms, leading to the definition of absolute zero. Expressed mathematically, Charles' Law (the second gas law) is:

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

where:

T = absolute temperature

V = volume

Whereas Boyle relates pressure (P) to temperature (T), Charles relates pressure (P) to temperature (T). Logically, temperature (T) also relates to pressure (P), as in:

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

Ideal Gas Law: Pressure, Temperature and Volume

The third or ideal gas law combines Boyle's and Charles' laws into the single equation:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

A change in one of the variables (absolute pressure, absolute temperature or volume) must result in a change in one or both of the other variables. The same relationship can be expressed as:

$$PV = nRT$$

where:

P = absolute pressure

V = volume

n = number of moles of gas molecules present

T = absolute temperature

R = universal gas constant = 3.4067 ft-lb/mol °F
(8.31434 Nm/mol K)

A mole is simply a collection of 6.023×10^{23} molecules. This large number turns out to be a convenient unit in chemistry, and the mass of one mole of any pure substance is known with great accuracy. For hydrogen, every mole of hydrogen molecules (H_2) has a mass of 4.445×10^{-3} lb (2.016×10^{-3} kg).

The gas relationship can therefore be written in terms of mass instead of moles *for a specific substance* as:

$$PV = mRT$$

Key Points & Notes

where:

m = mass of gas molecules present

R = specific gas constant. For hydrogen this constant is 766.8 ft-lb/lb °F (4124.18 Nm/kg K)

Furthermore, as density (ρ) is the amount of mass in a given volume (m/V), we can substitute density into the same equation:

$$P = \rho RT$$

This gas relationship was considered accurate into the 20th century, but was finally found to be only an approximation. We now describe the third gas law as the *ideal* gas law as we realize that it only describes an ideal gas, that is, a gas consisting of molecules occupying negligible space and without attraction for each other.

In reality, gas molecules do occupy space, although very little, and they do attract one another, although very weakly. The space that the molecules occupy slightly reduces the volume available to hold more gas, and the molecules attraction for each other slightly increases the pressure.

The ideal gas relationship can be used accurately to describe the behavior of real gases at pressures up to approximately 1450 psig (100 barg) at normal ambient temperatures. At higher pressures, the results become increasingly inaccurate as illustrated in Figure 1-10.

Key Points & Notes

The ideal gas law cannot be applied to liquids.

Hydrogen is commonly stored as a high-pressure gas at up to 3600 or even 5000 psig (250 to 350 barg) at ambient temperatures. Therefore, the ideal gas relationship cannot be used accurately at gas storage pressures.

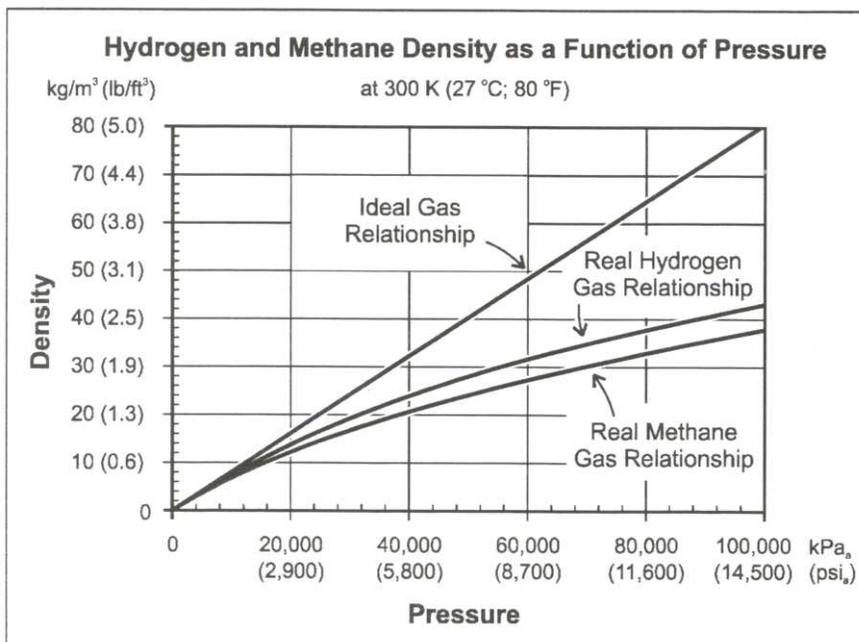


Figure 1-10 Hydrogen Density as a Function of Pressure

The resulting deviation from the ideal gas law is always in the form of compression — the gas occupies less space than the ideal gas law predicts. One of the simplest ways of correcting for this additional compression is through the addition of a compressibility factor, designated by the symbol Z .

Compressibility factors (or “ Z factors”) are derived from data obtained through experimentation and depend on temperature, pressure and the nature of the gas. The Z factor is then used as a multiplier to adjust the ideal gas law to fit actual gas behavior as follows:

$$P = Z\rho RT$$

Key Points & Notes

1.5 Key Engineering Parameters and Their Measurement

Key Points & Notes

The key parameters with respect to gases are:

- pressure
- temperature
- volume/capacity
- mass and weight
- mass flow

These parameters are measured in engineering units.

1.5.1 Pressure

Pressure can be measured by a variety of instruments, including:

- barometers and altimeters
- pressure gauges
- pressure transducers or transmitters (digital manometers)

Barometers measure atmospheric pressure, originally using mercury in a tube to measure pressure changes. Modern barometers are of aneroid type, consisting of a hermetically sealed metal box, exhausted of air. The top and bottom of the box are made of thin corrugated plates held apart by a spring. The top plate is pressed outwards by the spring and inwards by air pressure. Movement of the top plate with changes in air pressure is transferred to a pointer on a scale. The familiar altimeter is a type of sensitive aneroid barometer.

Pressure gauges are normally designed to read either *gauge* or *absolute* pressure. Gauge pressure is measured *relative* to the *pressure of the air* at sea level. Thus, gauge measurements of air pressure at sea level are always zero regardless of the units used. Absolute pressure is measured *relative* to a *perfect vacuum*. Thus, absolute measurements of air pressure at sea level result in a value of 14.7 psig (or equivalent, depending on the units).

Pressure gauges come in various designs. A U-tube manometer is a simple pressure gauge that either has both ends of the tube open to the atmosphere or one end closed in a vacuum over the scaling liquid. A ring balance pressure gauge

is similar to the U-tube type except that the tube is pivotally mounted.

Key Points & Notes

The widely used spring-tube (or Bourdon-tube) pressure gauge measures pressure on the basis of the deformation of an elastic measuring element (i.e. a curved tube). In a diaphragm pressure gauge the elastic element is a stiff metallic diaphragm held between two flanges; pressure is applied to the underside of the diaphragm and the movement of the latter is transmitted to a pointer.

A vacuum gauge is a differential pressure gauge. It measures the difference between atmospheric and less-than-atmospheric pressure.

Pressure transmitters or transducers have the advantage over pressure gauges that they can send an electronic signal to a control system. Pressure transmitters typically consist of a mechanical bellows in contact with the process stream upon which is bonded a strain gauge. As the bellows move due to a change in pressure, the strain gauge registers the motion and converts it to a proportional change in resistance. These pressure-induced resistance changes are too small to be monitored by the control system directly. As a result, a transmitter converts (conditions) the transducer resistance to a high-level analog voltage or current signal and sends this signal to the control system. This analog signal varies with pressure in the same way as the original resistance. Once received, the signal can be converted to engineering units for display on a digital readout device.

Units of Pressure

Pressure can be expressed in any unit that comprises a force divided by an area. Some common units of pressure are:

- pounds per square inch (psi)
- Pascals (Pa), Kilopascals (kPa), megapascals (MPa), and gigapascals (Gpa)
- bars and millibars (mbar)
- atmospheres (atm)

Pressure is given as either absolute, or relative to atmospheric pressure. The subscript (or postscript) *a* is used to denote absolute pressure, and *g* to denote *gauge* or pressure relative to atmospheric. When using pounds-per-square-inch, the values 15 psia and 0 psig are equivalent, as atmospheric pressure is approximately 15 psia (14.504 psig). Likewise in metric, 1.0 bara equals 0 barg.

Where no subscript is appended, it usually means the value is absolute (as in this manual), although some authors do the opposite and drop the subscript to mean gauge!

Other standard units of pressure are “inches of water” or “inches of mercury”. These measures refer to how high a column of water or mercury rises within a tube in response to pressure (at 68 °F; 20° C). Likewise, millimeters or centimeters of mercury are also used to quantify pressure. Each millimeter of mercury is also known as one “torr”.

The metric unit Pascal (Pa) is defined as one Newton per square meter (N/m^2). This unit is impractically small for most purposes, so the larger units of kilopascal ($\text{kPa} = 1000 \text{ Pa}$), megapascal ($\text{MPa} = 10^6 \text{ Pa}$), and gigapascal ($\text{Gpa} = 10^9 \text{ Pa}$) are more commonly used.

Conversions — Units of Pressure

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Standard to Standard			
psi	0.068 046	0.07	atm
psi	2.04	2	in Hg
Standard to Metric			
psi	6.894 757	7	kPa
psi	0.068 948	0.07	bar
atm	1.013 25	1	bar
Metric to Standard			
kPa	0.145038	0.15	psi
bar	14.50377	15	psi
Metric to Metric			
bar	1000		millibar
bar	100		kPa
kPa	1000		Pa
MPa	1000		kPa

Refer to Module 11 for additional conversions.

Key Points & Notes

1.5.2 Temperature

Key Points & Notes

Temperature is the degree or intensity of heat of a substance in relation to others. This should not be confused with heat, which is a form of energy arising from molecular motion. Heat is energy, whereas temperature is an arbitrary measure of relative heat intensity.

Temperature can be measured by a variety of means, but the most important are:

- thermometers
- temperature transducers (RTD's)
- thermocouples

Thermometers are most familiar to us as a measuring device that uses a column of mercury within a narrow glass tube. As the temperature rises, the mercury expands and rises up the tube. A calibrated temperature scale beside the tube indicates the corresponding temperature. Substances other than mercury are used for temperatures below -40° or for very high temperatures.

A thermometer can be based on any substance that changes in some manner with temperature. A resistance thermometer is based on the variation of electrical resistance with temperature. A bimetallic thermometer is made of two strips of dissimilar metal soldered together, so that the differing reaction to temperature of the two metals causes the soldered mass to lean in one direction or the other. Simple household thermostats use such a bimetal strip. A thermostat combines a thermometer with a switch that closes a circuit, or causes some action, when a temperature setting is reached.

Temperature transducers typically consist of an element that is in contact, directly or indirectly, with a process stream or equipment part. This element changes its resistance in proportion to its temperature and is commonly known as a *resistive temperature device* (RTD). These temperature-induced changes in resistance are too small to be monitored by the control system directly. As a result, a transmitter conditions the resistance to a high-level voltage or current signal and sends this signal to the control system. This analog signal varies with temperature in the same way as the original resistance. Once received, the signal can be converted to engineering units for display on a digital readout device.

Thermocouples also generate a voltage in proportion to temperature. A thermocouple consists of two wires of different metals connected together; a voltage develops at the junction in proportion to the temperature difference. This voltage can be used as an analog input signal to a control system much like an RTD.

Key Points & Notes

Conversions — Units of Temperature

The standard measure of temperature, degrees Fahrenheit ($^{\circ}\text{F}$), uses 0° as the temperature at which heavily *salted* water freezes, and 100° as approximately human body temperature. On this system, at one atmosphere, pure water freezes at 32° and boils at 212° — a range of 180° .

The metric measure of temperature, degrees Celsius or Centigrade ($^{\circ}\text{C}$), is based on the freezing and boiling points of pure water at one atmosphere. On this system, water freezes at 0° and boils at 100° — a range of 100° .

Comparing the ranges, each Fahrenheit degree is $100^{\circ}\text{C}/180^{\circ}\text{F}$ or $5/9$ of a Celsius degree. To convert specific temperatures, both the range and the zero point for the scales must be converted as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5/9 \quad ^{\circ}\text{F} = ^{\circ}\text{C} \times 9/5 + 32$$

A rough conversion is:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 30) \times 1/2 \quad ^{\circ}\text{F} = ^{\circ}\text{C} \times 2 + 30$$

The Fahrenheit and Celsius temperature scales give no indication of how much hotter or colder one temperature is from another in an absolute sense. To do this, an *absolute* temperature scale is needed relative to *absolute zero*, the lowest temperature in the universe. All molecular motion stops at absolute zero.

Both the standard and metric systems have absolute scales. In standard, the Rankine system uses the symbol $^{\circ}\text{R}$ for degrees *Fahrenheit* above absolute zero. In metric, the Kelvin system uses the symbol K for degrees *Celsius* above absolute zero. Absolute zero is 0°R or 0 K . (No degree symbol is used with K.) Since absolute zero is -273.15°C or -459.67°F , the conversions within systems are:

$$\text{K} = ^{\circ}\text{C} + 273.15 \quad ^{\circ}\text{R} = ^{\circ}\text{F} + 459.69$$

Both systems of absolute temperature use absolute zero as the zero point of their scales, so only the ranges need be converted between standard and metric:

$$\text{K} = ^{\circ}\text{R} \times 5/9 \quad ^{\circ}\text{R} = \text{K} \times 9/5$$

1.5.3 Volume and Capacity

Key Points & Notes

Volume is 3-dimensional space. Capacity (or “water capacity”) is the volume contained within a vessel.

As volume is 3-dimensional, it is represented by a cubed measure of length, such as cubic inches (in^3), cubic feet (ft^3), cubic miles (mi^3), cubic millimeters (mm^3), cubic centimeters (cm^3 or cc), cubic meters (m^3), etc. Any linear measure can be cubed to become a volumetric measure. Cubic measures cannot be a combination of different measures, such as ft-in^2 .

Capacity or liquid measure expresses the volume of a vessel. Standard capacity measures include fluid ounces (fl oz), cups (c), pints (pt), quarts (qt), and gallons (gal).

Imperial liquid measures used in Britain, Canada, Australia and other Commonwealth countries have fluid ounces that are 4% larger than in standard; and pints, quarts and gallons that contain $5/4$ as many fluid ounces as the standard measures of the same name. When referring to published specifications, and the type of liquid measure is not given, check the country of publication.

Metric measure of capacity centers around liters (L), and the correspondingly smaller milliliters (mL). In metric, volumetric measurements are directly linked to liquid measures. The relationship is expressed as:

$$1 \text{ cm}^3 = 1 \text{ mL} \quad 1000 \text{ cm}^3 (1 \text{ dm}^3) = 1 \text{ L} \quad 1 \text{ m}^3 = 1000 \text{ kL}$$

In standard units, there is no such intuitively convenient relationship between volumetric and liquid measures. Rather:

$$1 \text{ in}^3 = 0.6 \text{ fl oz} \quad 1 \text{ ft}^3 = 7.5 \text{ gal}$$

$$1 \text{ fl oz} = 1.8 \text{ in}^3 \quad 1 \text{ gal} = 0.13 \text{ ft}^3$$

Conversions — Units of Volume and Capacity

Key Points & Notes

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Standard to Standard			
ft ³ or cu ft (cubic feet)	1728	1700	in ³ or cu in (cubic inches)
ft ³	7.480519	7.5	gal
gal	0.133 681	0.13	ft ³
in ³	0.554	0.6	fl oz
fl oz (US fluid ounce)	1.804 688	2	in ³
gal (US gallon)	4		qt (quarts)
gal	128	130	fl oz
Standard to Metric			
in ³	16.387 064	16	cm ³ (cubic centimeter) or mL (milliliter)
ft ³	28.316 85	30	L (liter)
ft ³	0.028 317	0.03	m ³ (cubic meter) or kL (kiloliter)
fl oz	29.573 53	30	cm ³ or mL
gal	3.785 412	4	L
Metric to Standard			
cm ³ or mL	0.061 024	0.06	in ³
cm ³ or mL	0.033813	0.03	fl oz
m ³ or kL	35.314 475	35	ft ³
Metric to Metric			
cm ³ or mL	1000		mm ³
L	1000		cm ³
m ³ or kL	1000		L

Refer to Module 11 for
additional conversions.

1.5.4 Mass and Weight

Key Points & Notes

Mass and weight are not the same thing. Mass is the amount of matter that a body contains. Weight is a force, and a force is equal to mass times acceleration ($F = ma$). Thus, when a body experiences the acceleration of the earth's gravity, it exerts a force on the surface of the earth which is weight. A body in outer space does not experience weight, but it has mass.

The standard unit for both mass and weight is the pound (lb) which adds to the general confusion. Strictly speaking, a pound-mass (sometimes written lb_m) is the amount of mass that results in one pound of force under the influence of the earth's gravity. A pound-force (sometimes written lb_f) is a force of one pound, pure and simple.

The metric unit for mass is the kilogram (kg) and the unit for force, and therefore weight, is the Newton (N or $kg\cdot m/s^2$). Unfortunately, people tend to think of kilograms as weight thereby instilling the same confusion that surrounds the use of the unit pound. A "weight" of one kilogram is really the force exerted under the influence of the earth's gravity which is 9.8 N.

As the earth is not a sphere but an oblate spheroid (it bulges at the equator) the earth's gravity is not constant. This results in reduced gravity at the bulge or at higher elevations. An object that weighs 200 lb at the North Pole, also weighs 200 lb at the South Pole, but only 199 lb at the equator. The mass of the object, however, remains the same.

Spelling differentiates the standard ton and the metric tonne. The tonne of 1000 kg (2200 lb) is only 10% larger than the short ton of 2000 lb, and virtually the same as the long ton of 2240 lb.

In metric, the relationship between volume and capacity is extended to include mass in kilograms (kg) in the special case of water at one atmosphere and 4 °C. Specifically:

1000 cm³ or 1 L of water has the mass of 1 kg

Likewise, a milliliter has a mass of one gram, and a cubic meter of water has a mass of one tonne. This relationship makes it particularly easy to convert between the volume, capacity and mass of water. The 4 °C is used as water is at its maximum density at that temperature — water has the rare property that it expands through both cooling and heating.

To state the equivalent in standard units, also with fresh water at its maximum density (39 °F):

One cubic foot or 7.5 gallons of water weighs 62.5 pounds.

One gallon or 0.134 ft³ of water weighs 8.35 pounds.

Conversions — Units of Mass

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Standard to Standard			
lb (pound)	16		oz (ounce)
ton — short	2000		lb
Standard to Metric			
oz	28.350	30	g (gram)
lb	0.453 59	0.5	kg (kilogram)
ton — short	0.907 18	0.9	tonne
Metric to Standard			
g	0.035 273	0.035	oz
kg	2.204 586	2.2	lb
tonne	1.102 293	1.1	ton — short
Metric to Metric			
g	1000		mg
kg	1000		g
tonne	1000		kg

Refer to Module 11 for additional conversions.

1.5.5 Mass Flow

Gas flow is the motion of a gas from a higher pressure zone to a lower pressure zone. There is resistance to flow just as there is resistance to electricity passing through a wire. As the gas molecules pass through a pipe, some lose a certain amount of their energy due to friction against the sides of the pipe. Molecules against the sides the pipe move very slowly compared to those in the center.

Gas flow is typically measured using a rotameter or a mass flow meter.

A rotameter consists of one or more balls within a tube. The tube has a scale marked on the outside. As gas flows through the tube, the ball lifts indicating the amount of flow relative to the scale. Rotameters must be chosen to match

the expected flow range and calibrated relative to a specific gas composition, temperature and pressure.

Key Points & Notes

A mass flow meter accurately measures gas flow without requiring compensations for variations in pressure and temperature. The mass flow meter consists of a sensor, a shunt assembly and electronic circuitry. Gas flowing through the mass flow meter passes either through the sensor or the shunt assembly. These two gas flows are proportional to each other so that when the sensor flow is measured, the shunt assembly flow can be determined. The size of the opening in the shunt assembly limits the maximum amount of gas that can flow through the mass flow meter. This flow range, as sensed by the sensor, is converted by the electronic circuitry into a linear output voltage or current signal.

Units of Gas Flow

Common standard units of volumetric fluid flow (fluids include liquids and gases) are cubic feet per minute (ft³/min), and gallons per minute (gpm). In metric, volumetric flow is typically measured in liters per minute (Lpm).

Volumetric flow can be converted to mass flow by multiplying the volumetric flow by the density of the fluid. This yields standard units such as pounds per second (lb/s) and metric units such as kilograms per second (kg/s).

Liquid densities do not vary appreciably with temperature or pressure since liquids are essentially incompressible. However, gas densities vary significantly with both temperature and pressure as summarized by the ideal gas law. Thus, gas flow measurements must be stated relative to some standard temperature and pressure. A temperature of 0 °C (273 K) and a pressure of 1 atmosphere are used for this purpose.

Using the ideal gas law:

$$V_{STD} = V_M \times \frac{P_M}{P_{STD}} \times \frac{T_{STD}}{T_M} = V_M \times \frac{P_M}{1 \text{ atm}} \times \frac{273 \text{ K}}{T_M}$$

where:

- V_{STD} = standard volume or volumetric flow rate
- V_M = measured volume or volumetric flow rate
- P_M = absolute measured pressure
- P_{STD} = absolute standard pressure (1 atm)
- T_M = absolute measured temperature
- T_{STD} = absolute standard temperature (273 K)

Consistent units must be used throughout.

Gas volumes corrected in this way use units with the prefix “s” for “standard”; thus, slpm (standard liters per minute) or sft³/min (standard cubic feet per minute).

Key Points & Notes

Conversions — Gas Mass Flow

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Standard to Standard			
cfm (ft ³ /min)	60		cfs (ft ³ /s)
cfh (ft ³ /hr)	24		cfm (ft ³ /min)
gps (gallons per second)	60		gpm
gpm (gallons per minute)	8.020 833	8	cfh (ft ³ /hr)
Standard to Metric			
cfm	28.316 85	30	Lpm
cfm	0.028 317	0.03	m ³ /min
gpm	3.785 412	3.8	Lpm
Metric to Standard			
Lpm	0.035 315	0.035	cfm (ft ³ /min)
Metric to Metric			
m ³ /min	1000		LPM

Refer to Module 11 for additional conversions.

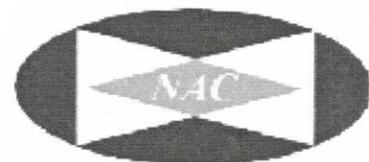
MODULE 2:

Hydrogen Use

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

2.1	HYDROGEN MANUFACTURE	2-1
2.1.1	ELECTROLYSIS	2-3
2.1.2	REFORMING	2-9
2.1.3	THERMOCHEMICAL WATER DECOMPOSITION	2-30
2.1.4	PHOTO CONVERSION	2-31
2.1.5	PRODUCTION FROM BIOMASS	2-33
2.1.6	INDUSTRIAL PROCESSES	2-34
2.2	HYDROGEN STORAGE	2-36
2.2.1	HIGH PRESSURE GAS	2-37
2.2.2	LIQUID	2-44
2.2.3	METAL HYDRIDES	2-46
2.2.4	OTHER STORAGE METHODS	2-51
2.3	HYDROGEN TRANSPORTATION	2-52
2.3.1	PIPELINES	2-52
2.3.2	MOBILE TRANSPORT	2-53
2.3.3	SITE Manufacture	2-54

OBJECTIVES

At the completion of this module, the technician will understand:

- the processes by which hydrogen is extracted from other substances
- how hydrogen is stored, and the inherent advantages and disadvantages of each method
- how hydrogen is transported, and the inherent advantages and disadvantages of each method

2.1 Hydrogen Manufacture

Key Points & Notes

The fundamental question underlying the use of hydrogen as a fuel is, Where do we get it from? Despite its abundance in the universe, hydrogen does not occur freely on earth, as it reacts very readily with other elements. For this reason, the vast majority of hydrogen is bound into molecular compounds.

To obtain hydrogen means to remove it from these other molecules. With respect to the energy required, it is easy to remove hydrogen from compounds that are at a higher energy state, such as fossil fuels. This process releases energy, reducing the amount of process energy required. It takes more energy to extract hydrogen from compounds that are at a lower energy state, such as water, as energy has to be added to the process.

The process of extracting hydrogen from fossil fuels is called reforming. Today, this is the principal and least expensive method of producing hydrogen. Unfortunately, reforming emits pollutants and consumes non-renewable fuels.

The process of extracting hydrogen from water is called electrolysis. In principal, electrolysis can be entirely non-polluting and renewable, but it requires the input of large amounts of electrical energy. Consequently, the total environmental impact of acquiring hydrogen through electrolysis is largely dependent on the impacts of the source power.

One way to assess the comparative environmental impact of electrolysis and the reforming of various fuels is by comparing the total amount of carbon dioxide emitted. A recent study used a Mercedes-Benz A-Class car as the basis for comparison, and calculated the total carbon dioxide emissions per 1000 km of travel. The total carbon dioxide emissions include those from the car's tailpipe, the fuel processor, and the powerplant that supplied the energy to the fuel processor.

The results of the study, shown in Figure 2-1, clearly indicate that environmental cleanliness of hydrogen is directly linked to its mode of manufacture. Although not included in the study, hydrogen derived from renewable, non-fossil energy sources would likely have no carbon dioxide emissions.

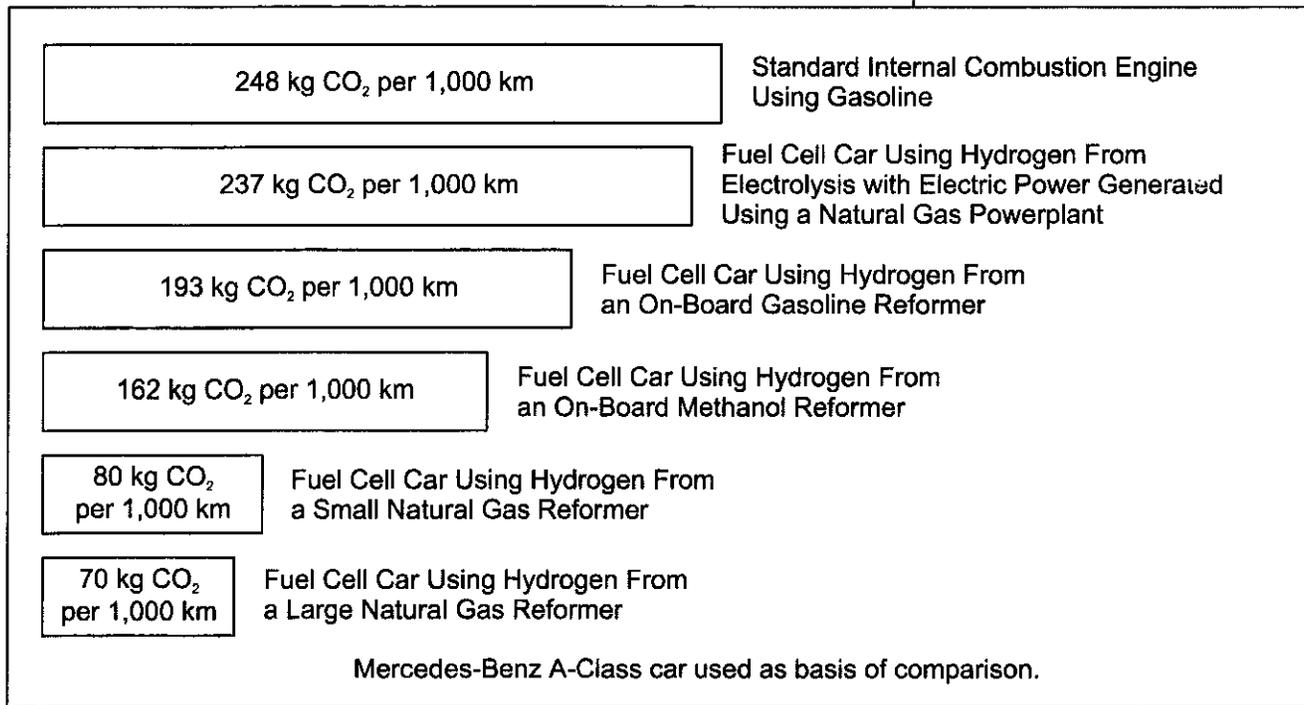


Figure 2-1 Total Carbon Dioxide Emissions for Comparative Hydrogen Production Methods

Key Points & Notes

Alternative methods of hydrogen production include thermochemical water decomposition, photoconversions, photobiological processes, production from biomass, and industrial processes. Although some of these methods show promise for the future, they are still largely experimental and capable of supplying only small amounts of hydrogen.

Hydrogen can be produced on a large scale at dedicated hydrogen production plants, or on a small scale at local production facilities. Large-scale production benefits from economies of scale and plants can be located near power and water, but suffers from the difficulties of hydrogen transportation. Some methods of hydrogen production, such as from coal or biomass, can only be undertaken on a large scale.

Small scale production can reduce the problems of hydrogen transportation by using energy that is easily brought to the facility, such as electricity, natural gas or solar. On the downside, the amount of equipment required for the amount of hydrogen produced is significantly higher than for large-scale facilities, due to the economy of scale.

At the extreme small scale, fossil fuels could be reformed to hydrogen on board a fuel cell vehicle, but the systems are complex and costly.

Currently, the vast majority of all hydrogen manufactured worldwide originates from fossil fuels, as a byproduct in chemical industries, or crude oil refining processes. Hydrogen production from renewable energy is not yet feasible on a large scale.

Production of hydrogen currently costs from 3 to 15 times more than natural gas, and from 1.5 to 9 times more than gasoline, depending on the method used. When extracted from fossil fuels, the initial production and refining of the fuel further increases the total cost.

2.1.1 Electrolysis

In electrolysis, electricity is used to decompose water into its elemental components: hydrogen and oxygen. Electrolysis is often touted as the preferred method of hydrogen production as it is the only process that need not rely on fossil fuels. It also has high product purity, and is feasible on small and large scales. Electrolysis can operate over a wide range of electrical energy capacities, for example, taking advantages of more abundant electricity at night.

At the heart of electrolysis is an electrolyzer. An electrolyzer is a series of cells each with a positive and negative electrode. The electrodes are immersed in water that has been made electrically conductive, achieved by adding hydrogen or hydroxyl ions, usually in the form of alkaline potassium hydroxide (KOH).

The anode (positive electrode) is typically made of nickel and copper and is coated with oxides of metals such as manganese, tungsten and ruthenium. The anode metals allow quick pairing of atomic oxygen into oxygen pairs at the electrode surface.

The cathode (negative electrode) is typically made of nickel, coated with small quantities of platinum as a catalyst. The catalyst allows quick pairing of atomic hydrogen into pairs at the electrode surface and thereby increases the rate of hydrogen production. Without the catalyst, atomic hydrogen would build up on the electrode and block current flow.

A gas separator, or diaphragm, is used to prevent intermixing of the hydrogen and oxygen although it allows free passage of ions. It is usually made of an asbestos-based material, and tends to break apart above 176 °F (80 °C).

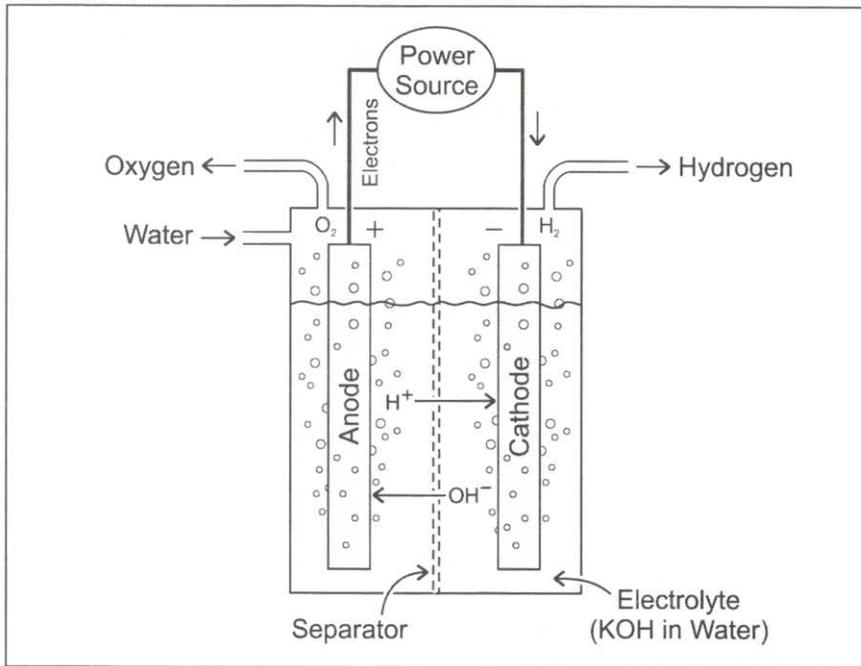


Figure 2-2 Typical Electrolysis Cell

Key Points & Notes

The reactions at the cathode are:

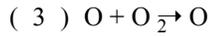
- (1) $K^+ + e^- \rightarrow K$ a positively charged potassium ion is reduced
- (2) $K + H_2O \rightarrow K^+ + H + OH^-$ the ion reacts with water to form a hydrogen atom and a hydroxyl ion
- (3) $H + H \rightarrow H_2$ the highly reactive hydrogen atom then bonds to the metal of the cathode and combines with another bound hydrogen atom to form a hydrogen molecule that leaves the cathode as a gas

The reactions at the anode are:

- (1) $OH^- \rightarrow OH + e^-$ a negatively charged hydroxyl ion is oxidized
- (2) $OH \rightarrow \frac{1}{2}H_2O + \frac{1}{2}O$ the ion reacts to form water and an oxygen atom

Hydrogen Fuel Cell Engines

MODULE 2: HYDROGEN USE

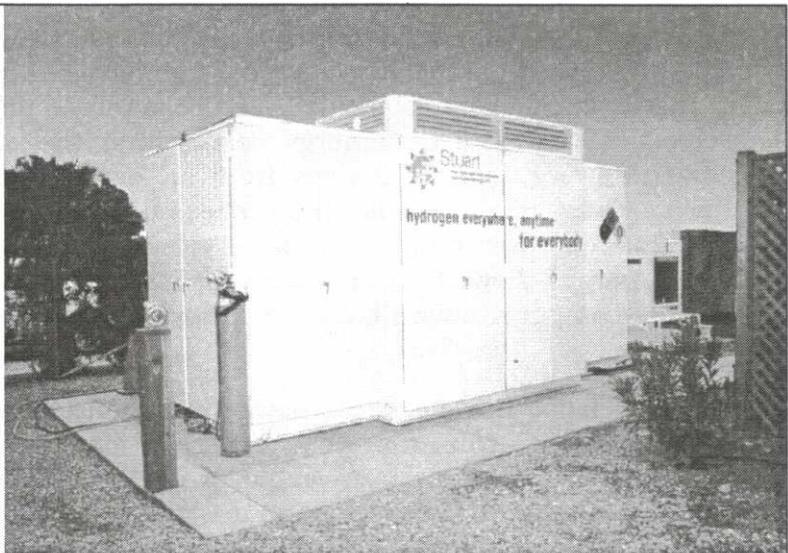


the highly reactive oxygen atom then bonds to the metal of the anode and combines with another bound oxygen atom to form an oxygen molecule that leaves the anode as a gas

Key Points & Notes

The rate of hydrogen generation is related to the current density (the amount of current divided by the electrode area measured in amps per area). In general, the higher the current density, the higher the source voltage required, and the higher the power cost per unit of hydrogen. However, higher voltages decrease the overall size of the electrolyzer and therefore result in a lower capital cost. State-of-the-art electrolyzers are reliable, have energy efficiencies of 65 to 80% and operate at current densities of about 186 A/ft² (2000 A/m²).

This large electrolyzer consumes a maximum of 240 HP (180 kW) of electrical power while generating 1,400 sft³/hr (660 slpm) of hydrogen. The hydrogen is delivered at up to 5,000 psig (345 barg) using an integral compressor.



This small electrolyzer consumes 10 HP (7.5 kW) of electrical power while generating a maximum of 42 sft³/hr (20 slpm) of hydrogen. The hydrogen is delivered at 30 to 100 psig (1 to 6.9 barg) at 99.7% purity.

Figure 2-3 Electrolyzers

A fuel cell reverses the process of electrolysis. Electrolysis adds electrical energy to low-energy water to release two high-energy gases. A fuel cell allows the gases to react and combine to form water, releasing electrical power. Both processes release heat, which represents an energy loss.

For electrolysis, the amount of electrical energy required can be somewhat offset by adding heat energy to the reaction. The minimum amount of voltage required to decompose water is 1.23 V at 77 °F (25 °C). At this voltage, the reaction requires heat energy from the outside to proceed. At 1.47 V (and same temperature) no input heat is required. At greater voltages (and same temperature) heat is released into the surroundings during water decomposition.

Operating the electrolyzer at lower voltages with added heat is advantageous, as heat energy is usually cheaper than electricity, and can be recirculated within the process. Furthermore, the efficiency of the electrolysis increases with increased operating temperature.

When viewed together with fuel cells, hydrogen produced through electrolysis can be seen as a way of storing electrical energy as a gas until it is needed. Hydrogen produced by electrolysis is therefore the energy carrier, not the energy source. The energy source derives from an external power generating plant. In this sense, the process of electrolysis is not very different from charging a battery, which also stores electrical energy. Viewed as an electricity storage medium, hydrogen is competitive with batteries in terms of weight and cost.

To be truly clean, the electrical power stored during electrolysis must derive from non-polluting, renewable sources. If the power is derived from natural gas or coal, the pollution has not been eliminated, only pushed upstream. In addition, every energy transformation has an associate energy loss. Consequently, fossil fuels may be used with greater efficiency by means other than by driving the electrolysis of hydrogen. Furthermore, the cost of burning fossil fuels to generate electricity for electrolysis is three to five times that of reforming the hydrogen directly from the fossil fuel.

Key Points & Notes

<p><i>The approximate efficiencies of modern thermal power stations are:</i></p> <p><i>Nuclear: 30-33%</i> <i>Natural gas: 30-40%</i> <i>Coal: 33-38%</i> <i>Oil: 34-40%</i></p>

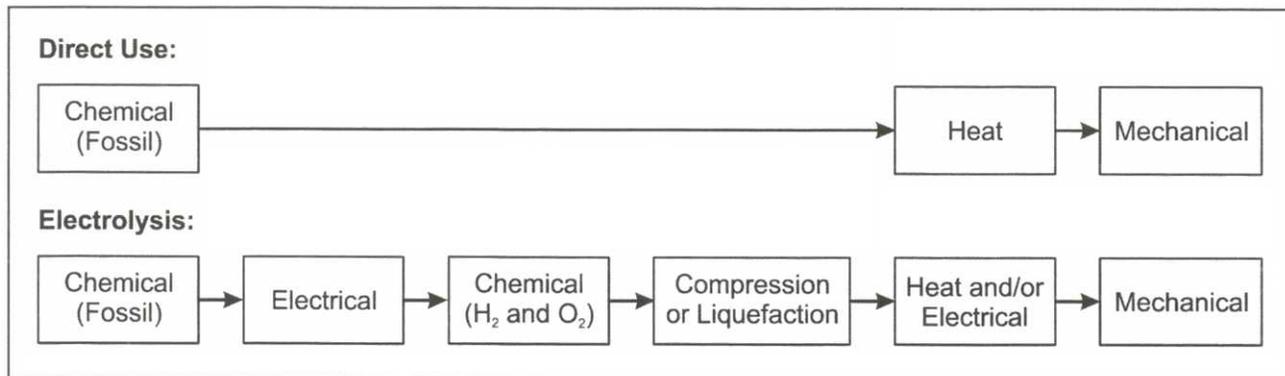


Figure 2-4 Energy Transformation Processes Based on Fossil Fuels

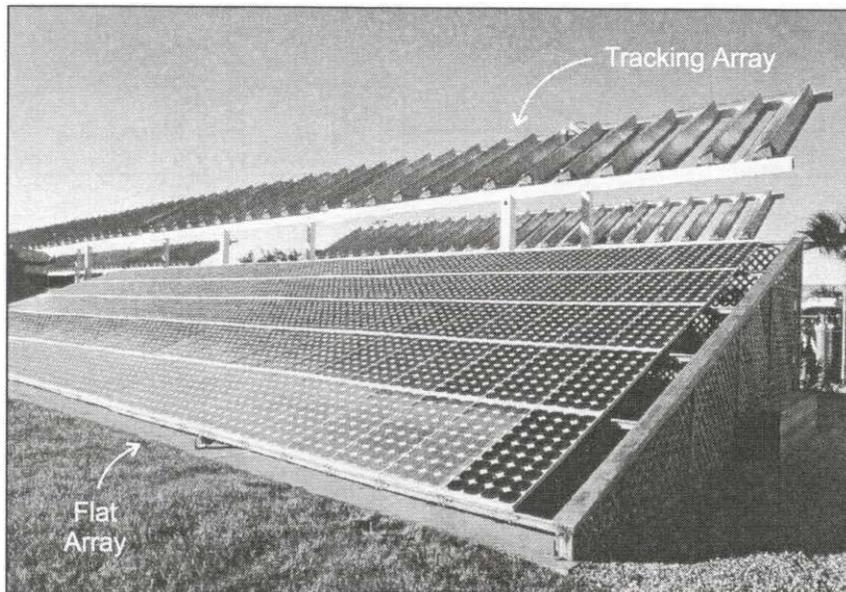
Key Points & Notes

Non-polluting renewable energy sources include hydroelectric, solar photovoltaic, solar thermal and wind. These methods of power generation are applicable only in specific geographic or climatic conditions. Furthermore, with the exception of hydroelectric, each of these power sources is intermittent. Despite growth in the use of these energy sources, they currently provide a very small amount of the power consumed today.

Hydroelectric power generation uses the energy of moving water to turn turbines that in turn rotate generators. Hydroelectric power is only feasible in areas with major rivers that undergo significant changes in height. Most suitable locations worldwide have already been developed. Hydroelectric power is a cheap source of clean power especially when utilizing excess, off-peak power. The efficiency of hydroelectric power generation can top 80%. This is probably the optimum form of renewable energy although the environmental and ecological cost of dams is high.

Solar electric power generation uses banks of solar cells to convert the energy of the sun directly into electrical power. Solar power is only feasible in areas with significant amounts of intense sunlight and requires large tracts of land to generate sufficient levels of power. The efficiency of solar cells currently ranges from 3 to 17%.

Key Points & Notes



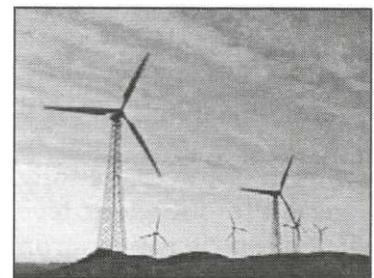
This solar cell array contains tracking and flat cells which can generate a combined rated total of 50 HP (37 kW) in bright sunlight. The power is supplied at 360 VDC with a maximum current of 103 A.

Figure 2-5 Solar Cell Array

Solar thermal power generation starts by concentrating the sun's heat into a fluid that has a high heat-carrying capacity, such as oil. The oil's heat is transferred through heat exchangers to water, generating steam for a steam turbine generator. Like solar electric power generation, solar thermal power generation is only feasible in areas with significant amounts of intense sunlight and requires large tracts of land in order to generate sufficient levels of power. The overall efficiency of converting sunlight to electricity for these systems is about 8 to 24% depending on the type of technology used.

Wind power generation uses the energy of moving air to turn turbines that in turn rotate generators. Wind power is only feasible in areas with favorable wind conditions and requires large tracts of land in order to generate sufficient levels of power. Wind has low energy density and wind turbines operating at optimum conditions (design speed) may obtain 30% efficiency at best. Real-world operating conditions may reduce this efficiency considerably.

Although a renewable energy source in conjunction with electrolysis would eliminate the dependence on fossil fuels, it does not reduce the number of energy transformations required to produce mechanical work using hydrogen. If clean, renewable power were available, it could also be used in other ways that require fewer energy transformations, such as direct storage in batteries or to compress air for propulsion.



Wind Turbines

Another consideration associated with electrolysis is the source of water. Water is already a precious commodity, and would be consumed in vast quantities in order to support a large hydrogen economy. The water would also have to be purified prior to use, increasing its cost.

Key Points & Notes

2.1.2 Reforming

Reforming is a chemical process that reacts hydrogen-containing fuels in the presence of steam, oxygen, or both into a hydrogen-rich gas stream. When applied to solid fuels the reforming process is called gasification. The resulting hydrogen-rich gas mixture is called reformat. The equipment used to produce reformat is known as a reformer or fuel processor.

The specific composition of the reformat depends on the source fuel and the process used, but it always contains other compounds such as nitrogen, carbon dioxide, carbon monoxide and some of the unreacted source fuel. When hydrogen is removed from the reformat, the remaining gas mixture is called raffinate.

In essence, reforming a fossil fuel consists of the following steps:

1. Feedstock purification (including sulfur removal).
2. Steam reforming or oxidation of feedstock to form hydrogen and carbon oxides.
3. Primary purification — conversion of carbon monoxide to carbon dioxide.
4. Secondary purification — further reduction of carbon monoxide.

The reforming reactions require the input of water and heat. Overall reformer thermal efficiency is calculated as the LHV of the product hydrogen divided by the LHV of the total input fuel. This thermal efficiency depends on the efficiencies of the individual processes, the effectiveness to which heat can be transferred from one process to another, and the amount of energy that can be recovered through means such as turbochargers. In the end, high temperature reformer efficiencies are approximately 65% and low temperature methanol reformers can achieve 70 to 75%.

The advantages of reforming fossil fuels are that they:

- uses existing fuel infrastructures
- reduces the need to transport and store hydrogen

- does not need the input of large amounts of energy as in electrolysis
- is less expensive than other hydrogen production methods

Key Points & Notes

The disadvantages of reformers are that they:

- can have relatively long warm-up times
- are difficult to apply to vehicle engines because of irregular demands for power (transient response)
- are complex, large and expensive
- introduce additional losses into the energy conversion process, especially those that have small thermal mass
- use non-renewable fossil fuels
- generate pollution

The pollution generated by reformers take three forms:

- carbon dioxide emissions
- incomplete reactions, leaving carbon monoxide and some of the source fuel in the reformat
- production of pollutants through combustion, such as nitrous oxides

Reforming fossil fuels only makes sense if the hydrogen is needed directly, as in a fuel cell engine. For internal combustion engines, it is always more efficient to use the fossil fuel directly without passing it through a reformer first.

Medium- or large-size reformers can be installed at fuel cell vehicle fueling stations. At these scales, the equipment complexity, warmup time and transient response are not issues, pollutants can be controlled more effectively, and existing power infrastructures can be used. The facility must store only small amounts of hydrogen, and hydrogen transportation is avoided.

Small-size reformers can be installed in fuel cell vehicles to entirely eliminate the problems associated with fueling, storing and handling hydrogen directly. In fact, many fuel cell experts think that the true challenge in fuel cell engine design now lies in the development of an efficient, compact, reliable and highly integrated fuel processor. Other experts think that the use of on-board reformers will never pose a realistic solution due to their size, complexity and cost.

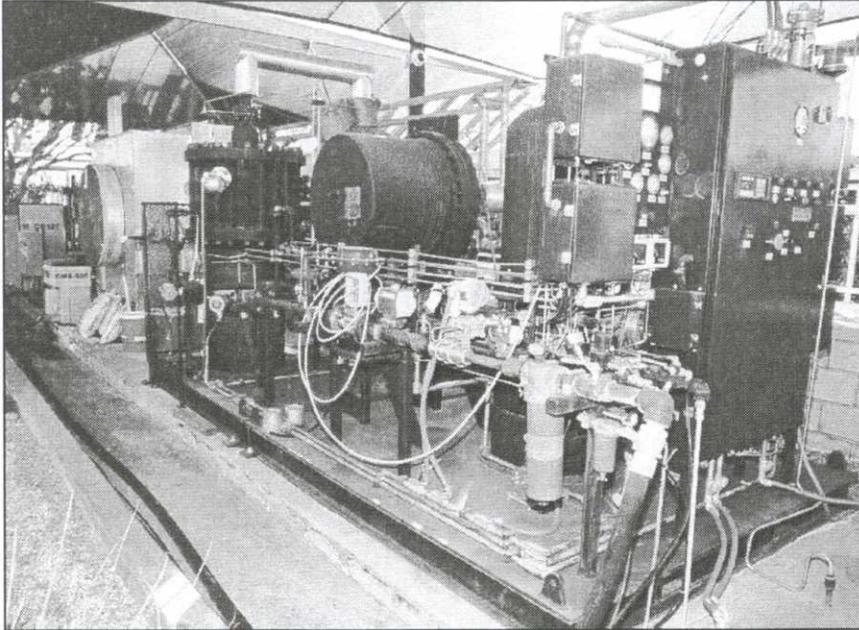


Figure 2-6 Medium-Scale Natural Gas Reformer

2.1.2.1 Potential Reforming Fuels

In theory, any hydrocarbon or alcohol fuel can serve as a feedstock to the reforming process. Naturally, fuels with existing distribution infrastructures are the most commonly used.

Methane (Natural Gas)

Natural gas has a well-established infrastructure and is the most economical of all reforming feedstocks. Natural gas contains low levels of sulfur compounds (primarily mercaptans) that must be removed, as they would block active catalyst sites in the reformer and fuel cells. These sulfur compounds requires fuel purification (hydro-desulfurization) prior to reforming.

Key Points & Notes

This natural gas reformer uses a partial oxidation reaction, a water/gas shift reaction, and pressure swing adsorption techniques to generate up to 4,200 sf^3/hr (1,980 slpm) of hydrogen. The hydrogen purity is 99.999%. Maximum water consumption is 4,000 gal/day (15,100 L/day).

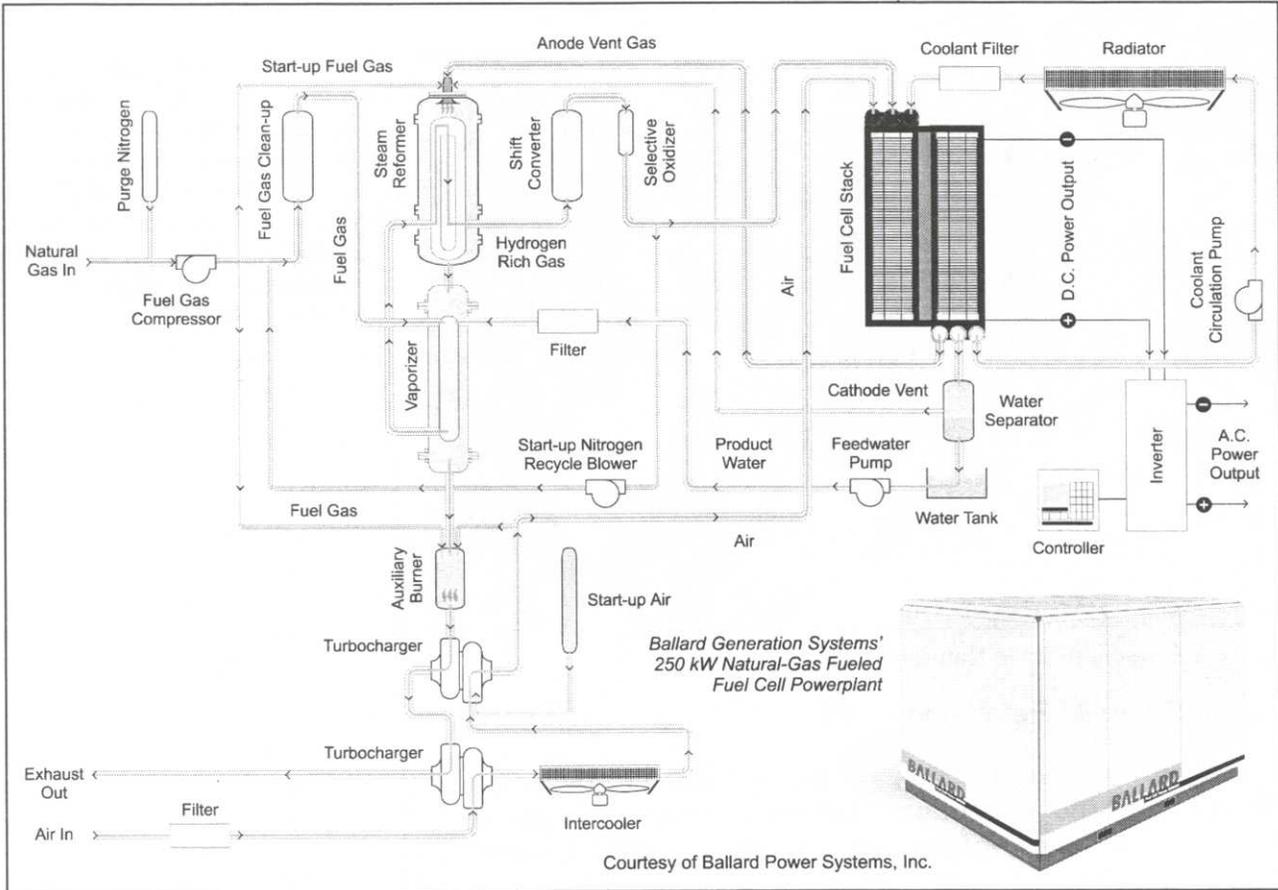


Figure 2-7 Typical Fuel Cell Process Schematic with Integral Natural Gas Stationary Reformer

Since methane is a gas at atmospheric conditions, it cannot be used to advantage on an on-board vehicular fuel processor, although it is an excellent source for stationary fuel reformers. Propane has similar reforming characteristics to natural gas.

Key Points & Notes

Methanol

Methanol is readily available and is a favorite for on-board vehicular fuel processors as it can be reformed at relatively low temperatures of 390 to 570 °F (200 to 300 °C). However, methanol has lower energy content and energy density than liquid hydrocarbon fuels.

Gasoline and Diesel

Gasoline and diesel have very well established infrastructures but have a lower hydrogen-to-carbon ration than other feedstocks. This results in a lower hydrogen yield relative to the amount of waste gas. In general, heavier hydrocarbons

also contain sulfur trapped in long chains and cyclic compounds that typically require higher processing pressures of 90 to 650 psig (6 to 45 barg) to remove.

In addition, petroleum products include compounds called olefins and aromatics that result from the refining process. Olefins are highly reactive and tend to form polymer gums or carbon. Aromatics are very stable and difficult to reform and may form carbon. Both gum and carbon formation block active catalyst sites and their formation are highly dependent on processing temperature. The presence of sulfur, olefin and aromatic compounds requires fuel purification and pre-reforming processes prior to reforming.

Coal

Coal has enormous supply potential but suffers from high impurity levels, low hydrogen yield, and is difficult to handle. Coal could only be reformed at large dedicated facilities and therefore faces the problems associated with transporting and storing hydrogen. Currently, coal reforming is the most expensive of all reforming methods.

Reformate Composition Comparison

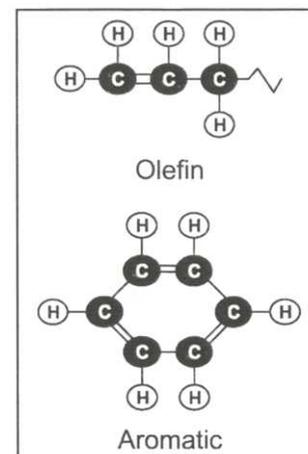
Typical reformate compositions are indicated in Table 2-1. For each source fuel, the yield is calculated based on both steam reforming and partial oxidation (POX) reforming techniques. In both cases, the resulting carbon monoxide is then converted to carbon dioxide using a water/gas shift reaction followed by a selective oxidation reaction. (These techniques are described in the sections that follow.)

	Methane		Methanol		Gasoline/Diesel		Coal	
	Steam	POX	Steam	POX	Steam	POX	Steam	POX
Hydrogen	75.7%	47.3%	71.1%	37.8%	71.1%	37.8%	63.1%	23.6%
Nitrogen	1.9%	33.5%	1.9%	39.8%	1.9%	39.8%	1.9%	49.2%
Carbon Dioxide	19.9%	16.7%	24.5%	19.9%	24.5%	19.9%	32.5%	24.7%
Source Fuel/Other	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%

Table 2-1 Typical Reformats Compositions

All oxygen is added in the form of air. Any excess water used in the reforming or purification reactions may contribute to the humidification of the gas mixture, but is not indicated as a portion of the overall mixture.

Key Points & Notes



Reformate can be used directly in (PEM) fuel cells instead of pure hydrogen although this has five important implications:

- Firstly, the carbon monoxide and source fuel impurities must be reduced to acceptable levels, as they are fuel cell poisons.
- Secondly, any unreacted *liquid* source fuel that passes into the fuel cells obstructs the power generation reaction.
- Thirdly, although nitrogen, carbon dioxide and gaseous source fuels pass through the fuel cells without detrimental effect, they dilute the amount of hydrogen present so that the fuel cell stacks and affiliated system equipment must be larger than if running on pure hydrogen.
- Fourthly, the presence of gases other than hydrogen precludes the use of the fuel in a “dead-ended” manner: pure hydrogen can be recirculated through a fuel cell until entirely consumed, whereas reformate must pass through and be vented to prevent the steady accumulation of non-reactive gases. Since fuel cells must operate with more fuel than is stoichiometrically required, this results in direct hydrogen wastage with an associated overall loss in efficiency.
- Fifthly, use of reformate usually eliminates the need for a fuel humidifier since the reforming process leaves the gas saturated with water.

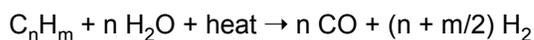
Key Points & Notes

2.1.2.2 Types of Reformers

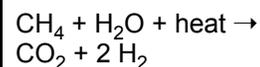
Reformers are of three basic types: steam reformers, partial oxidation reactors and thermal decomposition reactors. A fourth type results from the combination of partial oxidation and steam reforming in a single reactor, called an autothermal reformer.

Steam Reformers

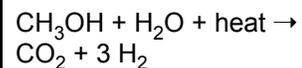
Steam reformers are currently the most efficient, economical and widely used technique of hydrogen production. Steam reforming is based on the principal that hydrogen-containing fuels decompose in the presence of steam over nickel-based catalysts to produce a mixture of hydrogen and carbon monoxide. The steam reforming process is illustrated schematically in Figure 2-8. The overall reaction for generic hydrocarbons is:



When applied to methane, the overall reaction reduces to:



For methanol:



The output products also contain some unreacted source fuel and water. In addition, only light hydrocarbons can be completely vaporized without leaving a carbon residue. The carbon monoxide must be converted to carbon dioxide using supplementary processes (Section 2.1.2.3).

A great benefit of steam reforming is that the hydrogen present in the water is released during the reaction and contributes to the overall hydrogen yield.

The steam reforming process typically requires temperatures of 840 to 1700 °F (450 °C to 925 °C) and pressures of approximately 290 to 500 psig (20 to 35 barg). These temperatures are achieved through combustion of a portion of the reformat. These flame temperatures are too low to form nitrous oxides, which begin forming at temperatures above 2700 °F (1480 °C).

Since the overall steam reforming reaction is endothermic (uses heat), the bulk of the heat energy can be recovered by feeding it back into the process. The extent to which the heat energy is recovered determines the thermal efficiency of the reformer, and can be as high as 85%. This high thermal efficiency is the primary feature of steam reformers.

Thermal efficiencies can reach 90% when steam reforming methanol. This is because the decomposition reaction occurs at the much lower temperatures of 390 to 570 °F (200 to 300 °C), decreasing thermal losses accordingly.

In addition to temperature and pressure, the fuel-to-water ratio plays a significant role in promoting the formation of hydrogen while suppressing undesired reactions. This water must either be drawn from an external source, or, if used in conjunction with a fuel cell, drawn from the fuel cell product water stream.

The complex interactions between the fuel-to-water ratio, available heat, thermal mass and hydrogen demand result in relatively slow startup characteristics and poor response to transient demands for steam reformers. As a result, steam reformers for automotive applications require complex control systems and creative engineering practices. Designs must be optimized to provide high surface area for heat transfer, high thermal inertia during transients and compact reactor dimensions.

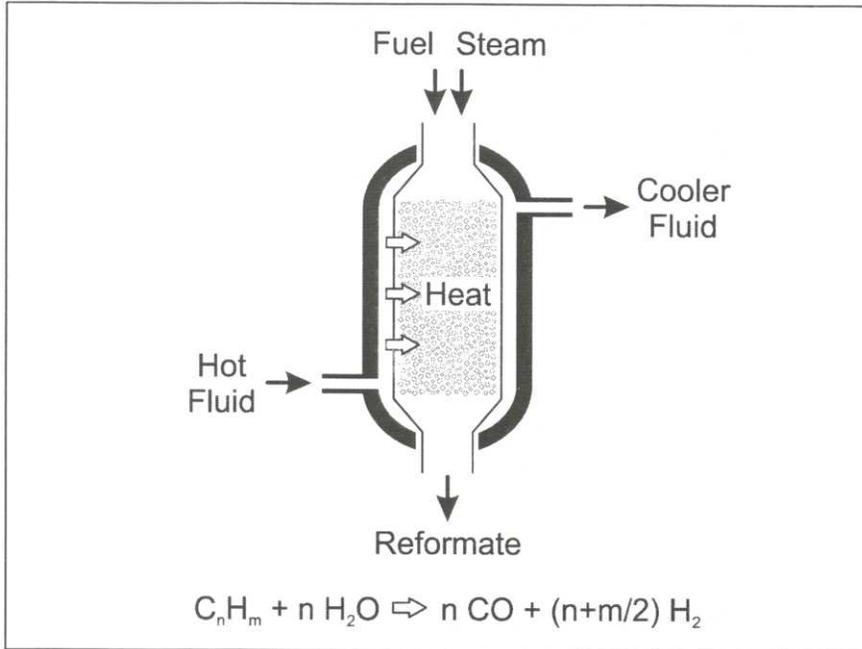
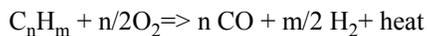


Figure 2-8 Steam Reforming Process

Steam reformers are not inherently compact. For a typical car, a methanol steam reformer would need a catalyst volume of 1.3 to 1.8 gallons (5 to 7 L) and a tank volume for the methanol/water mixture about three times the size of a comparable gasoline or diesel tank.

Partial Oxidation Reformers

Partial oxidation reformers (or “POX” reformers) react a lean mixture of oxygen (air) with fuel to produce a mixture of hydrogen and carbon monoxide. The partial oxidation process is illustrated schematically in Figure 2-9. The overall reaction for generic hydrocarbons is:



Since partial oxidation reformers use oxygen from air, nitrogen passes through the reactor along with the reaction products, thereby diluting the fuel stream. The output products also contain some unreacted source fuel. The carbon monoxide must be converted to carbon dioxide using supplementary processes (Section 2.1.2.3).

Unlike steam reformers, partial oxidation reformers are typically used to reform heavier hydrocarbons such as gasoline, diesel and heavy oil. A form of partial oxidation is used to gasify coal although the presence of sulfur and large amounts of ash, both of which must be removed, further complicates this process. These processes do not use catalysts and occur at 2100 to 2400 °F (1150 to 1315 °C) and on

Key Points & Notes

the order of 880 psig (60 barg). Lighter hydrocarbons, such as methane, can be partially oxidized using catalysts at 1090 °F (590 °C).

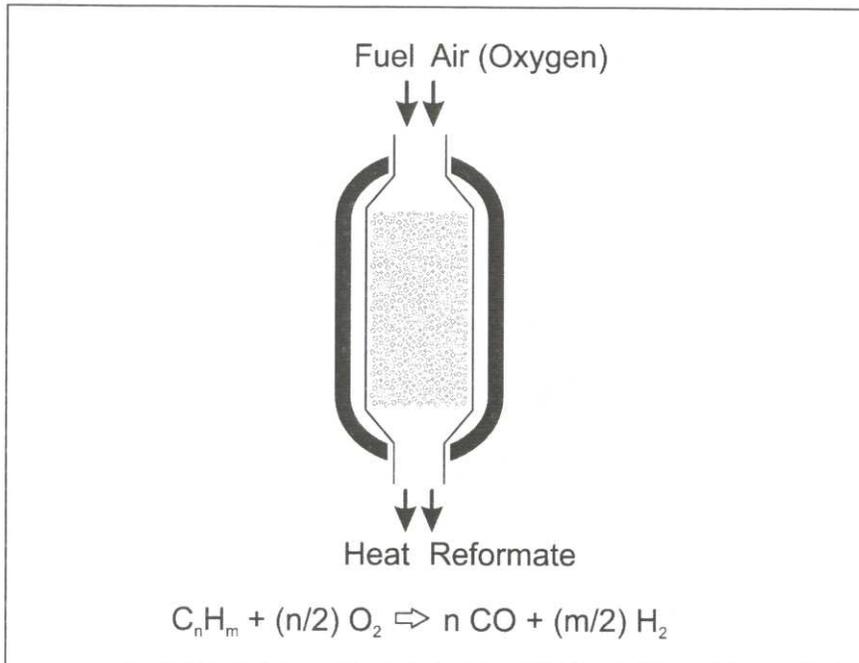


Figure 2-9 Partial Oxidation Process

Partial oxidation reformers offer both disadvantages and advantages compared to steam reformers. The key disadvantages of partial oxidation reformers are higher operating temperatures and pressures, lower thermal efficiency and lower hydrogen yield. The lower thermal efficiency stems primarily from the fact that the oxidation process is exothermic (releases heat). This means that a significant portion of the inlet fuel energy ends up as heat, which cannot be utilized by the reactor itself, nor by the fuel cell. The lower yield results from the fact that additional hydrogen is not added to the reaction in the form of water. The hydrogen yield is also diluted by large amounts of nitrogen when the oxygen is added in the form of air.

Larger heat rejection requirements also result in higher parasitic cooling losses. In a pressurized partial oxidation reactor, some of the waste energy can be recovered using a burner/ turboexpander combination to help pressurize the fuel cell process air. Nonetheless, exothermic partial oxidation reformers always face an overall efficiency handicap of 5 to 10% compared to endothermic steam reformers.

The effect of increased hydrogen dilution (due to the presence of nitrogen) increases the size of supplemental refor-

Key Points & Notes

mate purification equipment, and requires a larger fuel cell stack for a given power output.

Key Points & Notes

The key advantages of partial oxidation reformers are their relative compactness, and potentially good startup and load-following characteristics. The improvement in these areas is related to the exothermic nature of the oxidation reaction — there is no time lag for heat transfer from external sources. Furthermore, partial oxidation processes offer the potential to use readily available gasoline and diesel supplies.

Autothermal Reformers

Autothermal reformers attempt to combine the compactness and load following capabilities of partial oxidation reactors with the efficiency of steam reformers by combining the two reactors in one unit. The autothermal process is illustrated schematically in Figure 2-10. The overall reactions for generic hydrocarbons are:

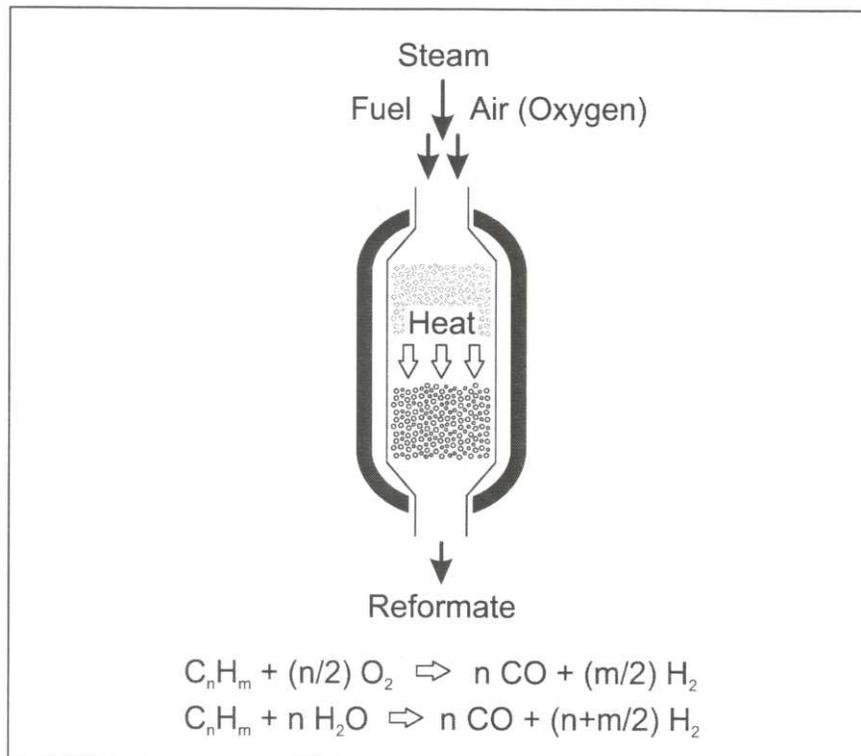
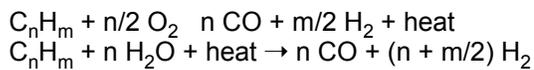


Figure 2-10 Autothermal Process

In an autothermal reformer, fuel, steam and oxygen (or air) are fed over a mixed catalyst bed that supports both partial oxidation and steam reforming reactions. The heat generated

by the partial oxidation reaction provides the heat required for the steam reforming reaction, and removes the need for an external burner or heat source. This process requires careful thermal integration and tight controls to ensure heat balance and temperature matching between the two reactions.

While autothermal reformers overcome some of the efficiency limitations of partial oxidation reformers, they still operate at efficiencies below those of steam reformers and result in a dilute hydrogen stream. Furthermore, autothermal reformers are the least developed of all reformer systems and still require significant engineering effort before they become practical.

Thermal Decomposition Reformers

Thermal decomposition reformers (or “catalytic crackers”) use heat to break down source fuels yielding high purity hydrogen (>95%) and solid carbon. The thermal decomposition process is illustrated schematically in Figure 2-11. The overall reaction for generic hydrocarbons is:

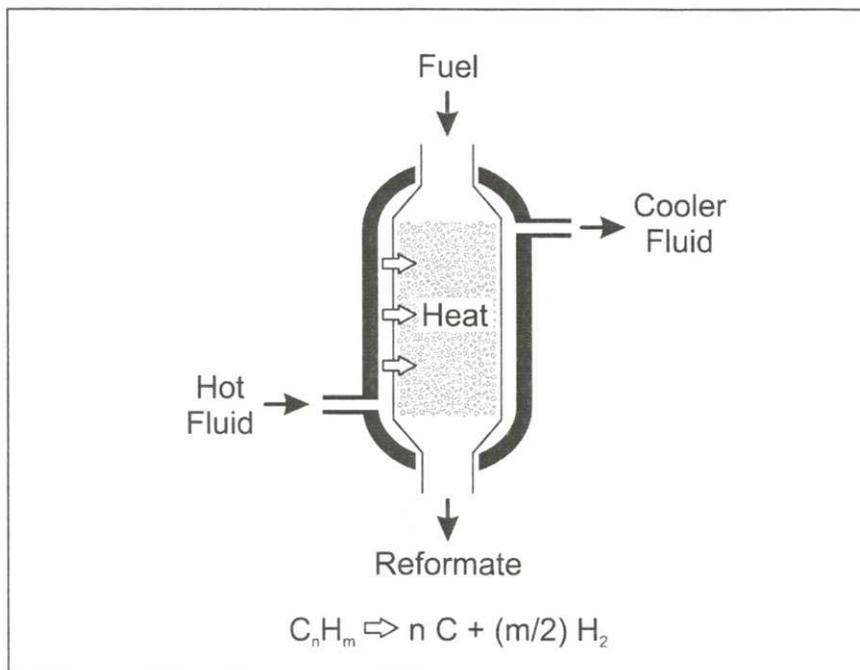
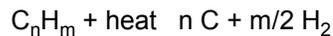


Figure 2-11 Thermal Decomposition Process

Thermal decomposition reformers are very compact with quick startup and load-following characteristics but have the lowest thermal efficiency of any of the reforming systems (55-65%). The thermal efficiency is so low partly because a

Key Points & Notes

great deal of the source fuel's energy remains trapped in the product carbon (rather than in the lower energy forms of carbon monoxide or carbon dioxide). Efficiencies would improve significantly if the product carbon could be burned for heat generation, but this would lead to undesirable emission levels of nitrous oxides and would substantially increase system complexity.

2.1.2.3 Reformate Purification

Steam, partial oxidation and autothermal reformers all convert the carbon contained in the source fuel into carbon monoxide. Depending on the feedstock, the reformate stream can also include sulfur compounds, liquid methanol other contaminants. All of these compounds poison or degrade fuel cell performance and must be removed to very low levels. For example, alkaline fuel cells can tolerate no more than 3% (by volume) carbon monoxide, and PEM fuel cells can tolerate no more than 50 ppm carbon monoxide. Other reformate gases, such as nitrogen and carbon dioxide, dilute fuel cell performance but do not damage the cells.

Reformate purification is a two-stage process. In the first stage, the bulk of the carbon monoxide is transformed into carbon dioxide using a water/gas shift reaction. In the second stage, the amount of carbon monoxide is further reduced using selective oxidation or methanation reactions, and/or the hydrogen is extracted from the reformate stream using a pressure swing adsorption process or by means of metal separation membranes.

The amount of reformate purification chosen is a trade-off between fuel cell longevity and performance, and overall system complexity, size and cost.

Water/Gas Shift Reaction

The water/gas shift reaction reacts carbon monoxide with steam over a catalyst to produce a mixture of hydrogen and carbon dioxide. The shift reaction process is illustrated schematically in Figure 2-12. The overall reaction is:



The water/gas shift reaction can be performed using high-temperature catalysts that support the reaction in excess of 570 °F (300 °C), or using low-temperature catalysts that support the reaction to about 285 °F (150 °C).

The water/gas shift reaction is an exothermic process; this heat can be recovered and used in other parts of the reform-

ing process to improve the overall thermal efficiency. Some shift reaction catalysts also oxidize exothermically when exposed to air. This can result in high temperatures that can pose a fire hazard and/or damage the catalyst.

Key Points & Notes

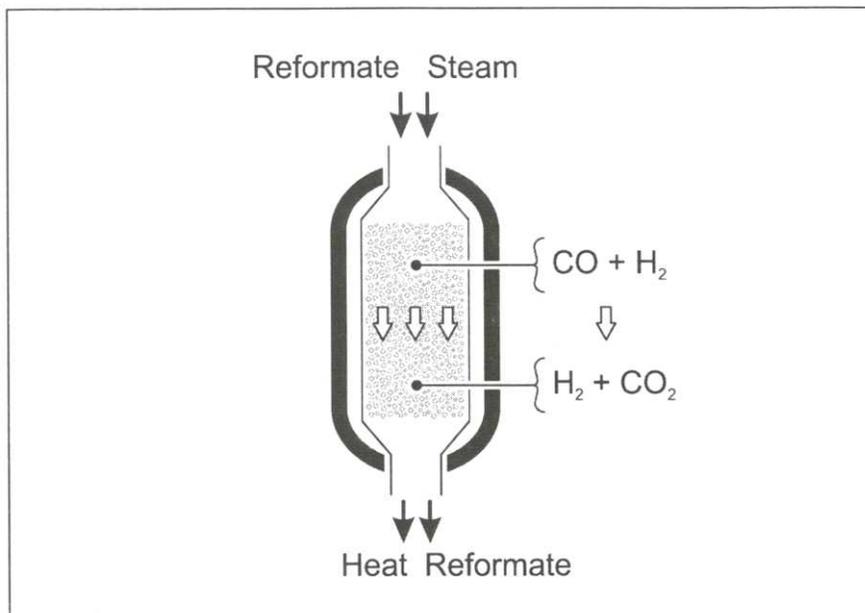


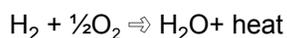
Figure 2-12 Water/Gas Shift Reaction Process

Like in a steam reformer, the water for the shift reaction must either be drawn from an external source, or if used in conjunction with a fuel cell, drawn from the fuel cell product water stream.

The water/gas shift reaction is an efficient method of eliminating the bulk of carbon monoxide in a reformate stream. Carbon monoxide typically comprises between 15 and 60% of the reformate stream, depending on the feedstock used. The water/gas shift reaction can reduce this to levels less than 1%, and even as low as 0.2%.

Selective Oxidation

Selective oxidation (or “selox”) is a chemical process that reacts carbon monoxide with oxygen (air) over a catalyst to produce carbon dioxide. The selective oxidation process is illustrated schematically in Figure 2-13. The catalyst bed facilitates both of the following competing reactions:



The former reaction is preferred and is selected by controlling the temperature profile within the selective oxidizer. Temperatures that are too high favor the water-producing

reaction whereas temperatures that are too low result in condensation. The selective oxidation reaction is an exothermic process; this heat can be recovered and used in other parts of the reforming process to improve the overall thermal efficiency.

Key Points & Notes

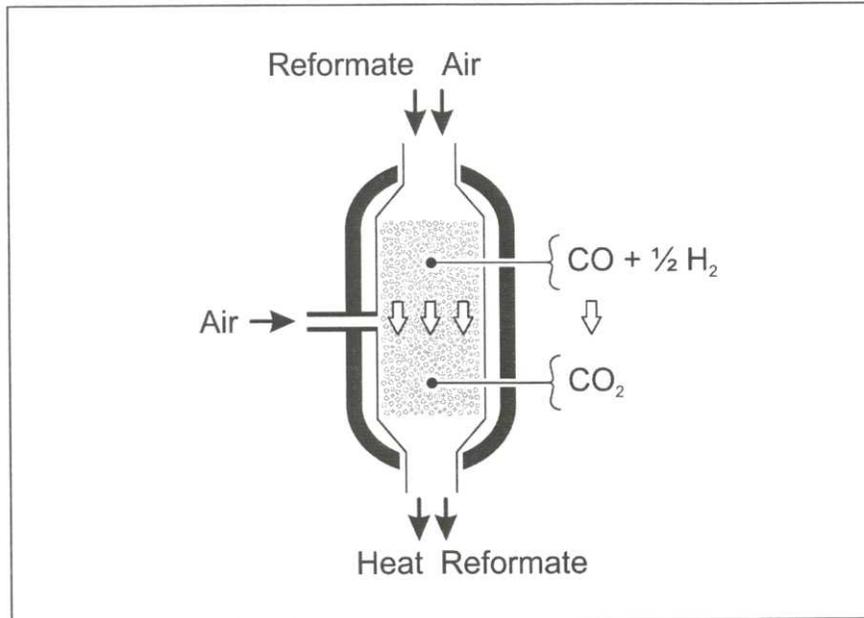


Figure 2-13 Selective Oxidation Process

Selective oxidation is the most compact of all purification methods and is capable of reducing carbon monoxide content to very low levels, such as 5 to 10 ppm. The main drawback of selective oxidizers is that they require complex control systems, especially to maintain low carbon monoxide levels during load transients.

Methanation

Methanation is a chemical process that reacts carbon monoxide and carbon dioxide with hydrogen to produce methane and water. The methanation process is illustrated schematically in Figure 2-14. The overall reactions are:



These reactions are the opposite of those that occur during steam reforming of methane and are therefore reversing the hydrogen production initially accomplished. If this process were performed on the reformate stream directly, virtually all of the product hydrogen would be consumed with no net yield. However, if the carbon dioxide is removed prior to methanation using some other means (such as pressure

swing adsorption), the remaining carbon monoxide can be successfully reduced to very low levels with little loss in overall hydrogen yield.

When reforming methanol, the methanation process has the side benefit of simultaneously converting previously unreacted methanol into carbon dioxide, hydrogen or methane. This not only increases the hydrogen yield, but also reduces the chance of liquid methanol entering the fuel cells where it can obstruct the power generation reaction.

Key Points & Notes

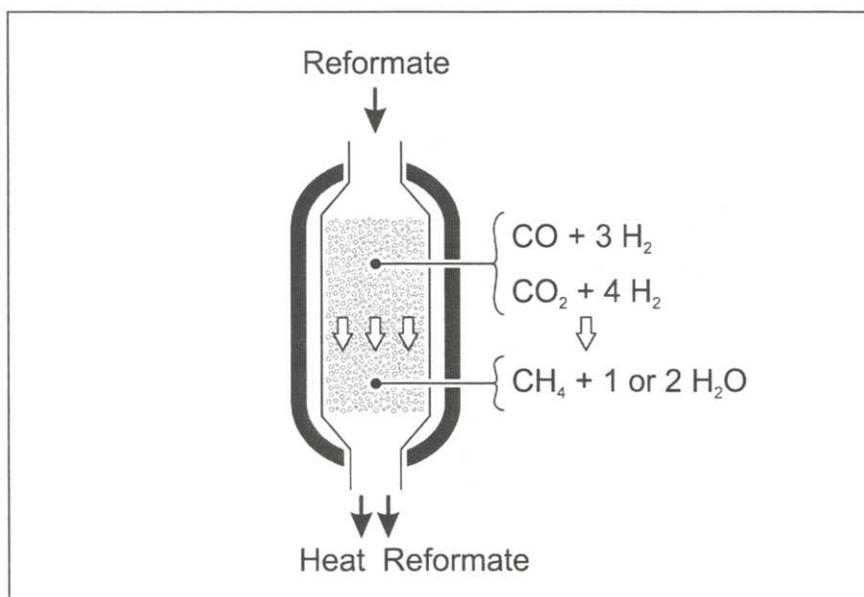


Figure 2-14 Methanation Process

Pressure Swing Adsorption (PSA)

Pressure swing adsorption (or “PSA”) is a common industrial method of separating a gas mixture into its various components. This technology has been used extensively in combination with steam reformers to extract hydrogen on an industrial scale. Very high purity is attainable (99.99%) while recovering up to 85% of the available hydrogen.

At the heart of the pressure swing adsorption process are materials called zeolites. A zeolite is a mineral with a highly structured crystalline surface that attracts gas molecules to its surface and holds them there through physical adsorption (*adsorb* means “to stick to the surface of”. This is different from *absorb* that means “to penetrate into the surface of”). Many different types of zeolites are manufactured commercially, each capable of selectively adsorbing specific gases or groups of gases. Combinations of zeolites can therefore be tailored to form “molecular sieves” capable of trapping unwanted gases while allowing desired gases to pass

unaffected. Pressure swing adsorption devices are routinely built to separate oxygen from air in the same manner that hydrogen is separated from fuel.

Physical adsorption involves relatively weak “van der Waals” and electrostatic forces. These bonds are easily broken when subjected to pressure and flow variations. This principle is used to flush the trapped unwanted gases out of the zeolites after the purified product has been removed. The pressure difference between the initial gas mixture and the exhaust stream drives the process; hence the term pressure swing adsorption. Repeated cycles result in a continuous flow of purified product.

Specifically, the pressure swing adsorption process involves four primary phases that together make up a complete cycle. During the first, or “feed pressurization” phase, reformat gas is introduced to the zeolite bed at high pressure. During the second, or “production” phase, the unwanted gases are adsorbed by the zeolites while purified hydrogen concentrates at the top of the bed and is drawn off. During the third, or “depressurization” phase, the pressure is reduced and some of the unwanted gases are expelled. During the fourth, or “low pressure purge” phase, some of the pure hydrogen gas is back-flushed through the bed at low pressure in order to desorb and purge out the remaining unwanted gases. The pressure swing adsorption process is illustrated schematically in Figure 2-15.

Key Points & Notes

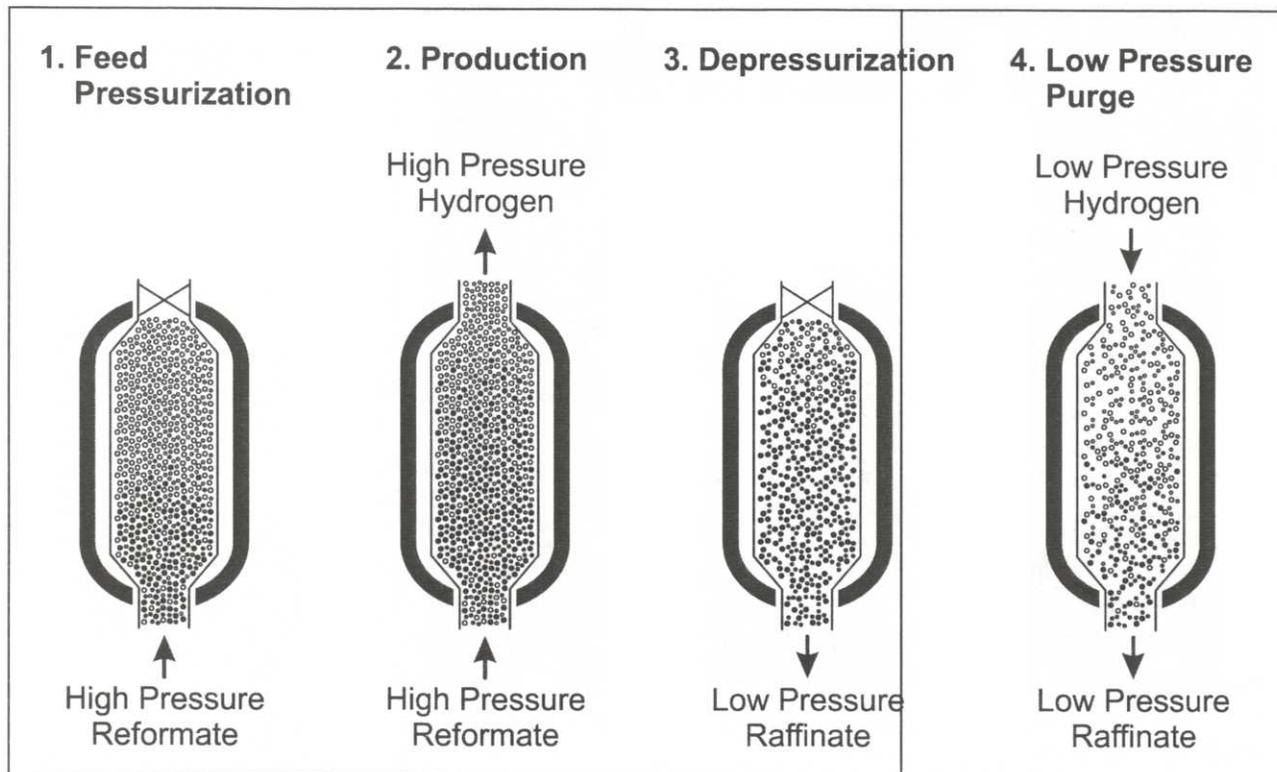


Figure 2-15 Pressure Swing Adsorption Process

Conventional pressure swing adsorption machines use stationary beds filled with small porous pellets formed of zeolite crystals mixed with a clay binder. These pellets can be as small as 0.5 mm in diameter but are more typically 2 or 3 mm in diameter. This configuration results in a very high surface area and therefore large adsorption capacity, but the size and arrangement of the pellets inhibits rapid gas transfer in and out of the pellets.

When operated quickly, the pellet arrangement results in a high pressure drop, fluidization (the pellets lift with the gas and act like a fluid), and attrition (the pellets rub together, break apart, and disappear). To compensate, conventional machines must operate at very low speed (typically at 0.5 cycles/min) and tend to be large. However, new developments in pressure swing adsorption technology use a proprietary adsorbent structure and novel rotary valve technology that allow two orders of magnitude increase in the gas separation cycle speed without fluidization or attrition. This allows the construction of devices that are a fraction of the size of conventional units with the potential for use on-board vehicles.

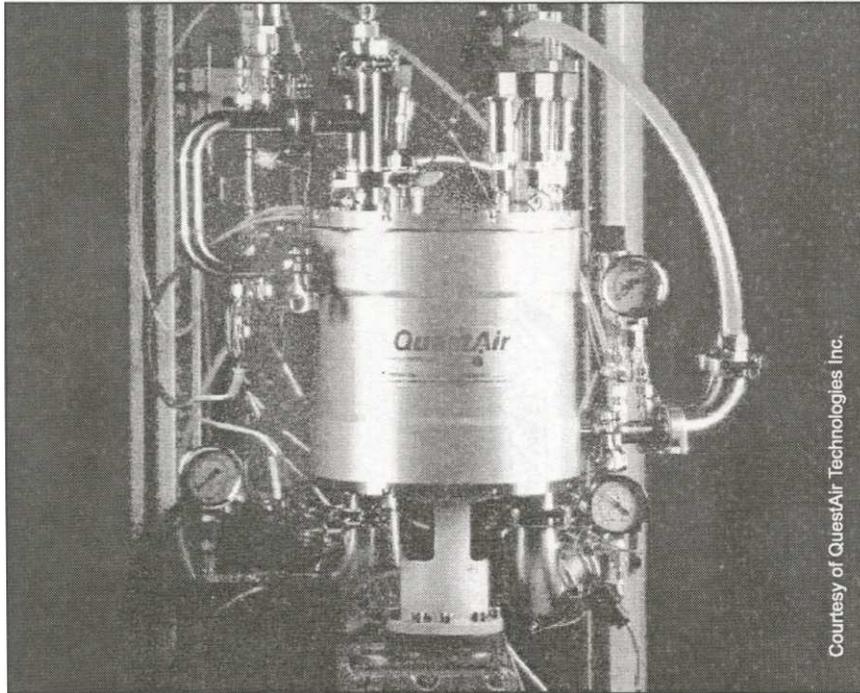


Figure 2-16 QuestAir Technologies' State-of-the-Art Compact Pressure Swing Adsorption Device

Key Points & Notes

The greatest problem associated with using pressure swing adsorption in conjunction with fuel cells is the fact that the gases that come into contact with the zeolites must be completely dry. This is because water adsorbs onto the surface of the zeolites and forms strong bonds that involve electron transfer and other strong forces. This is known as *chemical* adsorption, and is different from the *physical* adsorption that occurs with the waste gases.

Chemical adsorption bonds are too strong to be broken using pressure and flow fluctuations. As a result, these bonds displace potential physical adsorption bonds and render the zeolite bed less effective, ultimately disrupting the pressure swing adsorption process. Once formed, chemical adsorption bonds require heat to be broken. To prevent these bonds from forming, a desiccant must be used to adsorb water from the incoming wet gas stream before it comes into contact with the zeolites. This can be done concurrent with, and within the same machine as, the gas separation process so that there are two pressure swing adsorption cycles operating — one for water separation and the other for hydrogen.

Metal Separation Membranes

Metal separation membranes present an impermeable physical barrier to all gases except hydrogen.

To function, the reformat must be delivered to the membrane across a pressure gradient. Up to 85% of the hydrogen then diffuses from the high pressure (300 psig; 20 barg) reformat stream to form a low-pressure (30 psig; 2 barg) stream of very high purity (>99.999%). The remaining high-pressure raffinate can be combusted to provide heat for the reforming process. The metal separation membrane process is illustrated schematically in Figure 2-17.

Key Points & Notes

The advantages of metal separation membranes are that they provide high purity, undiluted hydrogen in a compact, simple and reliable manner. Metal separation membranes are also well suited to thermal integration with steam reformers and respond well to thermal transients.

The primary disadvantage of metal separation membranes is their very high material and construction costs. Traditionally, metal separation membranes are the most costly of all purification techniques, owing to their use of silver palladium or other alloys and the need to eliminate all pinholes and sealing leaks. However, new developments using thin film membranes promise to lower the materials cost to practical levels.

Other drawbacks to metal separation membranes include the need to re-humidify the hydrogen prior to use by fuel cells, and the need for a pressurized reformer. The use of a pressurized reformer results in increased reformer weight and size, although this is offset somewhat by the elimination of other purification equipment.

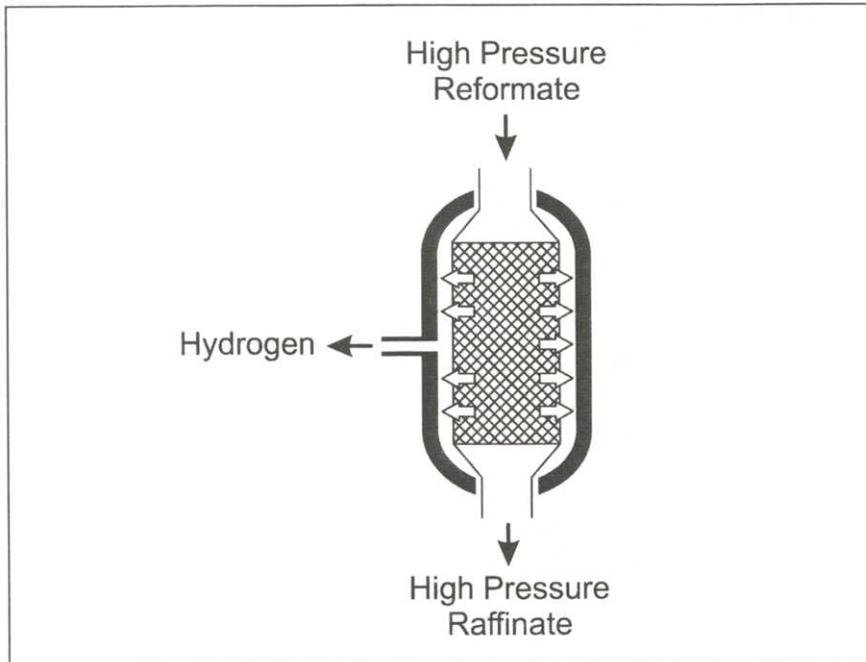


Figure 2-17 Metal Separation Membrane Process

Key Points & Notes

2.1.2.4 Heat Generation

Heat is an essential part of any reforming process. For endothermic reactions, such as steam reforming and thermal decomposition, heat must be supplied from an external source. For exothermic reactions, such as partial oxidation and autothermal reactions, heat is generated internally by the reaction itself.

The water/gas shift, selective oxidation, and methanation reformat purification reactions are also exothermic. Central to the thermal efficiency of a reformer is the thermal integration of both the reforming and purification stages. Through careful engineering design, heat can be moved from one part of the process to another, reducing the amount of net heat that must be added or removed.

Exothermic reactions have better startup and transient response than endothermic reactions as the heat of reaction is immediately available without the time lag associated with adding heat. Despite this advantage, exothermic processes can require complex control strategies in order to control temperatures and avoid overheating catalysts and materials over the entire operating range. Excess heat from exothermic reactions must be dissipated through a cooling system.

Endothermic reactions require the addition of heat in concert with the instantaneous load demand. To some extent, this problem can be lessened by designing reformers with

high thermal inertia that tend to smooth out the differences between transient peaks and valleys. Nevertheless, heat must be added using burners and complicated control systems that attempt to provide the required heat on demand.

Typical burner designs use flames or catalytic combustors, with or without a thermal buffer. Burners are usually fueled using the hydrogen-depleted raffinate, the fuel cell anode exhaust stream, a portion of the reformat, or some of the source fuel. Combustion can lead to NO_x emissions if the burner temperature exceeds 2700 °F (1480 °C).

Flame Burners

Flame burners generate heat through the direct combustion of the fuel with air.

Flame burners can supply the radiant heat of combustion directly to a metal reactor wall. This is a very common approach for high temperature steam reformers, and can also be applied in low temperature reforming systems.

Flame burning has the advantage of mechanical simplicity, although hot spots can easily occur where the flame contacts the reactor. This can lead to localized overheating and catalyst degradation, especially when used in a low temperature application. To overcome this, a thermal buffer can be used as an intermediate heat transfer medium, smoothing out the temperature profile.

Thermal buffers usually take the form of flue gases or thermal fluids, such as heating oils. Oils are applicable only to low-temperature reformer designs. Oils are particularly advantageous since they have high heat capacity, which allows heat to be stored in a small amount of fluid at temperatures significantly lower than that of the flame. This high heat capacity also allows the reformer to operate at a nearly constant temperature for optimum efficiency. Heat from an oil buffer can be transferred to the reformer and to the vaporizer beds through a coiled tube embedded in the vessel walls. Overheating remains a concern, though, as thermal oils begin to degrade above 645 °F (340 °C).

Catalytic Combustors

Catalytic combustors generate heat through the combustion of fuel with air over a catalyst such as platinum. This process allows for complete combustion without flames at lower temperatures than would be required without the catalyst. Combustion temperatures can be maintained at tempera-

Key Points & Notes

tures of 1290 °F (700 °C) or less using very lean air/fuel mixtures.

Like flame burners, catalytic combustors can supply the heat of combustion directly to a metal reactor wall or by way of a thermal buffer. In either case, the lower combustion temperature decreases the chance of overheating, either in the reactor or in the thermal oil.

Catalytic combustors also offer the advantages of very complete fuel combustion, low emissions (less than 5 ppm CO and no NO_x), and very effective and responsive temperature control. Response to load changes is very fast, which is excellent where rapid startup and good transient response are required.

The disadvantages of catalytic combustors are the increased capital cost associated with the catalyst, and the potential for catalyst poisoning in the event of fuel impurities.

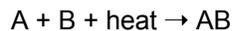
2.1.3 Thermochemical Water Decomposition

In thermochemical water decomposition, heat alone is used to decompose water. This process is similar to electrolysis, with the difference that all the energy is added as heat and none as electricity. The maximum theoretical efficiency for this process is about 50%.

Water decomposes directly at very high temperatures (>4500 °F; 2500 °C) which is too high to be practical. Instead, chemical reagents are used to decompose water in multi-step chemical reactions in the following sequence:

1. Oxygen production
2. Hydrogen production
3. Materials regeneration

These reactions take the generic form of:



This is essentially an oxidation-reduction reaction where A and B are chemical compounds that commonly include iron, oxygen or chlorine. This process can take place at about 1290 °F (700 °C).

Key Points & Notes

Selection of the specific chemical compounds for the reaction series depends on such factors as the:

Key Points & Notes

- amount of energy needed for each step
- stability of the reactants for each step
- ability for the products of one step to be easily reacted in the next
- reaction time
- reaction yield
- individual reaction temperature
- pressure and flow requirements
- number of steps
- amount of cleanup required
- composition of waste products

In addition, as with any other chemical process, heat recovery, mass transfer and materials issues affect the overall system design.

Thermochemical water decomposition, like electrolysis, is only as renewable and environmentally clean as its energy source. If waste heat is used from other processes, the resulting hydrogen increases the overall efficiency of the heat-generating parent process. If heat is obtained by burning fossil fuels, the resulting hydrogen will likely have generated more pollution than would have been by using the source fuel directly.

2.1.4 Photo Conversion

Photo conversion is an electrolysis process by which the electricity needed to decompose water into hydrogen and oxygen is generated directly using solar energy.

Water cannot absorb solar energy directly since it is transparent to the required wavelengths. The most common process uses a series of cells, each with a pair of semi-conductor photoelectrodes immersed in a watery electrolyte and separated by a membrane that allows ion transfer but prevents gas mixing. The cathode, is made of a “p-type” semiconductor material (that has an excess of positive “holes”). The anode, is made of a “n-type” semiconductor material (that has an excess of electrons). This is similar to a solar cell.

When the anode is illuminated by sunlight, electrons absorb the light energy and pass through an external circuit to the

cathode. This creates an “electron-hole” pair. The positive hole subsequently reacts with the water to create positive hydrogen ions and gaseous oxygen. The hydrogen ions pass through the membrane to recombine with the electrons at the cathode, resulting in hydrogen gas. Thus, the overall process results in photoelectrolysis of the water.

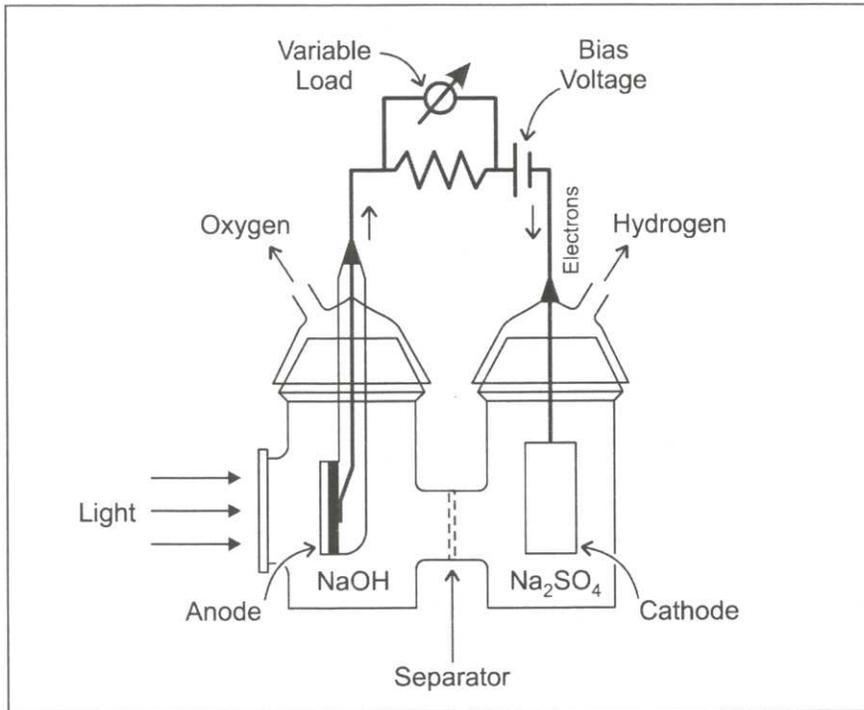


Figure 2-18 Semiconductor Photo Conversion Cell

A related method uses photochemical catalysts, suspended in alkaline or acidic solutions, as opposed to semiconductors. These catalysts absorb photon energy upon illumination, which creates an electric charge that drives a water-splitting reaction.

Like any solar energy power generation process, photo conversion can only work in areas of prolonged, concentrated sunlight. Furthermore, this type of system has maximum efficiencies of between 8 and 12%.

Photobiological Processes

Light energy can also produce hydrogen through photobiological processes, using biological systems such as cyanobacteria (blue-green) algae, photosynthetic algae or eukaryotic (green) algae. In principle, these algae contain hydrogen-metabolizing enzymes that feed off base compounds in an anaerobic environment and release hydrogen gas in the process. These algae use compounds such as water, whey, starches, sugar refinery waste, and distillery

waste as electron donors. Unfortunately, the efficiency of these processes is very low; typically less than 1%.

Key Points & Notes

2.1.5 Production from Biomass

Hydrogen can be produced from the decomposition of biomass. Biomass comprises all manner of plant and animal material that can be converted into energy. Biomass is organic in nature and can be derived from a variety of sources including residues, wastes and crops. Residues include the materials left over after the harvest of crops or trees. Wastes include those from food processing plants, sewage and municipal solid waste. Crops include those that can be grown specifically for their energy content, such as soybeans, trees and woody plants, among many others.

Potential U.S. biomass supplies for energy purposes have been estimated to be the energy equivalent of 7 million barrels of oil per day: 40% from biomass waste resources and 60% from biomass energy crops grown on 80 million acres of excess agricultural lands.

The appeal of hydrogen production from biomass is the obvious abundance of waste materials and its subsequent potential to supply large amounts of hydrogen. The primary problems are that the process is land and water intensive, and is hampered by the difficulties associated with handling solids. Furthermore, the associated technology is not well developed with the result that it is currently the most expensive means of obtaining hydrogen.

Hydrogen production from biomass takes two primary forms; thermochemical conversion and anaerobic digestion.

Thermochemical Conversion

Thermochemical conversion is a multistage process that includes feedstock pre-processing, gasification, gas cleanup, steam reforming, shift reaction and hydrogen separation (or alternatively, methanol synthesis and purification).

Gasification is at the heart of the thermochemical conversion process. Gasification occurs through the thermal decomposition (or "pyrolysis") of organic matter with the help of an auxiliary gas such as air, oxygen, or hydrogen to yield primarily gaseous products.

Typically, the feedstock reacts with steam and air (oxygen), at a temperature dictated by the feedstock characteristics, to rapidly yield a mixture of hydrogen, carbon monoxide, carbon dioxide, water and methane along with hydrogen sulfide and other trace impurities.

Hydrogen content is determined by the process temperatures and pressures and can constitute about 20% of the gas mixture. A major disadvantage of direct biomass gasification is the co-production of tars, phenolics and acids. Effective

separation and purification of the decomposition products and efficient gas cleanup for the removal of tars and oils remain as technical challenges.

Catalysts can be used to increase production efficiencies, reduce tar formation and eliminate the need for oxygen. The process can become even more profitable if undertaken under pressure, as the equipment needed becomes smaller and less expensive.

Anaerobic Digestion

Anaerobic digestion (or “methane fermentation”) is a multi-stage process in which the waste from one set of organisms is the food for another set. This process takes place in an anaerobic environment, usually in a digester, in the presence of a population of anaerobic bacteria.

Anaerobic digestion consists of three basic processes. First, cellulose and hemicellulose are broken down by enzymes to form soluble organic compounds. Then the soluble organic materials are converted to hydrogen, carbon dioxide, formate and acetate by acid-producing bacteria. Finally, methane is produced from those substances by methane-producing bacteria.

The resulting methane gas production is very slow at ambient temperatures, and the digester temperature must be increased to the order of 100 °F (37 °C). The resultant gas has medium fuel value, and the concentration of methane is only slightly higher than its carbon dioxide content. As a result of these two factors, anaerobic digestion processes use almost as much energy as they produce, or even more, depending on the design of the digester and the operating conditions. Although hydrogen can be obtained from methane through steam reforming, this additional step requires too much energy to be cost effective.

2.1.6 Industrial Processes

Hydrogen is produced as a byproduct of some conventional industrial processes. Hydrogen is:

- a byproduct of chlorine and polyvinylchloride production
- a by-product of the sodium hydroxide industry
- produced among other light gases in crude oil refineries
- produced from coal in coke oven gases
- emitted in chemical dehydrogenation processes

Key Points & Notes



Industrial Plant

Generally these by-product sources have insufficient capacity and are too costly to supply large quantities of hydrogen.

Key Points & Notes

2.2 Hydrogen Storage

Key Points & Notes

If the greatest challenge in hydrogen use is to extract it, the second greatest challenge is how to store it. As seen in Section 1, hydrogen has the lowest gas density and the second-lowest boiling point of all known substances, making it a challenge to store as either a gas or a liquid. As a gas, it requires very large storage volumes and pressures. As a liquid, it requires a cryogenic storage system.

Hydrogen's low density, both as a gas and a liquid, also results in very low energy density. Stated otherwise, a given volume of hydrogen contains less energy than the same volume of other fuels. This also increases the relative storage tank size, as more hydrogen is required to meet a given vehicle's range requirements. The amount of hydrogen needed for fuel cells is offset somewhat by the fact that it is used more efficiently than when burned in an internal combustion engine, so less fuel is required to achieve the same result.

Despite its low volumetric energy density, hydrogen has the highest energy-to-weight ratio of any fuel. Unfortunately, this weight advantage is usually overshadowed by the high weight of the hydrogen storage tanks and associated equipment. Thus, most hydrogen storage systems are considerably bulkier and/or heavier than those used for gasoline or diesel fuels.

For all practical purposes, hydrogen can be stored as either a high-pressure gas, a liquid in cryogenic containers, or a gas chemically bound to certain metals (hydrides). The volume and weight of each of these systems is compared to gasoline, methanol and battery storage systems (each containing 990,000 Btu (1,044,500 kJ) of stored energy; equivalent to 8.4 gallons of gasoline) in Figure 2-19. Ironically, the best way to store hydrogen is in the form of hydrocarbon fuels although it requires additional systems to extract it.

Hydrogen Fuel Cell Engines

MODULE 2: HYDROGEN USE

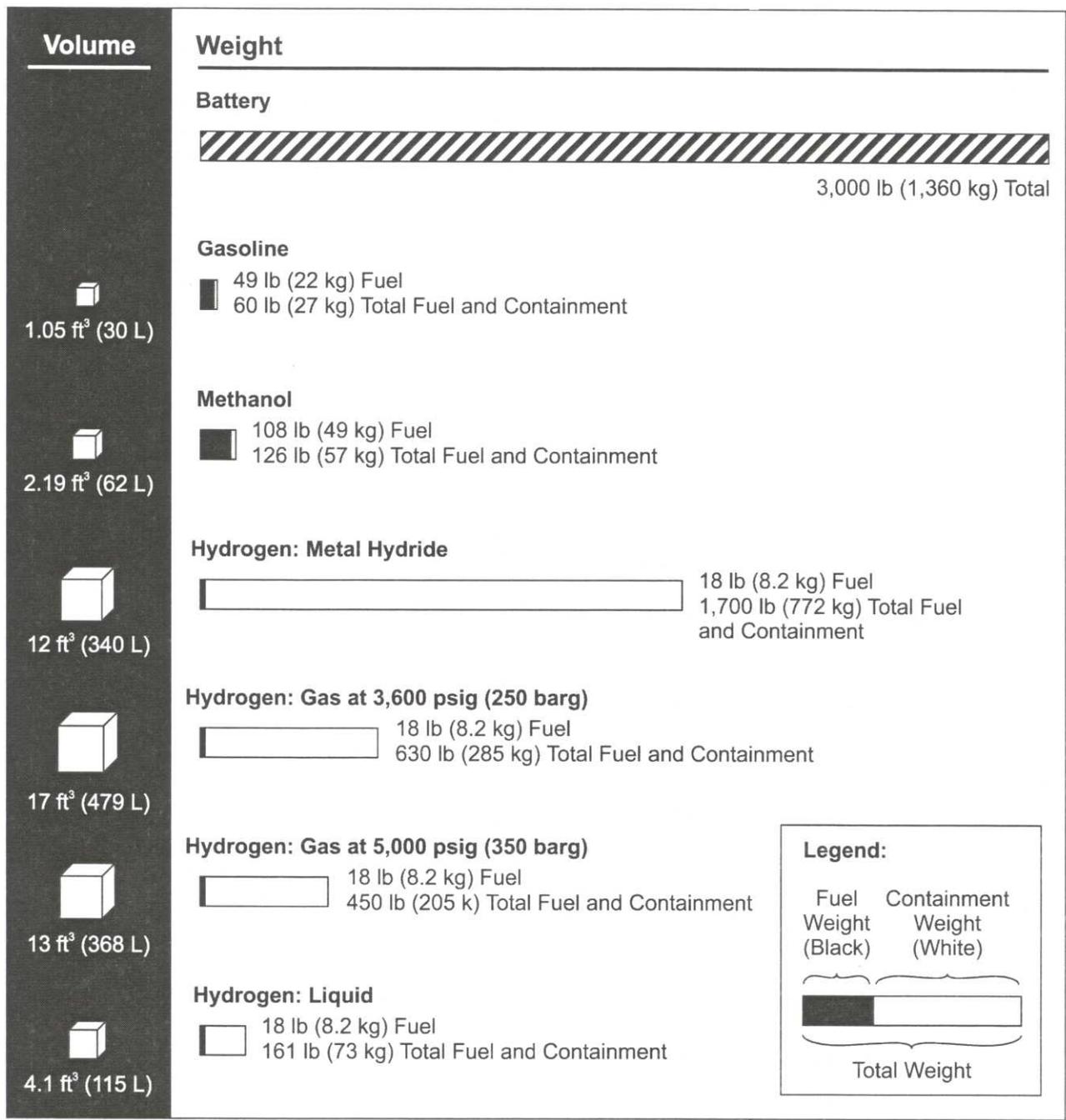


Figure 2-19 Storage Volume and Weight of Comparative Fuels Each With 990,000 Btu (1,044,500 kJ) of Stored Energy

Key Points & Notes

2.2.1 High Pressure Gas

High-pressure gas storage systems are the most common and most highly developed methods of storing hydrogen. Most existing fuel cell vehicles use this form of hydrogen storage.

High-pressure hydrogen is stored in cylinders, similar to those used for compressed natural gas. Most cylinders have a cylindrically shaped sidewall section with hemispherical end domes, although new conformal designs use multiple cylinders in tandem and distort the cylindrical shape in order to increase the usable volume.

Ports in the middle of each end dome allow the gas to flow into and out of the cylinder, with end bosses that control the gas flow. One end boss acts primarily as a plug, although it includes a pressure relief device vent port and may contain pressure and temperature transducers to measure gas conditions within the cylinder. The other end boss is a sophisticated portal device that includes a solenoid valve, an excess flow valve, a manual isolation valve, a check valve and a pressure relief device vent port.

Key Points & Notes

The terminology “high pressure gas” usually denotes pressures above 3000 psig (207 barg) when used in relation to gas storage systems. However, any gas pressure above 30 psig (2 barg) has the potential to cause serious human injury and should be considered “high pressure” in human terms.

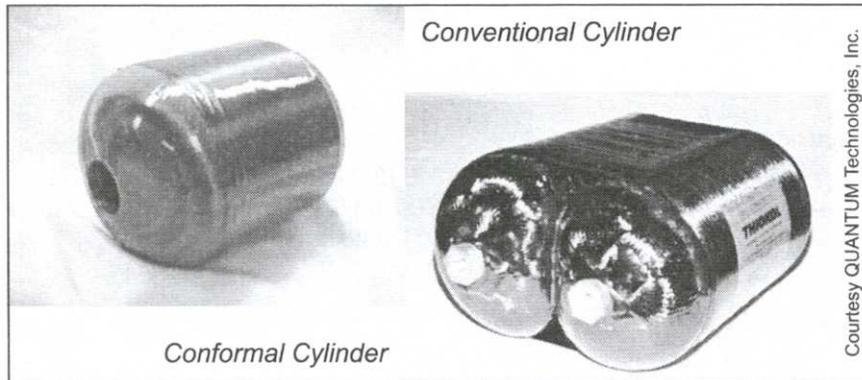


Figure 2-20 High Pressure Hydrogen Cylinder Designs

The solenoid valve is normally closed and isolates the cylinder whenever the vehicle is shut down. The excess flow valve closes whenever the gas flow leaving the cylinder is too great (such as if a pipe bursts). The manual isolation valve allows the cylinder contents to be either isolated or vented manually in the event of solenoid valve failure. The check valve allows fueling while the solenoid valve is closed. The pressure relief devices (at either end of the cylinder) release the cylinder contents when exposed to fire.

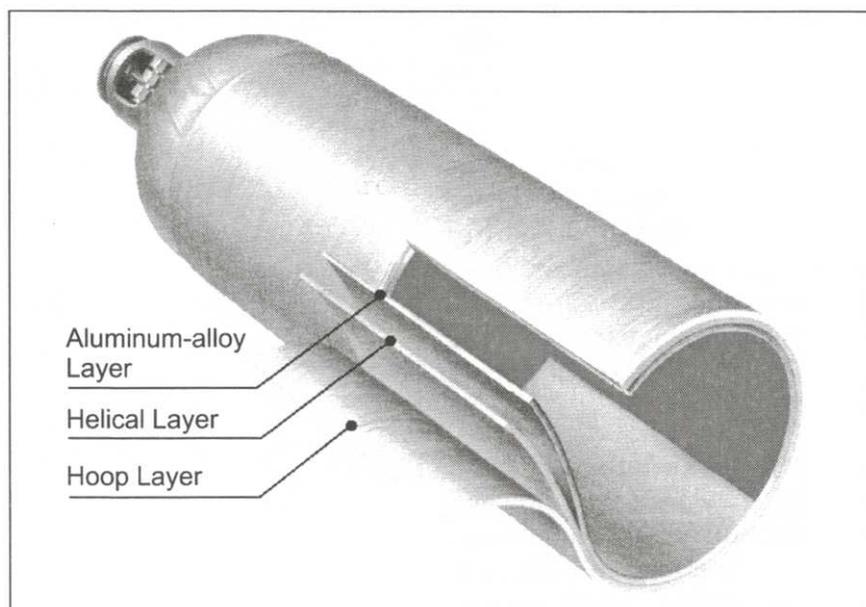
High-pressure gas cylinders must be made of thick-walled, high strength materials and must be very durable. Cylinders are classified into four types according to their materials of construction.

Designation	Description	% Load Taken by Metal vs. Composite
Type 1	A cylinder made wholly of steel or aluminum	100 / 0
Type 2	A cylinder with a metal line of steel or aluminum and a hoop-wrapped (circumferential) composite overwrap	55 / 45
Type 3	A cylinder with a thin metal liner of steel or aluminum and a fully wound composite overwrap	20 / 80
Type 4	A cylinder with a plastic liner and a fully wound composite overwrap	0 / 100

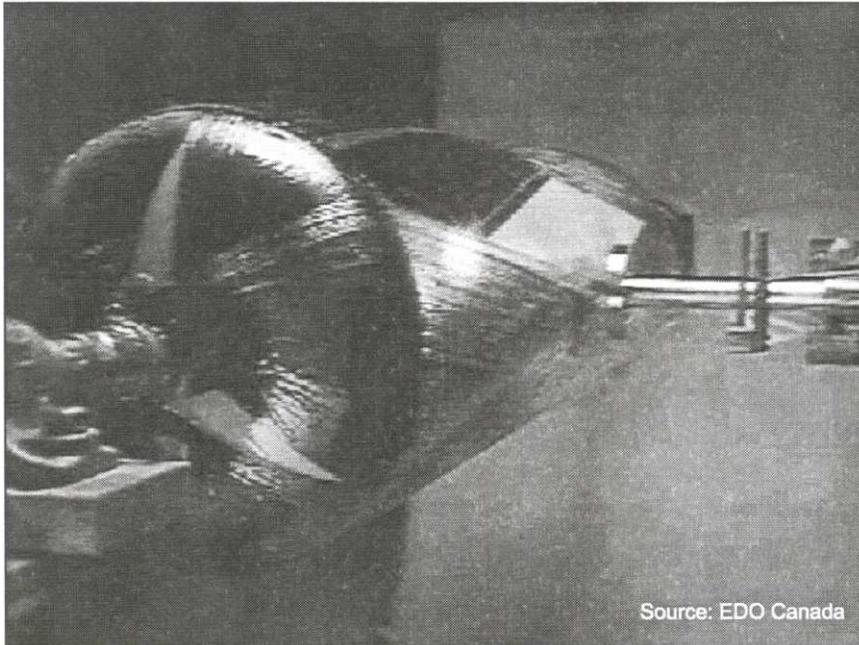
Key Points & Notes

Table 2-2 High Pressure Gas Cylinder Classifications

In general, the less metal used, the lower the weight. For this reason, Type 3 cylinders are usually used in hydrogen applications, and Type 4 cylinders will likely gain prominence in the future. Specific weights depend on individual manufacturers, but as a point of reference, a 3.5 ft³ (100 L) Type 1 (steel) cylinder weighs about 220 lb (100 kg) a Type 3 (aluminum/composite) cylinder weighs about 143 lb (65 kg), and a Type 4 cylinder weighs about 66 lb (30 kg).

**Figure 2-21:** Type 3 Cylinder Construction

Type 3 cylinders derive most of their strength from the composite overwrap that is wound around the inner liner. This composite consists of high-strength fibers (usually carbon) that are wrapped around the cylinder in many layers and glued together by a resin such as epoxy.



Source: EDO Canada

Figure 2-22: Composite Cylinder During Manufacturing**Key Points & Notes**

The combination of fibers and resin used in a composite cylinder is extremely strong provided that the fibers and resin remain undamaged. Composite surfaces are less tough than metal surfaces and are more susceptible to physical damage (cuts, abrasion, impacts, etc.) and chemical damage (ammonia, acids, etc.), although they are less susceptible to corrosion.

Cylinder manufacturers strive to attain the highest storage pressures possible in order to reduce the required storage volume. High-pressure cylinders typically store hydrogen at up to 3600 psig (250 barg) although new designs have been certified for 5000 psig (350 barg) operation. State-of-the-art technology currently under development has exceeded the accepted burst test standard of 23,500 psig (1620 barg) using a 10,000 psig (700 barg) Type 4 cylinder.

High temperatures from hot ambient conditions, or as a result of compression during fueling, may increase storage pressures by 10% or more. Any gas stored at these high pressures is extremely dangerous and is capable of releasing a gas stream with explosive force or propelling small projectiles like a bullet. An unrestrained cylinder could turn into a rocket if the gas were suddenly released through a small opening.

Despite the potential danger, high-pressure cylinders have an excellent safety record. Cylinder designs must conform to

Cylinders are certified for a specific gas and must survive rigorous tests before being put into service.

rigorous standards and survive certification tests that demonstrate:

- no failures during 13,000 pressure cycles to 100% service pressure plus 5000 cycles to 125% service pressure. Some standards also demand 30 cycles to 166% service pressure.
- no failures (after pre-conditioning) during 5000 pressure cycles to 100% service pressure at 140 °F (60 °C) followed by 5000 cycles at -40 °F (-40 °C).
- burst pressure of 2.25 to 3.0 times the service pressure, depending on the standard.
- impact resistance to flaws, drops and pendulum impact.
- safe venting of contents when exposed to a bonfire.
- no fragmentation when exposed to gunfire.

Some cylinder tests performed on a Type 4 cylinder are illustrated Figure 2-23.

During manufacture, each cylinder is subjected to hydrostatic and leak tests, and selected cylinders from each lot are subjected to cyclic and burst tests. Cylinders are labeled by the manufacturer as to the construction standard, serial number, service pressure, maximum fill pressure, and end-of-service date. Cylinders that are not subjected to severe external abuse or gas pressures above normal service levels can expect a service life of 15 years or 11,250 fills. Inspections and leak tests are a routine part of cylinder maintenance.

A typical vehicle application uses a series of cylinders mounted on a common manifold. At a service pressure of 3600 psig (250 barg), the fuel storage system weighs nearly four times that of a comparable liquid hydrogen storage system and occupies more than four times the space. When compared to gasoline, the gaseous hydrogen storage system is 15 times greater by volume and 23 times by weight. To put this into perspective, approximately 50% of a transit bus roof must be covered with hydrogen cylinders in order to replace its standard diesel tank.

Despite this volume, the entire weight of hydrogen fuel is only 90 to 110 lb (40 to 50 kg), which is negligible compared to the weight of the cylinders and associated equipment. Storing gas at an even higher pressure results in a smaller storage volume, but the overall storage weight to hydrogen volume does not change much as the cylinders must be more robust. The current record for the highest hydrogen

Key Points & Notes

storage by weight ever recorded at 11.3% as achieved using
a 5,000 psig (350 barg) Type 4 cylinder.

Key Points & Notes

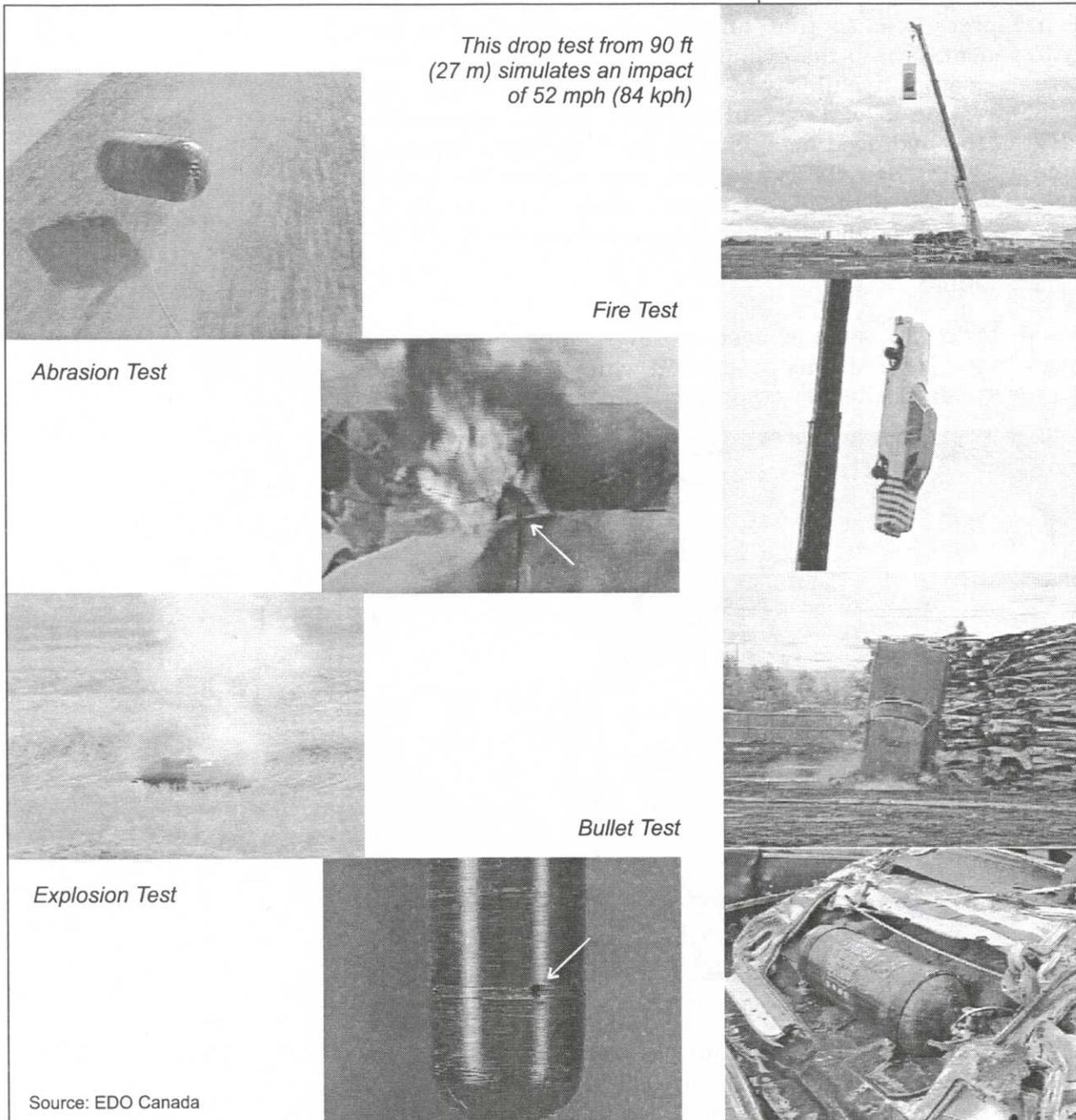


Figure 2-23: Cylinder Qualification Tests

Key Points & Notes

Gas compression is an energy intensive process. The higher the end pressure, the greater the amount of energy required. However, the *incremental* energy required to achieve higher and higher pressures decreases so that the initial compression is the most energy intensive part of the process.

The energy economy of higher compression levels is counterbalanced by an incremental decrease in gas density at higher pressures, so that further compression packs less hydrogen mass into the cylinders (even if suitable cylinders were to exist). A useful way of understanding the energy cost of compression is as a percentage of the total energy content (LHV) of the hydrogen being stored. In these terms, approximately 5% of the LHV is required to compress the gas to 5000 psig (350 barg). Exact energy usage depends on the flow capacity and efficiency of the compressors used.

2.2.2 Liquid

Liquid hydrogen storage systems overcome many of the weight and size problems associated with high-pressure gas storage systems, albeit at cryogenic temperatures.

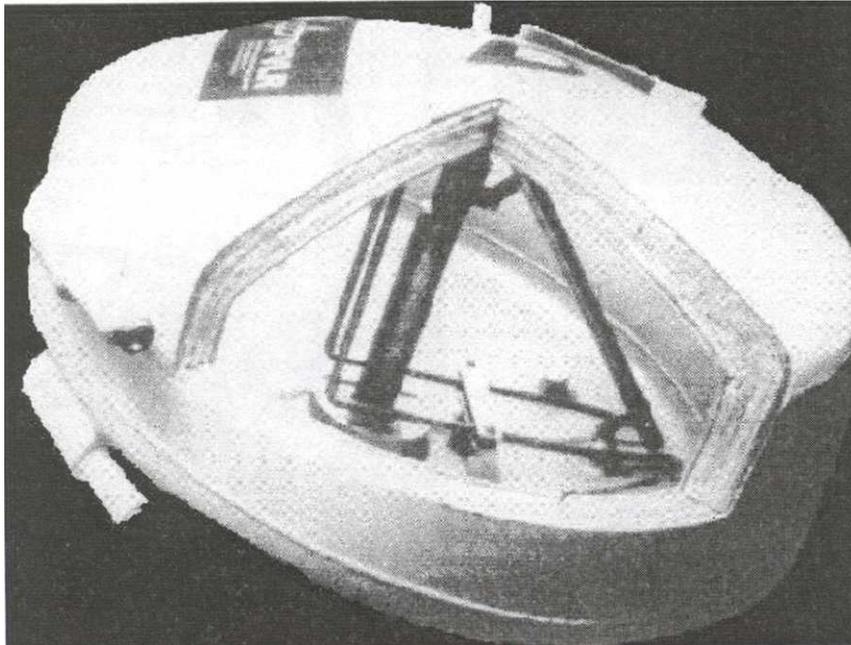
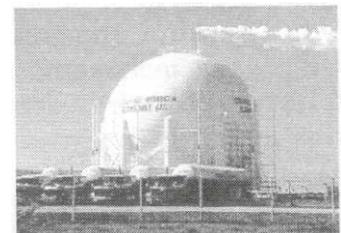


Figure 2-24: Automotive Liquid Hydrogen Tank, Sectioned

Liquid hydrogen can be stored just below its normal boiling point of $-424\text{ }^{\circ}\text{F}$ ($-253\text{ }^{\circ}\text{C}$; 20 K) at or close to ambient pressure in a double-walled, super-insulating tank (or "dewar"). This insulation takes the form of a vacuum jacket, much like in a Thermos bottle. Liquid hydrogen tanks do not need to be as strong as high-pressure gas cylinders although they do need to be adequately robust for automotive use.

Hydrogen cannot be stored in liquid form indefinitely. All tanks, no matter how good the insulation, allow some heat to transfer from the ambient surroundings. The heat leakage rate depends on the design and size of tank — in this case,

Key Points & Notes



bigger is better. This heat causes some of the hydrogen to vaporize and the tank pressure to increase. Stationary liquid hydrogen storage tanks are often spherical since this shape offers the smallest surface area for a given volume, and therefore presents the smallest heat transfer area.

Tanks have a maximum overpressure capacity of about 72 psi (5 bar); if the hydrogen is not consumed as quickly as it vaporizes, the pressure builds to a point where it vents through a pressure relief valve. This vented hydrogen is not only a direct loss of usable fuel, but it also poses a flammability hazard if the vehicle is parked indoors. Provision must be made to vent the hydrogen safely without the potential for accumulation. Current automotive hydrogen tank technology provides a venting (or “boil-off”) rate of about 1 to 2% per day.

Hydrogen can be drawn from the tank either as a liquid or as gas. When used in an internal combustion engine, liquid hydrogen can be injected directly into the cylinders in order to increase the amount of fuel combusted in each power stroke. When used in a fuel cell engine, gaseous hydrogen can be drawn off at sufficient pressure to feed the power generating reaction.

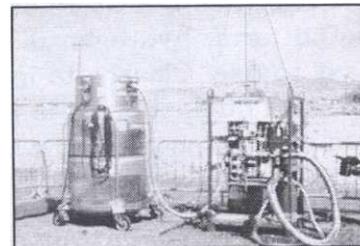
Although liquid hydrogen storage systems eliminate the danger associated with high pressures, they introduce dangers associated with low temperatures. A severe frostbite hazard exists in association with the liquid hydrogen, its vapors and contact surfaces. Carbon steel exposed to temperatures below $-22\text{ }^{\circ}\text{F}$ ($-30\text{ }^{\circ}\text{C}$), either directly or indirectly, becomes brittle and is susceptible to fracture. Air may liquefy on the outside of exposed liquid hydrogen lines or under insulation resulting in an oxygen concentration that poses a fire or explosion hazard if it drips onto combustible materials.

Liquid hydrogen is considerably more dense than gaseous hydrogen but is still much more bulky than gasoline on an equivalent energy basis. Liquid hydrogen storage systems can be four to ten times larger and heavier than an equivalent gasoline tank.

Hydrogen liquefaction is a very energy intensive process due to the extremely low temperatures involved. Liquefaction involves several steps, including:

1. Compression of hydrogen gas using reciprocating compressors; pre-cooling of the compressed gas to liquid nitrogen temperatures $-319\text{ }^{\circ}\text{F}$ ($-195\text{ }^{\circ}\text{C}$; 78 K)

Key Points & Notes



Liquid Hydrogen Filling Tank

2. Expansion through turbines
3. Catalytic conversion to its stable “parahydrogen” form (Section 1.1)

Key Points & Notes

In total, the energy required for the liquefaction process is the equivalent of up to 40% of the LHV of hydrogen. Once in liquid form, hydrogen is relatively efficient to transport and easy to use. Clearly, to maximize the energy investment paid during liquefaction, it is prudent to store and use the hydrogen directly as a liquid whenever possible.

The worst scenario in terms of energy investment is to liquefy the hydrogen, transport it in liquid form, re-convert it to a gas, and store in on-board a vehicle as a high pressure gas. This erodes the net available energy twice, once during liquefaction and again during compression, while still being left with the disadvantages of a bulky and heavy on-board gaseous fuel storage system.

2.2.3 Metal Hydrides

Rare Earth Hydrides

Metal hydride storage systems are based on the principle that some metals readily absorb gaseous hydrogen under conditions of high pressure and moderate temperature to form metal hydrides. These metal hydrides release the hydrogen gas when heated at low pressure and relatively high temperature. In essence, the metals soak up and release hydrogen like a sponge.

The advantages of metal hydride storage systems revolve around the fact that the hydrogen becomes part of the chemical structure of the metal itself and therefore does not require high pressures or cryogenic temperatures for operation. Since hydrogen is released from the hydride for use at low pressure (and must be released before it can burn rapidly), hydrides are the most intrinsically safe of all methods of storing hydrogen.

There are many types of specific metal hydrides, but they are primarily based on metal alloys of magnesium, nickel, iron and titanium. In general, metal hydrides can be divided into those with a low or high hydrogen desorption (release) temperature.

The high temperature hydrides may be less expensive and hold more hydrogen than the low temperature hydrides, but require significant amounts of heat in order to release the hydrogen. Low temperature hydrides can get sufficient heat

from an engine, but high temperature hydrides require an external source of heat.

Key Points & Notes

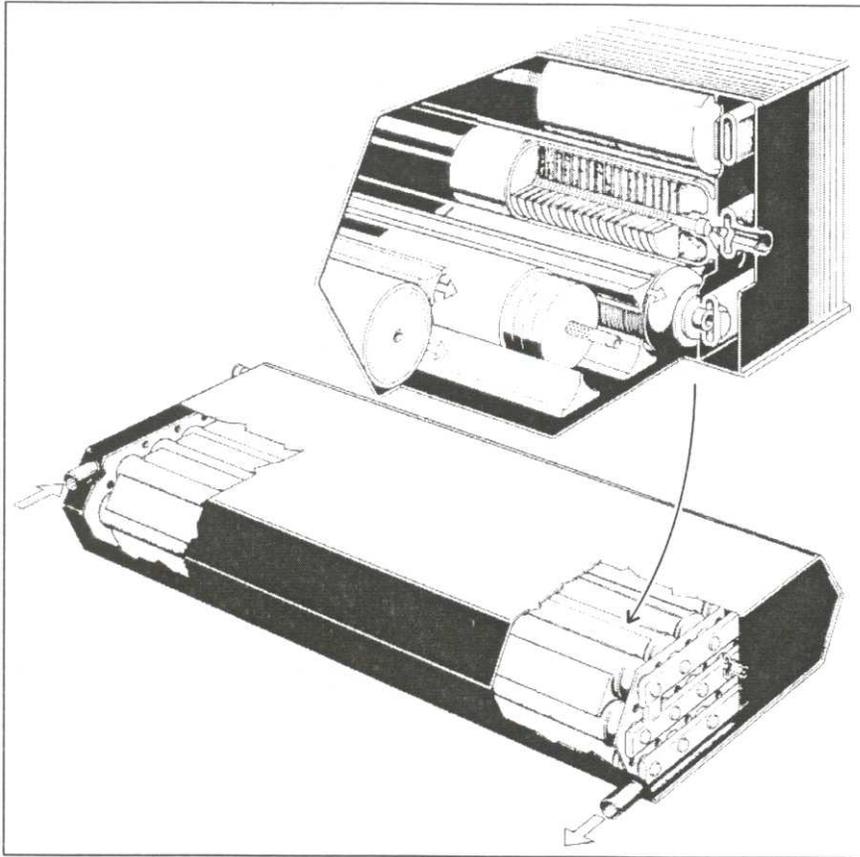


Figure 2-25: Metal Hydride Vehicle Storage Tank, Sectioned

The low desorption temperatures associated with some hydrides can be a problem since the gas releases too readily at ambient conditions. To overcome this, low temperature hydrides need to be pressurized, increasing the complexity of the process. The characteristics of typical metal hydrides are summarized in Table 2-3.

The main disadvantage of metal hydride storage systems is not so much the temperatures and pressures needed to release the hydrogen, but rather their low mass energy density. Even the best metal hydrides contain only 8% hydrogen by weight and therefore tend to be very heavy and expensive. Metal hydride storage systems can be up to 30 times heavier and ten times larger than a gasoline tank with the same energy content.

Another disadvantage of metal hydride storage systems is that they must be charged with only very pure hydrogen or they become contaminated with a corresponding loss of capacity. Oxygen and water are prime culprits as they

chemically adsorb onto the metal surface displacing potential hydrogen bonds. The storage capacity lost through contamination can to some extent be reactivated with heat.

Key Points & Notes

Key Points & Notes

Characteristic	Low Temperature				High Temperature		
	Ti ₂ Ni-H _{2.5}	FeTi-H ₂	VH-VH ₂	LaNi ₅ -H _{6.7}	Mg ₂ Cu-H ₃	Mg ₂ Ni-H ₄	Mg-H
Alloy mass that can absorb hydrogen	1.61%	1.87%	1.92%	1.55%	2.67%	3.71%	8.25%
Hydride mass equivalent to the energy in 0.264 gal (1 L) of gasoline	342 lb 155 kg	295 lb 134 kg	286 lb 130 kg	355 lb 161 kg	No Data	149 lb 67.5 kg	79 lb 35 kg
Alloy mass necessary to accumulate 5.5 lb (2.5 kg) of hydrogen	478 lb 217 kg	414 lb 188 kg	401 lb 182 kg	496 lb 225 kg	No Data	209 lb 95 kg	110 lb 50 kg
Desorption temperature at 145 psig (10 barg)	93 °F 34 °C 307 K	125 °F 52 °C 325 K	127 °F 53 °C 326 K	163 °F 73 °C 346 K	604 °F 318 °C 591 K	662 °F 350 °C 623 K	683 °F 362 °C 635 K
Desorption temperature at 22 psig (1.5 barg)	26 °F -3 °C 270 K	44 °F 7 °C 280 K	59 °F 15 °C 288 K	70 °F 21 °C 294 K	480 °F 245 °C 522 K	512 °F 267 °C 540 K	565 °F 296 °C 569 K
Charging	Easy	No Data	No Data	Very Difficult	No Data	Difficult	Very Difficult
Safety	Safe	No Data	No Data	No Data	Highly Flam- mable	Safe	Highly Flam- mable

Table 2-3 Metal Hydride Characteristics

A further problem associated with metal hydrides relates to their structure. Metal hydrides are typically produced in a granular or powder form so that they have a large surface for gas storage. These particles are susceptible to attrition, which both reduces their effectiveness and may plug relief systems or other piping.

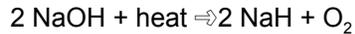
No specific metal hydride has outstanding performance on all accounts (high absorption capacity, high density, low heat requirement and low cost). In some cases, a mixture of low and high temperature hydrides can be used to maintain some of the advantages inherent to each while at the same time introducing some of disadvantages of each.

Alkaline Earth Hydrides

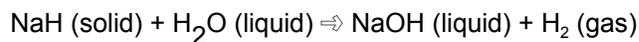
A recent hydride variation that offers some advantages over previous methods involves the use of pelletized sodium, potassium or lithium compounds. These hydride compounds react with water to release hydrogen without the addition of heat.

The most commercially developed process involves the use of sodium hydroxide (NaOH), which is abundantly available as

a waste material from paper, paint, textiles, plastic, petroleum and other industries. Sodium hydroxide is converted to sodium hydride (NaH) by driving off the oxygen through the addition of heat as follows:



The sodium hydride can then be pelletized, using a process similar to that used to pelletize charcoal briquettes, and coated with a waterproof plastic coating or skin. In this form, the sodium is non-volatile and can be transported easily. To release the hydrogen, the pellets are cut as needed while immersed in water to react as follows:



This reaction is fast, and results in a hydrogen pressure of 125 to 150 psig (8.6 to 10.3 barg). The resulting sodium hydroxide can be retrieved and returned to the original process for reuse.

This process shares the advantages with other hydrides of not requiring high pressures or cryogenic temperatures for operation. It has the added advantages of not requiring heat to release the hydrogen, overcomes contamination and structural problems, and can be handled with relative ease.

Like other hydride systems, sodium hydrides are heavy and have a mass energy density that is comparable with high temperature hydride systems as indicated in Table 2-4. Disadvantages of the sodium hydride process include the mechanical complications related to cutting the pellets in a controlled fashion, and the materials reclamation issues that surround the waste sodium hydroxide and used plastic coatings.

Characteristic	NaH
Alloy mass that can absorb hydrogen	4.4%
Hydride mass equivalent to the energy in 0.264 gal (1 L) of gasoline	90 lb 41 kg
Alloy mass necessary to accumulate 5.5 lb (2.5 kg) hydrogen	130 lb 59 kg

Table 2-4 Sodium Hydride Characteristics

This sodium hydride process is interesting as a combination of hydrogen generation and storage in one step. Like electrolysis, the hydrogen in sodium hydride is an energy carrier, not an energy source, since the source sodium hydroxide is at a low energy state and must be “charged” through the addition of heat energy. As before, this process

Key Points & Notes

is only as renewable and environmentally friendly as the source energy. Also like electrolysis, water is consumed during hydrogen release.

Key Points & Notes

2.2.4 Other Storage Methods

A variety of other hydrogen storage methods are currently being researched, and are not currently commercially viable. Among these are carbon adsorption, glass microsphere and iron oxidation techniques.

Carbon Adsorption

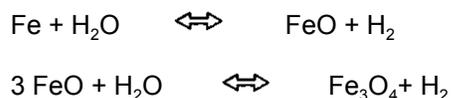
Carbon adsorption is a technique similar to that employed with metal hydrides wherein hydrogen is bound chemically onto the surface of highly porous carbon granules. The carbon is adsorbed at -300 to -120°F (-185 to -85 °C) and 300 to 700 psi (21 to 48 barg). The amount of carbon adsorption increases at lower temperatures. Heat in excess of 300 °F (150 °C) releases the hydrogen.

Glass Microsphere

Glass microsphere storage systems use tiny, hollow glass balls into which hydrogen is forced under very high pressure. Once stored, the balls can be stored at ambient conditions without hydrogen loss. Moderate heat releases the hydrogen again. Experiments are being done to increase the hydrogen release rate by crushing the spheres.

Iron Oxidation

Iron oxidation is a process by which hydrogen is formed when sponge iron (the raw ingredient for steel-making furnaces) is reacted with steam as follows:



The byproduct of this process is rust. Once the iron is fully rusted, it must be exchanged for a new tank and then be converted back to sponge iron using industrial methods. The steam and heat needed for the on-board reaction could potentially be provided by the exhaust of an internal combustion engine or the coolant stream of a fuel cell engine.

Although iron is cheap, it is heavy, so the process is only 4.5% effective by weight. Furthermore, a catalyst (which is expensive) is required to maintain the reaction at practical temperatures of 175 to 390 °F (80 to 200 °C).

2.3 Hydrogen Transportation

Hydrogen transportation issues are directly related to hydrogen storage issues. In general, compact forms of hydrogen storage are more economical to transport and diffuse forms are more costly.

2.3.1 Pipelines

Pipelines can carry hydrogen as gas or as a liquid.

Gas Pipelines

Gaseous hydrogen can be transported by pipeline in a similar fashion as natural gas.

Hydrogen, being less dense than natural gas, results in less mass transport for a given pipeline size and operating pressure. In addition, the energy density of hydrogen is only one-third that of natural gas on a volumetric basis; hence, three times the amount of hydrogen gas must be pumped through a pipeline to transmit an equivalent amount of energy.

To compensate for both of these properties, hydrogen pipelines need to be designed to operate at higher pressure in order to be practical. All pumps and other equipment must be hydrogen compatible. Furthermore, hydrogen pipelines must be resistant to hydrogen embrittlement in order to prevent cracking.

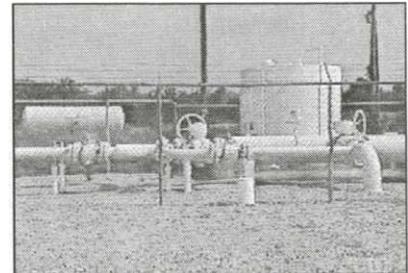
Existing hydrogen gas pipelines operate in some parts of the world. In the US there are 450 miles (725 km) of pipelines, including those in Texas, Indiana, New Jersey and Louisiana. Several hydrogen pipelines exist in Canada. In Europe, pipelines operate within Germany (210 km) and between Belgium and France (400 km), among several others. Compared to pipelines of other gases, these lengths are very short, however, they indicate that the high cost of transporting hydrogen by gas pipeline is already worth it in some areas.

Liquid Hydrogen Pipelines

Hydrogen can be transported in a pipeline as a liquid, but liquid hydrogen pipelines have been accomplished over very short distances only. These pipelines require thorough insulation in order to maintain cryogenic temperatures and prevent the formation of a two-phase (liquid/gas) flow. If exposed to air, the low pipeline temperature would cause air to liquefy and oxygen to concentrate on the surface of the pipe, increasing the fire hazard.

Key Points & Notes

There are 285,000 miles of natural gas pipelines throughout the continental US with a daily movement of over 50 billion standard cubic feet (scf) and a capacity of approximately 90 billion scf/day.



Hydrogen Pipeline

2.3.2 Mobile Transport

Mobile transport includes transport by truck, rail or barge. The hydrogen is stored in tanks appropriate to hydrogen storage method and transport medium.

Gas Transport

Hydrogen as a high-pressure gas can be transported in cylinders at pressures ranging from 2200 to 5800 psig (150 to 400 barg).

For trucks, specially designed tube trailers carry a number of large, high-strength steel tubes linked together through a common manifold. This design works well in providing small quantities of hydrogen, but is very inefficient in terms of transport energy. The weight of cylinders required is such that the gas is only 2 to 4% of the cargo weight.

Key Points & Notes



This tube trailer holds 104,000 sft³ (2,945 m³) of hydrogen at 3,160 psig (218 barg). The two additional tubes on the ground next to the tube trailer hold an additional 12,500 sft³ (354 m³) of hydrogen at 4,000 psig (275 barg).

Figure 2-26: Tube Trailer

Liquid Transport

Hydrogen can be transported by truck, rail or barge as a cryogenic liquid in double-walled, super-insulated vacuum-lined tanks. Transporting liquid hydrogen is far more efficient than as a high-pressure gas, particularly where larger quantities are needed. On the downside, maintenance costs are much higher for liquid transportation.

As a point of reference, 150 lb (70 kg) of liquid hydrogen occupies a volume of 35.3 ft³ (1000 L) and requires a transport container weighing between 440 and 660 lb (200 to 300 kg). The same weight of hydrogen, transported as a gas or

hydride would require between two and five tons of containers. The liquid option is obviously much more efficient.

Key Points & Notes

Liquid hydrogen transport trailers include standard 40-foot and 80-foot truck trailers. The largest containers used in transport reach 7,000,000 ft³ (200,000 m³).

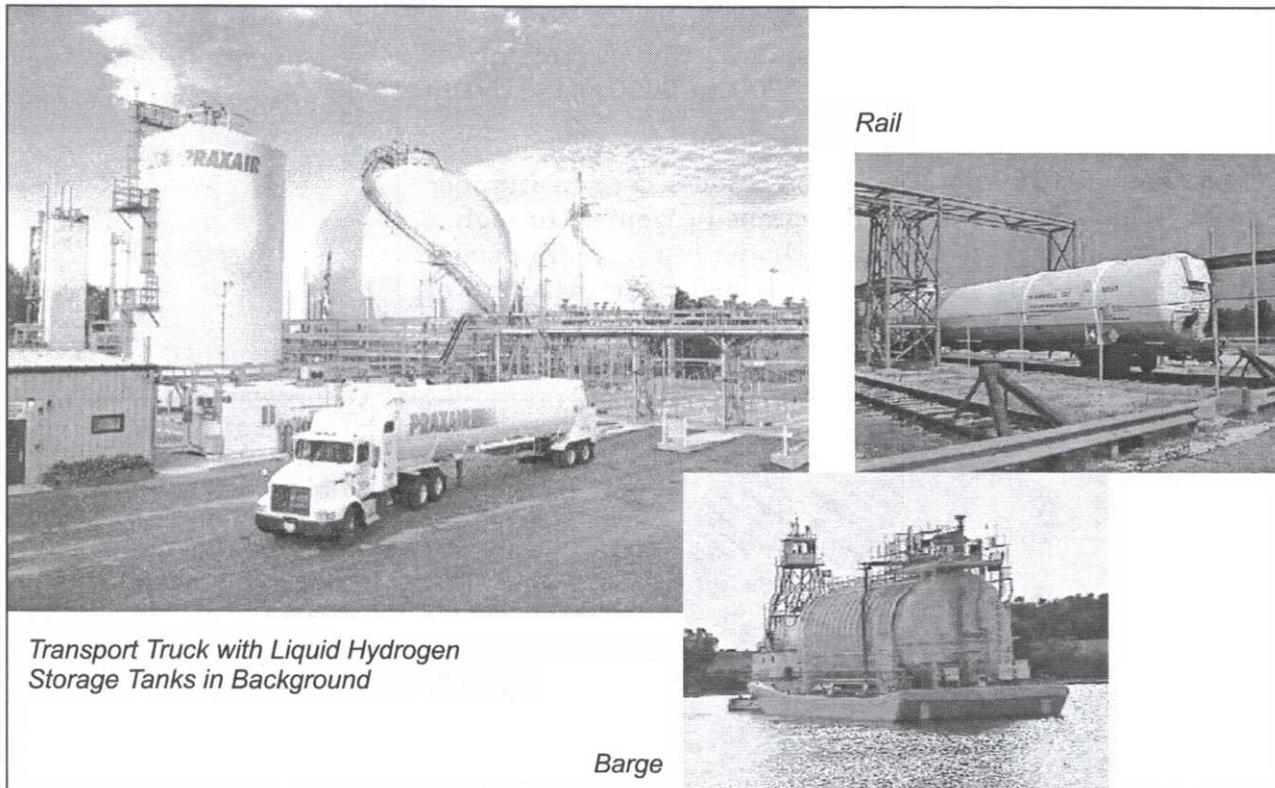


Figure 2-27: Liquid Hydrogen Transport

2.3.3 Site Manufacture

Site manufacture of hydrogen sidesteps the issue of transporting it. The energy for the manufacture of hydrogen is moved to the site, rather than the hydrogen itself. The energy might be in the form of electrical power to an electrolysis system, or a fossil fuel piped or trucked to a reformer.

By manufacturing hydrogen at or near the location where it is required, the high cost and energy inefficiency of transport is avoided, and advantage is taken of the high transport efficiency of other forms of energy.

MODULE 3:

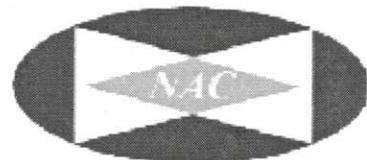
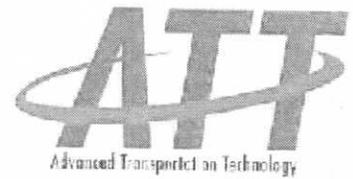
Hydrogen Use In Internal Combustion Engines

College of the Desert

Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

3.1	HYDROGEN ENGINES	3-1
3.2	COMBUSTIVE PROPERTIES OF HYDROGEN	3-3
3.3	AIR/FUEL RATIO	3-6
3.4	PRE-IGNITION PROBLEMS AND SOLUTIONS	3-9
3.4.1	FUEL DELIVERY SYSTEMS	3-9
3.4.2	THERMAL DILUTION	3-12
3.4.3	ENGINE DESIGN	3-12
3.5	IGNITION SYSTEMS	3-14
3.6	CRANKCASE VENTILATION	3-15
3.7	THERMAL EFFICIENCY	3-16
3.8	EMISSIONS	3-17
3.9	POWER OUTPUT	3-19
3.10	HYDROGEN GAS MIXTURES	3-20
3.11	CURRENT STATUS	3-23

OBJECTIVES

At the completion of this module, the technician will understand:

- the combustive properties of hydrogen that relate to its use as a combustive fuel
- the air/fuel ratio of hydrogen fuel mixtures and how it compares to other fuels
- the types of pre-ignition problems encountered in a hydrogen internal combustion engine and their solutions
- the type of ignition systems that may be used with hydrogen internal combustion engines
- crankcase ventilation issues that pertain to hydrogen use in an internal combustion engine
- the thermal efficiency of hydrogen internal combustion engines
- the type of emissions associated with hydrogen internal combustion engines
- the power output of hydrogen internal combustion engines
- the effect of mixing hydrogen with other hydrocarbon fuels

3.1 Hydrogen Engines

The small number of vehicles using hydrogen internal combustion engines (HICE) makes it difficult to explain how to repair them. Therefore, this section does not serve as a repair manual, but as an outline describing the operation of a hydrogen engine and its major components, its benefits, drawbacks and how components can be modified or re-designed to reduce the drawbacks.

In general, getting an internal combustion engine to run on hydrogen is not difficult. Getting an internal combustion engine to run well, however, is more of a challenge. This section points out the key components and techniques required to make the difference between a hydrogen engine that just runs and one that runs well.

The earliest attempt at developing a hydrogen engine was reported by Reverend W. Cecil in 1820. Cecil presented his work before the Cambridge Philosophical Society in a paper entitled "On the Application of Hydrogen Gas to Produce Moving Power in Machinery." The engine itself operated on the vacuum principle, in which atmospheric pressure drives a piston back against a vacuum to produce power. The vacuum is created by burning a hydrogen-air mixture, allowing it to expand and then cool. Although the engine ran satisfactorily, vacuum engines never became practical.

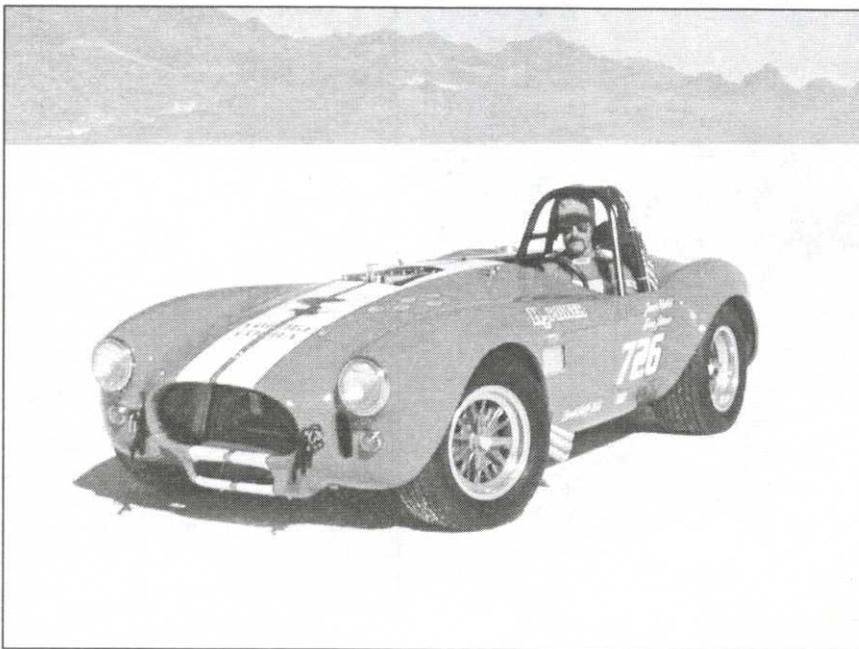


Figure 3-1 Hydrogen-Powered 1965 Cobra Replica

Hydrogen Fuel Cell Engines

MODULE 3: HYDROGEN USE IN INTERNAL COMBUSTION ENGINE

Sixty years later, during his work with combustion engines in the 1860s and 1870s, N. A. Otto (the inventor of the Otto cycle) reportedly used a synthetic producer gas for fuel, which probably had a hydrogen content of over 50%. Otto also experimented with gasoline, but found it dangerous to work with, prompting him to return to using gaseous fuels. The development of the carburetor, however, initiated a new era in which gasoline could be used both practically and safely, and interest in other fuels subsided.

Key Points & Notes

Hydrogen has since been used extensively in the space program since it has the best energy-to-weight ratio of any fuel. Liquid hydrogen is the fuel of choice for rocket engines, and has been utilized in the upper stages of launch vehicles on many space missions including the Apollo missions to the moon, Skylab, the Viking missions to Mars and the Voyager mission to Saturn.

In recent years, the concern for cleaner air, along with stricter air pollution regulation and the desire to reduce the dependency on fossil fuels have rekindled the interest in hydrogen as a vehicular fuel.



Figure 3-2 Hydrogen-Powered Pickup

3.2 Combustive Properties of Hydrogen

Key Points & Notes

The properties of hydrogen are detailed in Section 1. The properties that contribute to its use as a combustible fuel are its:

- wide range of flammability
- low ignition energy
- small quenching distance
- high autoignition temperature
- high flame speed at stoichiometric ratios
- high diffusivity
- very low density

Wide Range of Flammability

Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion engine over a wide range of fuel-air mixtures. A significant advantage of this is that hydrogen can run on a lean mixture. A lean mixture is one in which the amount of fuel is less than the theoretical, stoichiometric or chemically ideal amount needed for combustion with a given amount of air. This is why it is fairly easy to get an engine to start on hydrogen.

Generally, fuel economy is greater and the combustion reaction is more complete when a vehicle is run on a lean mixture. Additionally, the final combustion temperature is generally lower, reducing the amount of pollutants, such as nitrogen oxides, emitted in the exhaust. There is a limit to how lean the engine can be run, as lean operation can significantly reduce the power output due to a reduction in the volumetric heating value of the air/fuel mixture.

Low Ignition Energy

Hydrogen has very low ignition energy. The amount of energy needed to ignite hydrogen is about one order of magnitude less than that required for gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition.

Unfortunately, the low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of ignition, creating problems of premature ignition and flashback. Preventing this is one of the challenges associated with running an engine on hydrogen. The wide flammability range of

hydrogen means that almost any mixture can be ignited by a hot spot.

Small Quenching Distance

Hydrogen has a small quenching distance, smaller than gasoline. Consequently, hydrogen flames travel closer to the cylinder wall than other fuels before they extinguish. Thus, it is more difficult to quench a hydrogen flame than a gasoline flame. The smaller quenching distance can also increase the tendency for backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame.

High Autoignition Temperature

Hydrogen has a relatively high autoignition temperature. This has important implications when a hydrogen-air mixture is compressed. In fact, the autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio. The temperature rise is shown by the equation:

$$T_2 = T_1 \left(\frac{V_1}{V_2} \right)^{\gamma-1}$$

where:

V_1/V_2	= the compression ratio
T_1	= absolute initial temperature
T_2	= absolute final temperature
γ	= ratio of specific heats

The temperature may not exceed hydrogen's autoignition temperature without causing premature ignition. Thus, the absolute final temperature limits the compression ratio. The high autoignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine.

This higher compression ratio is important because it is related to the thermal efficiency of the system as presented in Section 3.7. On the other hand, hydrogen is difficult to ignite in a compression ignition or diesel configuration, because the temperatures needed for those types of ignition are relatively high.

High Flame Speed

Hydrogen has high flame speed at stoichiometric ratios. Under these conditions, the hydrogen flame speed is nearly an

order of magnitude higher (faster) than that of gasoline. This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle. At leaner mixtures, however, the flame velocity decreases significantly.

Key Points & Notes

High Diffusivity

Hydrogen has very high diffusivity. This ability to disperse in air is considerably greater than gasoline and is advantageous for two main reasons. Firstly, it facilitates the formation of a uniform mixture of fuel and air. Secondly, if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized.

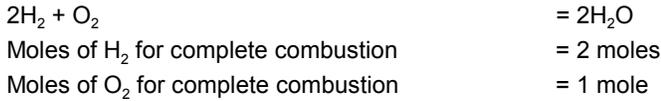
Low Density

Hydrogen has very low density. This results in two problems when used in an internal combustion engine. Firstly, a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range. Secondly, the energy density of a hydrogen-air mixture, and hence the power output, is reduced.

3.3 Air/Fuel Ratio

Key Points & Notes

The theoretical or stoichiometric combustion of hydrogen and oxygen is given as:



Because air is used as the oxidizer instead oxygen, the nitrogen in the air needs to be included in the calculation:

$$\begin{aligned} \text{Moles of N}_2 \text{ in air} &= \text{Moles of O}_2 \times (79\% \text{ N}_2 \text{ in air} / 21\% \text{ O}_2 \text{ in air}) \\ &= 1 \text{ mole of O}_2 \times (79\% \text{ N}_2 \text{ in air} / 21\% \text{ O}_2 \text{ in air}) \\ &= 3.762 \text{ moles N}_2 \\ \text{Number of moles of air} &= \text{Moles of O}_2 + \text{moles of N}_2 \\ &= 1 + 3.762 \\ &= 4.762 \text{ moles of air} \\ \text{Weight of O}_2 &= 1 \text{ mole of O}_2 \times 32 \text{ g/mole} \\ &= 32 \text{ g} \\ \text{Weight of N}_2 &= 3.762 \text{ moles of N}_2 \times 28 \text{ g/mole} \\ &= 105.33 \text{ g} \\ \text{Weight of air} &= \text{weight of O}_2 + \text{weight of N} && (1) \\ &= 32\text{g} + 105.33 \text{ g} \\ &= 137.33 \text{ g} \\ \text{Weight of H}_2 &= 2 \text{ moles of H}_2 \times 2 \text{ g/mole} \\ &= 4 \text{ g} \end{aligned}$$

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

$$\begin{aligned} \text{A/F based on mass:} &= \text{mass of air/mass of fuel} \\ &= 137.33 \text{ g} / 4 \text{ g} \\ &= 34.33:1 \\ \text{A/F based on volume:} &= \text{volume(moles) of air/volume (moles) of fuel} \\ &= 4.762 / 2 \\ &= 2.4:1 \end{aligned}$$

The percent of the combustion chamber occupied by hydrogen for a stoichiometric mixture:

$$\begin{aligned} \% \text{ H}_2 &= \text{volume (moles) of H}_2 / \text{total volume} && (2) \\ &= \text{volume H}_2 / (\text{Volume air} + \text{volume of H}_2) \\ &= 2 / (4.762 + 2) \end{aligned}$$

**Hydrogen Fuel
Cell Engines**
**MODULE 3: HYDROGEN USE IN INTERNAL
COMBUSTION ENGINES**

=29.6%

Key Points & Notes

As these calculations show, the stoichiometric or chemically correct A/F ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This means that for complete combustion, 34 pounds of air are required for every pound of hydrogen. This is much higher than the 14.7:1 A/F ratio required for gasoline.

Since hydrogen is a gaseous fuel at ambient conditions it displaces more of the combustion chamber than a liquid fuel. Consequently less of the combustion chamber can be occupied by air. At stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline. Figure 3-3 compares combustion chamber volumes and energy content for gasoline and hydrogen fueled engines.

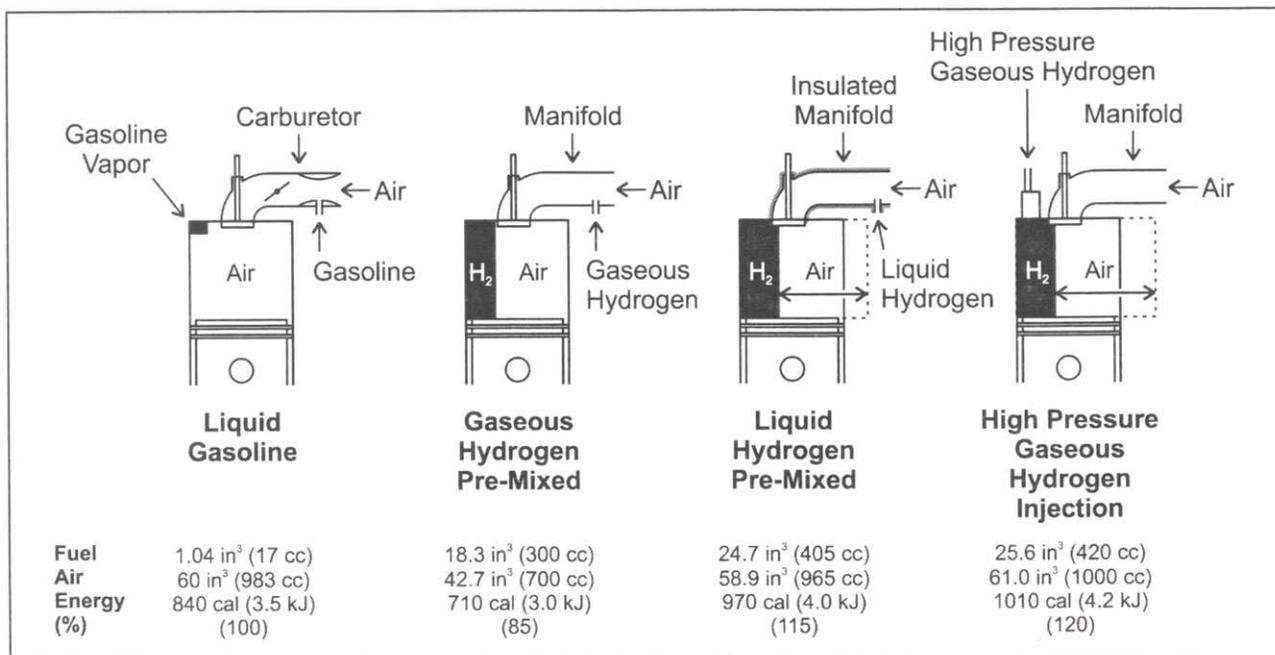


Figure 3-3 Combustion Chamber Volumetric and Energy Comparison for Gasoline and Hydrogen Fueled Engines

Depending the method used to meter the hydrogen to the engine, the power output compared to a gasoline engine can be anywhere from 85% (intake manifold injection) to 120% (high pressure injection).

Because of hydrogen's wide range of flammability, hydrogen engines can run on A/F ratios of anywhere from 34:1 (stoichiometric) to 180:1. The A/F ratio can also be expressed in terms of equivalence ratio, denoted by phi (Φ). Phi is equal to the stoichiometric A/F ratio divided by the actual A/F ratio. For a stoichiometric mixture, the actual A/F ratio

is equal to the stoichiometric A/F ratio and thus the phi equals unity (one). For lean A/F ratios, phi will be a value less than one. For example, a phi of 0.5 means that there is only enough fuel available in the mixture to oxidize with half of the air available. Another way of saying this is that there is twice as much air available for combustion than is theoretically required.

Key Points & Notes

3.4 Pre-Ignition Problems and Solutions

Key Points & Notes

The primary problem that has been encountered in the development of operational hydrogen engines is premature ignition. Premature ignition is a much greater problem in hydrogen fueled engines than in other IC engines, because of hydrogen's lower ignition energy, wider flammability range and shorter quenching distance.

Premature ignition occurs when the fuel mixture in the combustion chamber becomes ignited before ignition by the spark plug, and results in an inefficient, rough running engine. Backfire conditions can also develop if the premature ignition occurs near the fuel intake valve and the resultant flame travels back into the induction system.

A number of studies have been aimed at determining the cause of pre-ignition in hydrogen engines. Some of the results suggest that pre-ignition are caused by hot spots in the combustion chamber, such as on a spark plug or exhaust valve, or on carbon deposits. Other research has shown that backfire can occur when there is overlap between the opening of the intake and exhaust valves.

It is also believed that the pyrolysis (chemical decomposition brought about by heat) of oil suspended in the combustion chamber or in the crevices just above the top piston ring can contribute to pre-ignition. This pyrolysed oil can enter the combustion chamber through blow-by from the crankcase (i.e. past the piston rings), through seepage past the valve guide seals and/or from the positive crankcase ventilation system (i.e. through the intake manifold).

3.4.1 Fuel Delivery Systems

Adapting or re-designing the fuel delivery system can be effective in reducing or eliminating pre-ignition.

Hydrogen fuel delivery system can be broken down into three main types: central injection (or "carbureted"), port injection and direct injection.

Central and port fuel delivery systems injection form the fuel-air mixture during the intake stroke. In the case of central injection or a carburetor, the injection is at the inlet of the air intake manifold. In the case of port injection, it is injected at the inlet port.

Direct cylinder injection is more technologically sophisticated and involves forming the fuel-air mixture inside the combustion cylinder after the air intake valve has closed.

Central Injection or Carbureted Systems

Key Points & Notes

The simplest method of delivering fuel to a hydrogen engine is by way of a carburetor or central injection system. This system has advantages for a hydrogen engine. Firstly, central injection does not require the hydrogen supply pressure to be as high as for other methods. Secondly, central injection or carburetors are used on gasoline engines, making it easy to convert a standard gasoline engine to a hydrogen or a gasoline/hydrogen engine.

The disadvantage of central injection is that it is more susceptible to irregular combustion due to pre-ignition and backfire. The greater amount of hydrogen/air mixture within the intake manifold compounds the effects of pre-ignition.

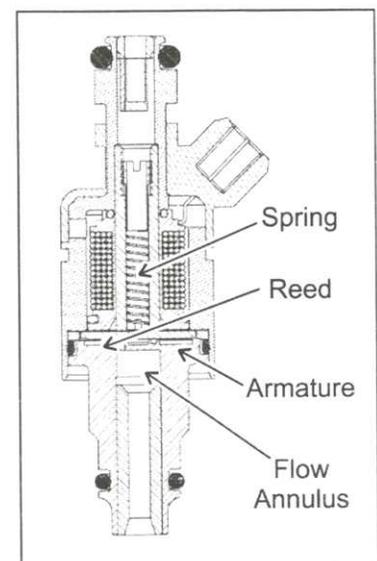
Port Injection Systems

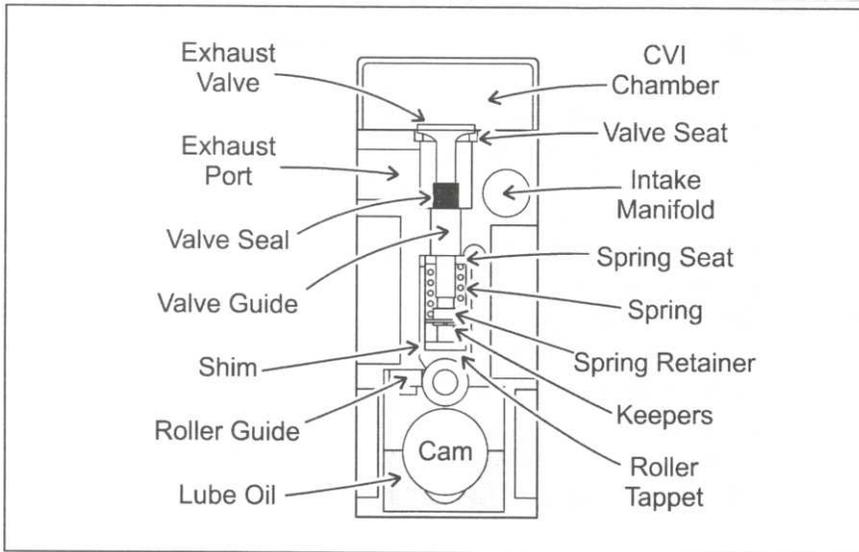
The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. At this point conditions are much less severe and the probability for premature ignition is reduced.

In port injection, the air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. Since less gas (hydrogen or air) is in the manifold at any one time, any pre-ignition is less severe. The inlet supply pressure for port injection tends to be higher than for carbureted or central injection systems, but less than for direct injection systems.

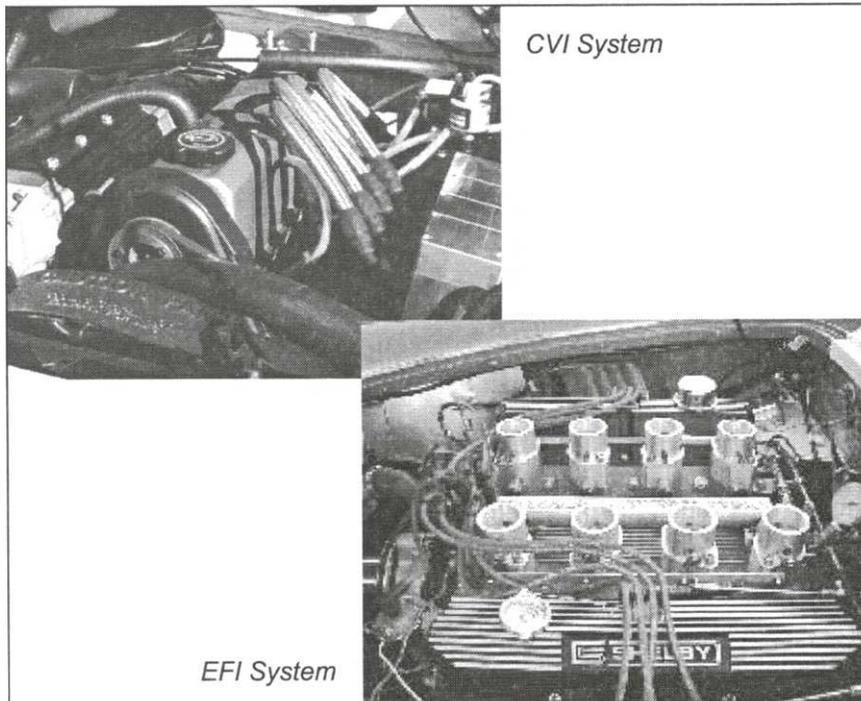
The constant volume injection (CVI) system uses a mechanical cam-operated device to time the injection of the hydrogen to each cylinder. The CVI block is shown on the far right of the photo with four fuel lines exiting on left side of the block (one fuel line for each cylinder)

The electronic fuel injection (EFI) system meters the hydrogen to each cylinder. This system uses individual electronic fuel injectors (solenoid valves) for each cylinder and are plumbed to a common fuel rail located down the center of the intake manifold. Whereas the CVI system uses constant injection timing and variable fuel rail pressure, the EFI system uses variable injection timing and constant fuel rail pressure.

*Electronic Fuel Injector*

**Figure 3-4** Constant Volume Injector

Examples of port injection type systems are shown in Figure 3-5.

**Figure 3-5** CVI and EFI Port Injection Systems

Key Points & Notes

Direct Injection Systems

More sophisticated hydrogen engines use direct injection into the combustion cylinder during the compression stroke. In direct injection, the intake valve is closed when the fuel is injected, completely avoiding premature ignition during the

intake stroke. Consequently the engine cannot backfire into the intake manifold.

The power output of a direct injected hydrogen engine is 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor.

While direct injection solves the problem of pre-ignition in the intake manifold, it does not necessarily prevent pre-ignition within the combustion chamber. In addition, due to the reduced mixing time of the air and fuel in a direct injection engine, the air/fuel mixture can be non-homogenous. Studies have suggested this can lead to higher NO_x emissions than the non-direct injection systems. Direct injection systems require a higher fuel rail pressure than the other methods.

3.4.2 Thermal Dilution

Pre-ignition conditions can be curbed using thermal dilution techniques such as exhaust gas recirculation (EGR) or water injection.

As the name implies, an EGR system recirculates a portion of the exhaust gases back into the intake manifold. The introduction of exhaust gases helps to reduce the temperature of hot spots, reducing the possibility of pre-ignition. Additionally, recirculating exhaust gases reduce the peak combustion temperature, which reduces NO_x emissions. Typically a 25 to 30% recirculation of exhaust gas is effective in eliminating backfire.

On the other hand, the power output of the engine is reduced when using EGR. The presence of exhaust gases reduces the amount of fuel mixture that can be drawn into the combustion chamber.

Another technique for thermally diluting the fuel mixture is the injection of water. Injecting water into the hydrogen stream prior to mixing with air has produced better results than injecting it into the hydrogen-air mixture within the intake manifold. A potential problem with this type of system is that water can get mixed with the oil, so care must be taken to ensure that seals do not leak.

3.4.3 Engine Design

The most effective means of controlling pre-ignition and knock is to re-design the engine for hydrogen use, specifically the combustion chamber and the cooling system.

Key Points & Notes

A disk-shaped combustion chamber (with a flat piston and chamber ceiling) can be used to reduce turbulence within the chamber. The disk shape helps produce low radial and tangential velocity components and does not amplify inlet swirl during compression.

Since unburned hydrocarbons are not a concern in hydrogen engines, a large bore-to-stroke ratio can be used with this engine. To accommodate the wider range of flame speeds that occur over a greater range of equivalence ratios, two spark plugs are needed. The cooling system must be designed to provide uniform flow to all locations that need cooling.

Additional measures to decrease the probability of pre-ignition are the use of two small exhaust valves as opposed to a single large one, and the development of an effective scavenging system, that is, a means of displacing exhaust gas from the combustion chamber with fresh air.

Key Points & Notes

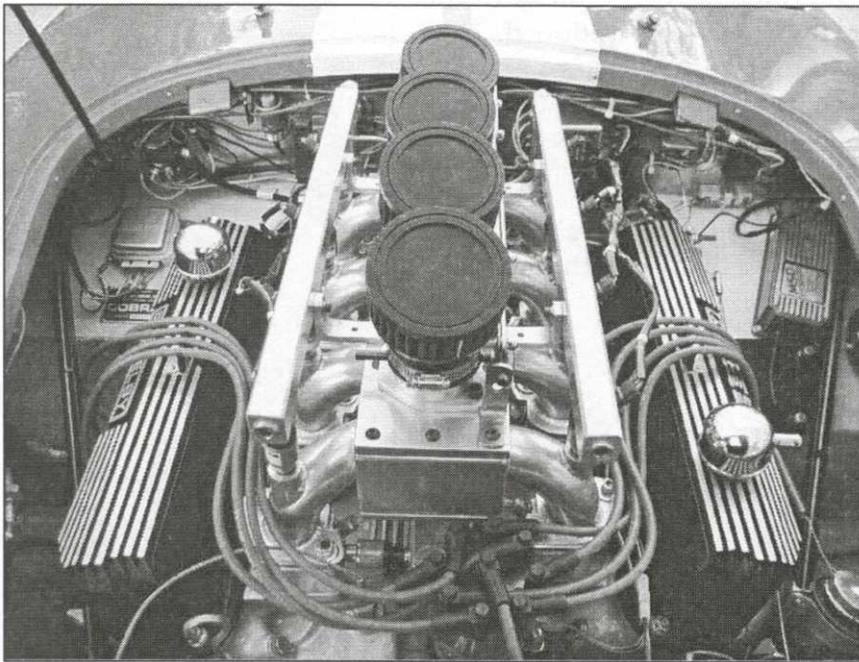


Figure 3-6 Hydrogen Internal Combustion Engine

3.5 Ignition Systems

Key Points & Notes

Due to hydrogen's low ignition energy limit, igniting hydrogen is easy and gasoline ignition systems can be used. At very lean air/fuel ratios (130:1 to 180:1) the flame velocity is reduced considerably and the use of a dual spark plug system is preferred.

Ignition systems that use a waste spark system should not be used for hydrogen engines. These systems energize the spark each time the piston is at top dead center whether or not the piston is on the compression stroke or on its exhaust stroke. For gasoline engines, waste spark systems work well and are less expensive than other systems. For hydrogen engines, the waste sparks are a source of pre-ignition.

Spark plugs for a hydrogen engine should have a cold rating and have non-platinum tips. A cold-rated plug is one that transfers heat from the plug tip to the cylinder head quicker than a hot-rated spark plug. This means the chances of the spark plug tip igniting the air/fuel charge is reduced. Hot-rated spark plugs are designed to maintain a certain amount of heat so that carbon deposits do not accumulate. Since hydrogen does not contain carbon, hot-rated spark plugs do not serve a useful function.

Platinum-tip spark plugs should also be avoided since platinum is a catalyst, causing hydrogen to oxidize with air.

3.6 Crankcase Ventilation

Key Points & Notes

Crankcase ventilation is even more important for hydrogen engines than for gasoline engines.

As with gasoline engines, unburnt fuel can seep by the piston rings and enter the crankcase. Since hydrogen has a lower energy ignition limit than gasoline, any unburnt hydrogen entering the crankcase has a greater chance of igniting. Hydrogen should be prevented from accumulating through ventilation.

Ignition within the crankcase can be just a startling noise or result in engine fire. When hydrogen ignites within the crankcase, a sudden pressure rise occurs. To relieve this pressure, a pressure relief valve must be installed on the valve cover. A typical pressure relief valve installation is shown in Figure 3-7.

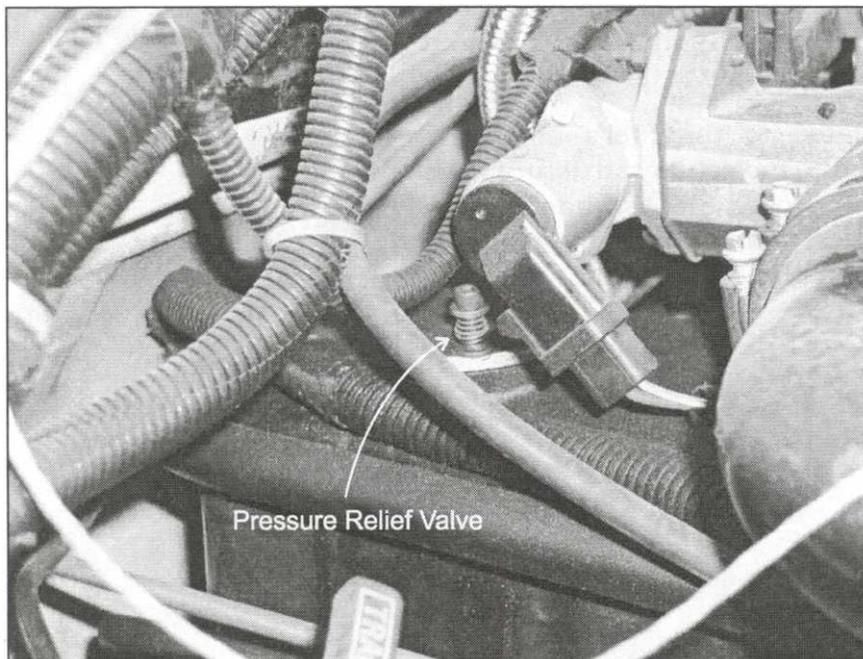


Figure 3-7 Pressure Relief Valve on Engine Crankcase

Exhaust gases can also seep by the piston rings into the crankcase. Since hydrogen exhaust is water vapor, water can condense in the crankcase when proper ventilation is not provided. The mixing of water into the crankcase oil reduces its lubrication ability, resulting in a higher degree of engine wear.

3.7 Thermal Efficiency

Key Points & Notes

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the specific-heat ratio of the fuel as shown in the equation:

$$\eta_{th} = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}}$$

where:

V_1/V_2 = the compression ratio

γ = ratio of specific heats

η_{th} = theoretical thermodynamic efficiency

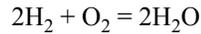
The higher the compression ratio and/or the specific-heat ratio, the higher the indicated thermodynamic efficiency of the engine. The compression ratio limit of an engine is based on the fuel's resistance to knock. A lean hydrogen mixture is less susceptible to knock than conventional gasoline and therefore can tolerate higher compression ratios.

The specific-heat ratio is related to the fuel's molecular structure. The less complex the molecular structure, the higher the specific-heat ratio. Hydrogen ($\gamma = 1.4$) has a much simpler molecular structure than gasoline and therefore its specific-heat ratio is higher than that of conventional gasoline ($\gamma = 1.1$).

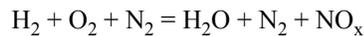
3.8 Emissions

Key Points & Notes

The combustion of hydrogen with oxygen produces water as its only product:



The combustion of hydrogen with air however can also produce oxides of nitrogen (NO_x):



The oxides of nitrogen are created due to the high temperatures generated within the combustion chamber during combustion. This high temperature causes some of the nitrogen in the air to combine with the oxygen in the air. The amount of NO_x formed depends on:

- the air/fuel ratio
- the engine compression ratio
- the engine speed
- the ignition timing
- whether thermal dilution is utilized

In addition to oxides of nitrogen, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to seeped oil burning in the combustion chamber.

Depending on the condition of the engine (burning of oil) and the operating strategy used (a rich versus lean air/fuel ratio), a hydrogen engine can produce from almost zero emissions (as low as a few ppm) to high NO_x and significant carbon monoxide emissions.

Figure 3-8 illustrates a typically NO_x curve relative to phi for a hydrogen engine. A similar graph including other emissions is shown in Figure 3-9 for gasoline.

Hydrogen Fuel Cell Engines

MODULE 3: HYDROGEN USE IN INTERNAL COMBUSTION ENGINE

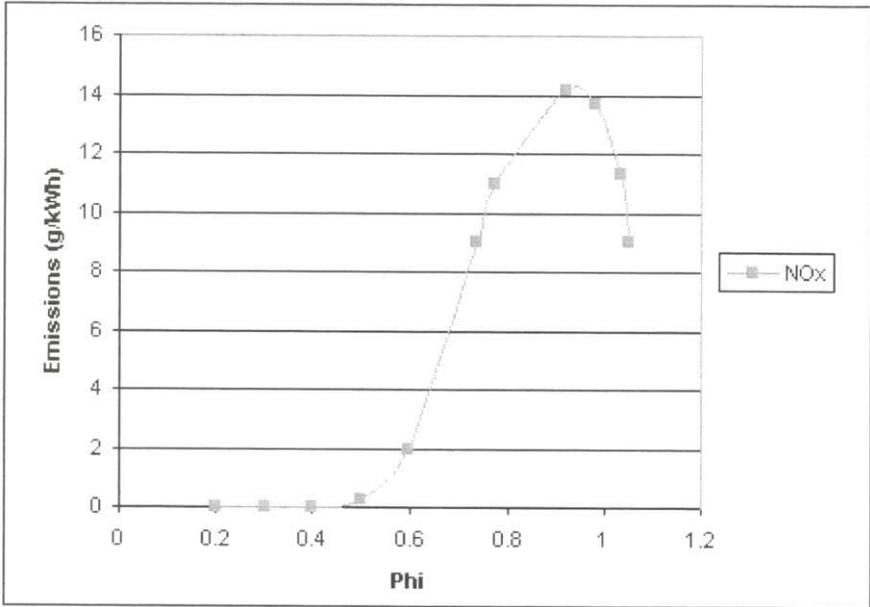


Figure 3-8 Emissions For A Hydrogen Engine

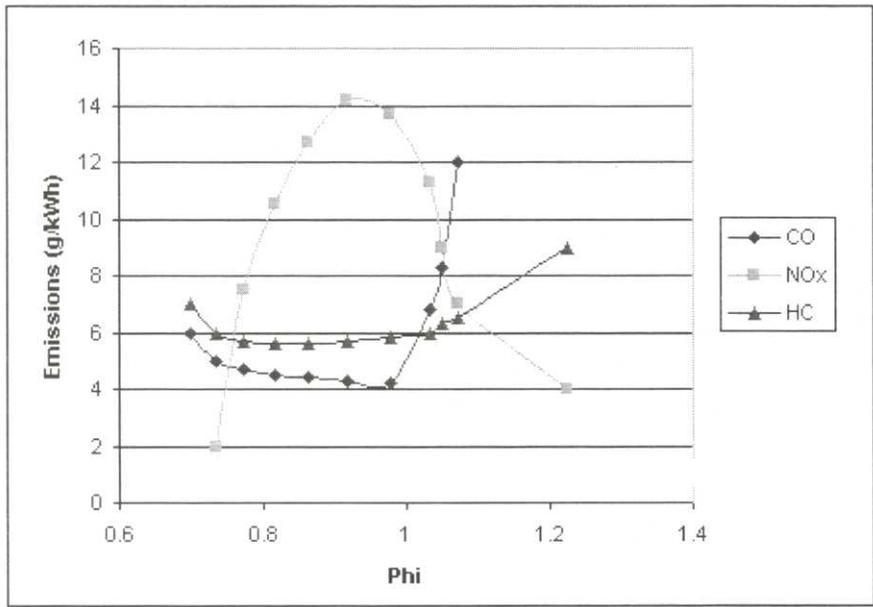


Figure 3-9 Emissions For A Gasoline Engine

Key Points & Notes

As Figure 3-9 shows, the NOx for a gasoline engine is reduced as phi decreases (similar to a hydrogen engine). However, in a gasoline engine the reduction in NOx is compromised by an increase in carbon monoxide and hydrocarbons.

3.9 Power Output

Key Points & Notes

The theoretical maximum power output from a hydrogen engine depends on the air/fuel ratio and fuel injection method used.

As mentioned in Section 3.3, the stoichiometric air/fuel ratio for hydrogen is 34:1. At this air/fuel ratio, hydrogen will displace 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline (since gasoline is a liquid, it only occupies a very small volume of the combustion chamber, and thus allows more air to enter).

Since both the carbureted and port injection methods mix the fuel and air prior to it entering the combustion chamber, these systems limit the maximum theoretical power obtainable to approximately 85% of that of gasoline engines. For direct injection systems, which mix the fuel with the air after the intake valve has closed (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines.

Therefore, depending on how the fuel is metered, the maximum output for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a stoichiometric air/fuel ratio is used. However, at a stoichiometric air/fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NO_x), which is a criteria pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio.

Typically hydrogen engines are designed to use about twice as much air as theoretically required for complete combustion. At this air/fuel ratio, the formation of NO_x is reduced to near zero. Unfortunately, this also reduces the power output to about half that of a similarly sized gasoline engine. To make up for the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.

3.10 Hydrogen Gas Mixtures

Hydrogen can be used advantageously in internal combustion engines as an additive to a hydrocarbon fuel

Hydrogen is most commonly mixed with high pressure natural gas for this purpose since both gases can be stored in the same tank. If hydrogen is blended with other fuels, it usually has to be stored separately and mixed in the gaseous state immediately before ignition. In general, it is impractical to use hydrogen in conjunction with other fuels that also require bulky storage systems, such as propane.

Gaseous hydrogen cannot be stored in the same vessel as a liquid fuel. Hydrogen's low density will cause it to remain on top of the liquid and not mix. Furthermore, liquid fuels are stored at relatively low pressures so that very little hydrogen could be added to the vessel.

Liquid hydrogen cannot be stored in the same vessel as other fuels. Hydrogen's low boiling point will freeze other fuels resulting in fuel "ice"!

Hydrogen can be used in conjunction with compact liquid fuels such as gasoline, alcohol or diesel provided each are stored separately. In these applications, the fuel tanks can be formed to fit into unused spaces on the vehicle. Existing vehicles of this type tend to operate using one fuel or the other but not both at the same time. One advantage of this strategy is that the vehicle can continue to operate if hydrogen is unavailable.

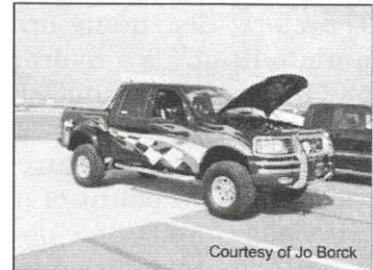
Hydrogen cannot be used directly in a diesel (or "compression ignition") engine since hydrogen's autoignition temperature is too high (this is also true of natural gas). Thus, diesel engines must be outfitted with spark plugs or use a small amount of diesel fuel to ignite the gas (known as pilot ignition). Although pilot ignition techniques have been developed for use with natural gas, no one is currently doing this with hydrogen.

One commercially available gas mixture known as Hythane contains 20% hydrogen and 80% natural gas. At this ratio, no modifications are required to a natural gas engine, and studies have shown that emissions are reduced by more than 20%. Mixtures of more than 20% hydrogen with natural gas can reduce emissions further but some engine modifications are required.

Key Points & Notes



*NGR Tech Natural Gas /
Hydrogen Ford Pickup*



Ford Alcohol-Fueled Pickup

Lean operation of any internal combustion engine is advantageous in terms of oxides of nitrogen emissions and fuel economy.

Key Points & Notes



Figure 3-10 Hythane Powered Bus

For hydrocarbon engines, lean operation also leads to lower emissions of carbon monoxide and unburned hydrocarbons. As more oxygen is available than required to combust the fuel, the excess oxygen oxidizes more carbon monoxide into carbon dioxide, a less harmful emission. The excess oxygen also helps to complete the combustion, decreasing the amount of unburned hydrocarbons.

As with hydrogen, the drawback of lean operation with hydrocarbon fuels is a reduced power output. Lean operation of hydrocarbon engines has additional drawbacks. Lean mixtures are hard to ignite, despite the mixture being above the LFL of the fuel. This results in misfire, which increases unburned hydrocarbon emissions, reduces performance and wastes fuel. Another disadvantage is the reduced conversion efficiency of 3-way catalytic converters, resulting in more harmful emissions.

To some extent, mixing hydrogen with other hydrocarbon fuels reduces all of these drawbacks. Hydrogen's low ignition energy limit and high burning speed makes the hydrogen/hydrocarbon mixture easier to ignite, reducing misfire and thereby improving emissions, performance and fuel economy. Regarding power output, hydrogen augments the mixture's energy density at lean mixtures by increasing the hydrogen-to-carbon ratio, and thereby improves torque at wide-open throttle conditions.

However, the difficulty associated with storing adequate amounts of hydrogen can reduce vehicle range.

Key Points & Notes

3.11 Current Status

Key Points & Notes

A few auto manufacturers have been doing some work in the development of hydrogen-powered vehicles (Ford has recently announced that they have developed a “production ready” hydrogen-powered vehicle using an ICE and BMW has completed a world tour displaying a dozen or so hydrogen-powered 750i vehicles). However, it is not likely that any hydrogen-powered vehicles will be available to the public until there is an adequate refueling infrastructure and trained technicians to repair and maintain these vehicles.



Figure 3-11 BMW's Hydrogen-Powered Internal Combustion Vehicle

Like current gasoline-powered vehicles, the design of each hydrogen-powered vehicle will most likely vary from manufacturer to manufacturer and model to model. One model may be simple in design and operation, for example, a lean-burning fuel metering strategy using no emission control systems such as EGR, catalytic converter, evaporate fuel canister, etc. Another model may be very sophisticated in design and operation, for example, using an EGR fuel metering strategy with a catalytic converter, multiple spark plugs, etc.

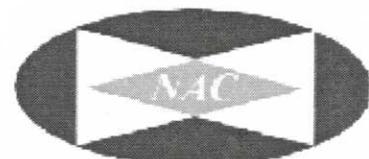
Until such time that a hydrogen infrastructure exists, hydrogen/natural gas fuel blends provide a logical transition to fully hydrogen-powered vehicles. These vehicles can operate on either fuel, depending on availability.

MODULE 4:
Fuel Cell Technology

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

4.1	FUEL CELL TECHNOLOGY USE	4-1
4.1.1	HISTORY	4-1
4.1.2	ADVANTAGES OF FUEL CELLS	4-1
4.1.3	DISADVANTAGES OF FUEL CELLS	4-5
4.1.4	APPLICATIONS	4-7
4.2	PRINCIPLE OF OPERATION	4-14
4.2.1	GALVANIC CELLS	4-14
4.2.2	FUEL CELLS	4-17
4.3	TYPES OF FUEL CELLS	4-21
4.3.1	MOLTEN CARBONATE FUEL CELLS	4-22
4.3.2	SOLID OXIDE FUEL CELLS	4-24
4.3.3	ALKALINE FUEL CELLS	4-27
4.3.4	PHOSPHORIC ACID FUEL CELLS	4-30
4.3.5	PROTON EXCHANGE MEMBRANE (PEM) FUEL CELLS	4-31
4.4	PEM FUEL CELL STACK CONSTRUCTION	4-35
4.4.1	MEMBRANE ELECTRODE ASSEMBLY (MEA)	4-37
4.4.2	FLOW FIELD PLATES	4-39
4.4.3	HUMIDIFIERS	4-41
4.5	PEM FUEL CELL PERFORMANCE	4-43
4.5.1	EFFICIENCY	4-43
4.5.2	POLARIZATION CHARACTERISTICS	4-47
4.5.3	POWER CHARACTERISTICS	4-48
4.5.4	TEMPERATURE AND PRESSURE EFFECTS	4-49
4.5.5	STOICHIOMETRY EFFECTS	4-52
4.5.6	HUMIDITY EFFECTS	4-53

OBJECTIVES

At the completion of this module, the technician will understand the:

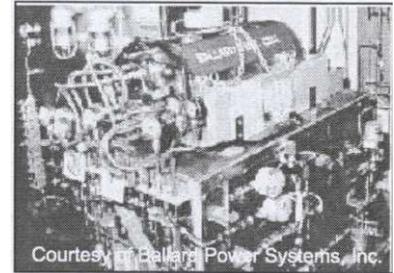
- advantages and disadvantages of fuel cells over conventional means of power production
- principles upon which fuel cells work
- operating principles and chemical reactions of different types of fuel cells
- comparative advantages and disadvantages of different kinds of fuel cells
- detailed construction of PEM fuel cells and fuel cell stacks
- effect of various parameters on PEM fuel cell performance

Key Points & Notes

4.1 Fuel Cell Technology Use**4.1.1 History**

The developments leading to an operational fuel cell can be traced back to the early 1800's with Sir William Grove recognized as the discoverer in 1839. Throughout the remainder of the century, scientists attempted to develop fuel cells using various fuels and electrolytes. Further work in the first half of the 20th century served as the foundation for systems eventually used in the Gemini and Apollo space flights. However, it was not until 1959 that Francis T. Bacon successfully demonstrated the first fully operational fuel cell.

Proton exchange membrane fuel cells were first used by NASA in the 1960's as part of the Gemini space program, and were used on seven missions. Those fuel cells used pure oxygen and hydrogen as the reactant gases and were small-scale, expensive and not commercially viable. NASA's interest pushed further development, as did the energy crisis in 1973. Since then, fuel cell research has continued unabated and fuel cells have been used successfully in a wide variety of applications.



5 kW Fuel Cell System at NASA



Figure 4-1 Various Proton Exchange Membrane Fuel Cell Stacks

4.1.2 Advantages of Fuel Cells

Fuel cell systems are usually compared to internal combustion engines and batteries and offer unique advantages and disadvantages with respect to them.

Fuel cell systems offer the following advantages:

- Fuel cell systems operate without pollution when run on pure hydrogen, the only by-products being pure water and heat. When run on hydrogen-rich reformat gas mixtures, some harmful emissions result although they are less than those emitted by an internal combustion engine using conventional fossil fuels. To be fair, internal combustion engines that combust lean mixtures of hydrogen and air also result in extremely low pollution levels that derive mainly from the incidental burning of lubricating oil.
- Fuel cell systems operate at higher thermodynamic efficiency than heat engines. Heat engines, such as internal combustion engines and turbines, convert chemical energy into heat by way of combustion and use that heat to do useful work. The optimum (or "Carnot") thermodynamic efficiency of a heat engine is known to be:

Key Points & Notes

$$\text{Efficiency}_{\text{MAX}} = 1 - \frac{T_2}{T_1}$$

Where:

T_1 = Absolute temperature of inlet (hot) gas (in °R or K)
 T_2 = Absolute temperature of outlet (cold) gas (in °R or K)

This formula indicates that the higher the temperature of the hot gas entering the engine and the lower the temperature of the cold outlet gas after expansion, the higher the thermodynamic efficiency. Thus, in theory, the upper temperature can be raised an arbitrary amount in order to achieve any desired efficiency, since the outlet temperature cannot be lower than ambient.

However, in a real heat engine the upper temperature is limited by material considerations. Furthermore, in an internal combustion engine, the inlet temperature is the operating temperature of the engine, which is very much lower than the ignition temperature.

Since fuel cells do not use combustion, their efficiency is not linked to their maximum operating temperature. As a result, the efficiency of the power conversion step (the actual electrochemical reaction as opposed to the actual combustion reaction) can be significantly higher. The electrochemical reaction efficiency is not the same as overall system efficiency as discussed in Section 4.1.2. The efficiency characteristics of fuel cells compared with other electric power generating systems are shown in Figure 4-2.

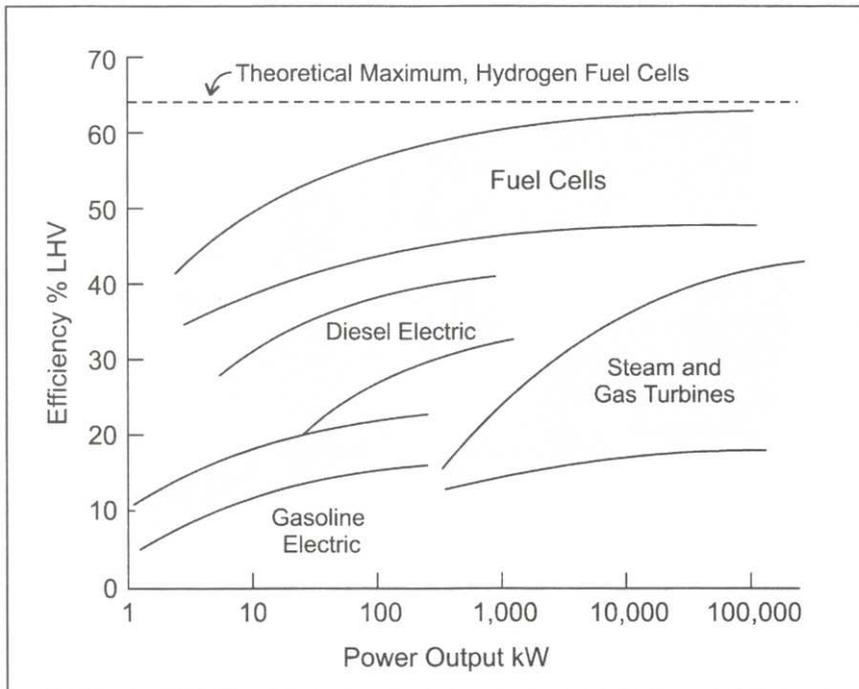


Figure 4-2 Power Generating Systems Efficiency Comparison

Key Points & Notes

- In addition to having higher specific thermal efficiency than heat engines, fuel cells also exhibit higher part-load efficiency and do not display a sharp drop in efficiency as the powerplant size decreases. Heat engines operate with highest efficiency when run at their design speed and exhibit a rapid decrease in efficiency at part load.

Fuel cells, like batteries, exhibit higher efficiency at part load than at full load and with less variation over the entire operating range. Fuel cells are modular in construction with consistent efficiency regardless of size. Reformers, however, perform less efficiently at part load so that overall system efficiency suffers when used in conjunction with fuel cells.

- Fuel cells exhibit good load-following characteristics. Fuel cells, like batteries, are solid state devices that react chemically and instantly to changes in load. Fuel cell systems, however, are comprised of predominantly mechanical devices each of which has its own response time to changes in load demand.

Nonetheless, fuel cell systems that operate on pure hydrogen tend to have excellent overall response. Fuel cell systems that operate on reformate using an on-board reformer, however, can be sluggish, particularly if steam reforming techniques are used.

- When used as an electrical energy generating device, fuel cells require fewer energy transformations than those associated with a heat engine. When used as a mechanical energy generating device, fuel cells require an equal number of conversions, although the specific transformations are different.
- Every energy transformation has an associated energy loss so that the fewer transformations there are, the better the efficiency. Thus fuel cells are more ideally suited to applications that require electrical energy as the end product, rather than mechanical energy. Comparative energy transformations for fuel cells, batteries and heat engines are shown in Figure 4-3.

Key Points & Notes

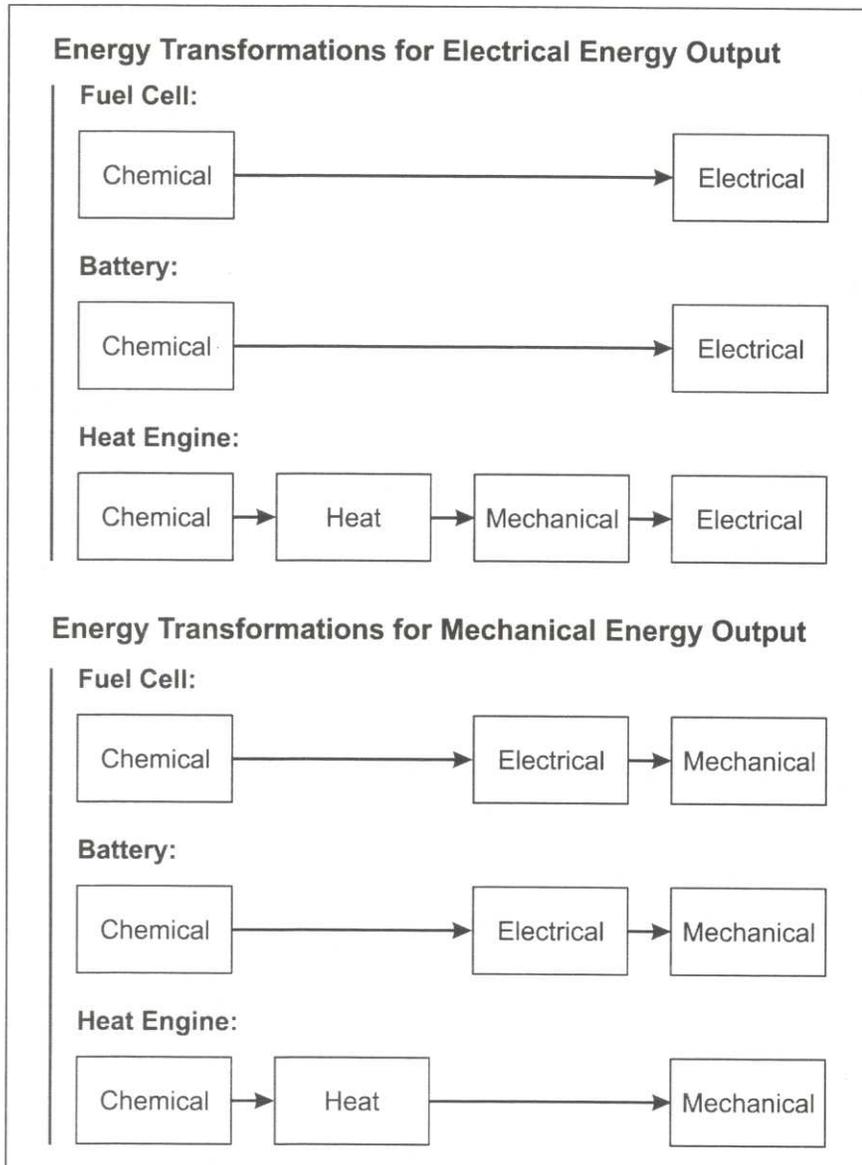


Figure 4-3 Comparative Energy Transformations

- Fuel cell systems suitable for automotive applications operate at low temperatures (typically less than 212 °F/ 100 °C). This is an advantage in that the fuel cells require little warmup time, high temperature hazards are reduced, and the thermodynamic efficiency of the electrochemical reaction is inherently better. This is a disadvantage in that medium-grade waste heat is harder to expel (especially in hot climates) so that cooling systems must be larger, and the electrochemical reaction proceeds more slowly than at high temperatures. Reformers used in conjunction with fuel cells operate at high temperatures and therefore may require prolonged warmup periods.
- Fuel cell systems can be used in co-generation applications. In addition to electrical power, fuel cells generate pure hot water and medium-grade heat, both of which can potentially be used in association with domestic or industrial applications. When this is done, the overall efficiency of the combined systems increases.
- Fuel cell systems do not require tuning.
- Fuel cell systems do not require recharging. Rather, fuel cell systems must be re-fueled, which is faster than charging a battery and can provide greater range depending on the size of the storage tank.

Key Points & Notes

4.1.3 Disadvantages of Fuel Cells

Fuel cell systems suffer the following disadvantages:

- Ironically, hydrogen which is of such benefit environmentally when used in a fuel cell, is also its greatest liability in that it is difficult to manufacture and store. Current manufacturing processes are expensive and energy intensive, and often derive ultimately from fossil fuels. An effective hydrogen infrastructure has yet to be established.
- Gaseous hydrogen storage systems are large and heavy to accommodate the low volumetric energy density of hydrogen. Liquid hydrogen storage systems are much smaller and lighter, but must operate at cryogenic temperatures. Alternatively, if hydrogen is stored as a hydrocarbon or alcohol and released on demand by way of an on-board reformer, the storage and handling issues simplify, but some of the environmental benefits are lost.
- Fuel cells require relatively pure fuel, free of specific contaminants. These contaminants include sulfur and carbon compounds, and residual liquid fuels (depending on the type of fuel cell) that can deactivate the fuel cell cata-

lyst effectively destroying its ability to operate. None of these contaminants inhibit combustion in an internal combustion engine.

Key Points & Notes

- Fuel cells suitable for automotive applications typically require the use of a platinum catalyst to promote the power generation reaction. Platinum is a rare metal and is very expensive.
- Fuel cells must not freeze with water inside. Fuel cells generate pure water during the power generating reaction and most fuel cells suitable for automotive applications use wet reactant gases. Any residual water within the fuel cells can cause irreversible expansion damage if permitted to freeze. During operation, fuel cell systems generate sufficient heat to prevent freezing over normal ambient temperatures, but when shut down in cold weather the fuel cells must be kept warm or the residual water must be removed before freezing. This normally entails bringing the vehicle into a heated facility or the use of a localized hot air heating device.
- Fuel cells that use proton exchange membranes must not dry out during use and must remain moist during storage. Attempts to start or operate these fuel cells under dry conditions can lead to membrane damage.
- Fuel cells require complex support and control systems. Fuel cells themselves are solid state devices, but the systems required to support fuel cell operation are not. Of particular note is the requirement for compressed air; this necessitates a high-speed compressor that imposes a large parasitic load on the overall system. System complexity increases significantly when the fuel cells are operated in conjunction with an on-board reformer.
- Fuel cell systems are heavy. Fuel cells themselves are not excessively heavy, but the combined weight of the fuel cells, their support systems and their fuel storage is presently greater than for a comparable internal combustion engine system. Systems that include an on-board reformer are heavier still. Fuel cell systems are generally lighter than comparable battery systems even though the battery systems require less support equipment. System weight will likely continue to decrease as the technology develops. Despite their weight, existing fuel cell prototype vehicles have shown that systems can be made sufficiently compact for automotive use.
- Fuel cells are an emerging technology. As with any new technology, reductions in cost, weight and size concur-

rent with increases in reliability and lifetime remain primary engineering goals.

Key Points & Notes

4.1.4 Applications

Fuel cells are inherently modular and therefore lend themselves to a wide range of applications, from large stationary powerplants to small portable power packs.

Stationary Powerplants

Stationary powerplant applications have been demonstrated in a number of pilot projects using a variety of fuel cell technologies over the past decades. The largest powerplant to date is the Ballard Generation Systems 250 kW natural gas fueled proton exchange membrane fuel cell powerplant currently operating at a number of sites worldwide. Although 250 kW is a small amount of power compared to conventionally powered generating stations, it is adequate to service isolated neighborhoods or to provide emergency backup power to critical facilities, such as hospitals.

Stationary powerplants are obvious candidates for operation using conventional fuels, such as natural gas, which can be piped to the powerplant and reformed on site. Overall size and warmup time are less critical issues than in smaller, mobile applications. In addition to the high operating efficiency, low emissions and good transient response characteristic of fuel cell systems, stationary applications also produce copious amounts of hot water and waste heat that can be used directly in the surrounding community, further increasing the overall system effectiveness.

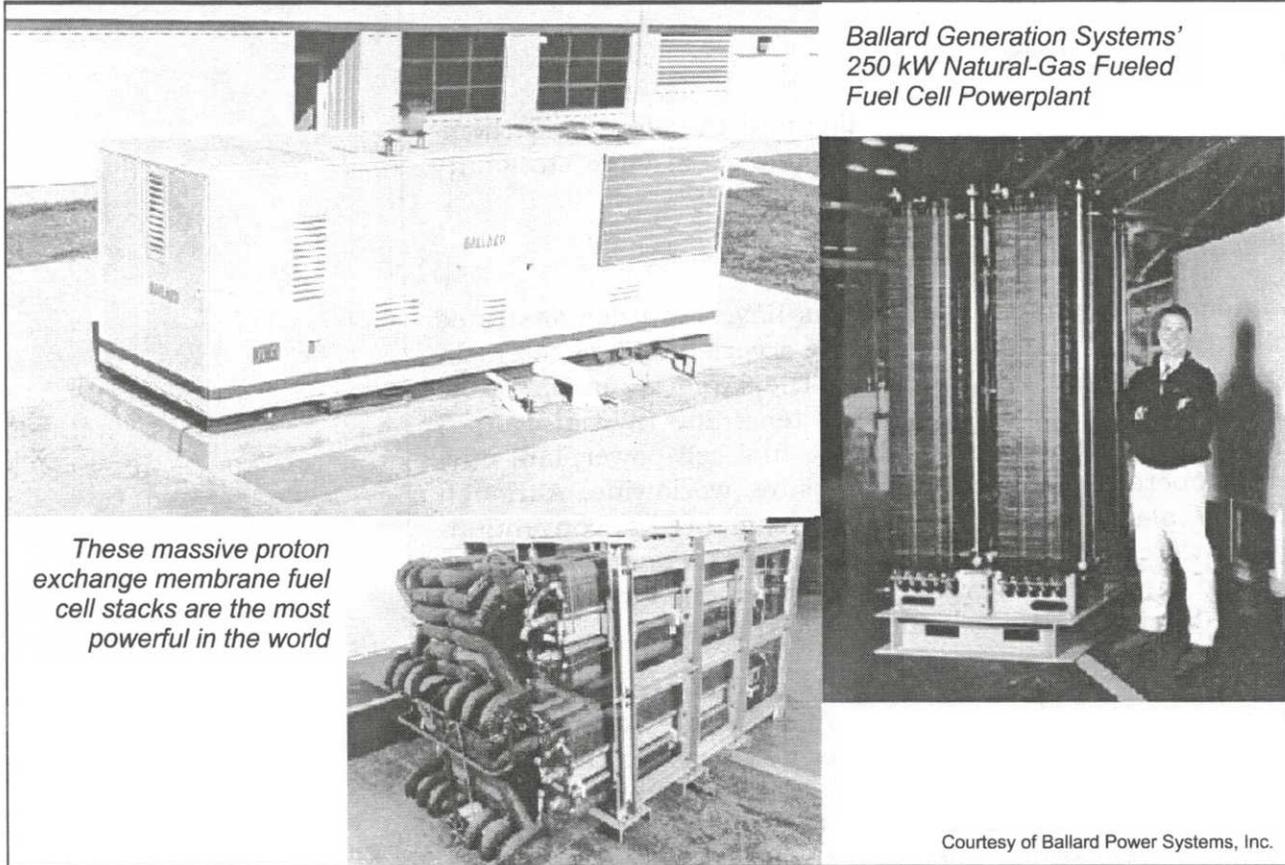
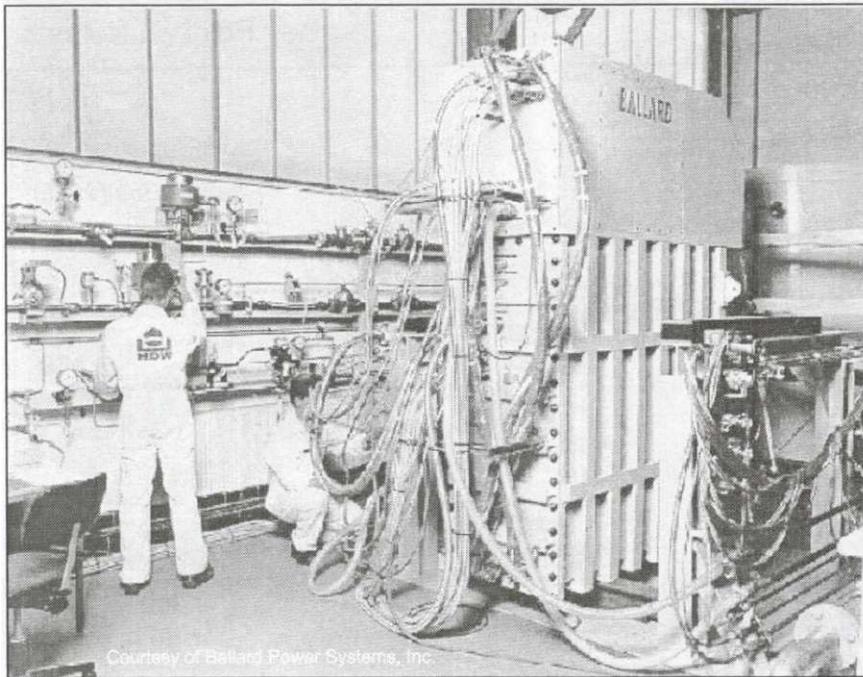


Figure 4-4 250 kW Stationary Fuel Cell Powerplant

Key Points & Notes

Submarines

Fuel cells systems are attractive for military submarine applications due to their low noise and infrared signatures. In many ways, fuel cells are a logical replacement for the banks of batteries currently used to power many submarines. As with stationary powerplants, hot product water can be used for on-board domestic purposes. Prototype systems using pure reactants and on-board reformers have been demonstrated in recent years.



This 80 kW powerplant was built by Ballard Power Systems for German submarine manufacturer Howaldtswerke-Deutsche Werft AD and operates using pure hydrogen and oxygen.

Figure 4-5 Submarine Fuel Cell Powerplant

Key Points & Notes

Buses

Buses are the most commercially advanced of all fuel cell applications to date. Successful demonstration programs have been carried out by XCELLSiS Fuel Cell Engines, Inc., with the introduction of three buses each in Vancouver, BC and Chicago, IL into revenue service for a period of two years, and a year-long field trial program in Palm Springs, CA. In the near future, additional buses will enter service throughout Europe and in other areas of the world. All of these buses use pure hydrogen stored as a high-pressure gas; other demonstration vehicles have used liquid fuels and incorporate on-board reformer systems.

Buses are a logical starting point for the introduction of fuel cell technology into the transportation sector for several reasons: they offer a reasonably large platform for system components and fuel storage, they can be fueled at a central fueling station, and they are regularly maintained by trained personnel.

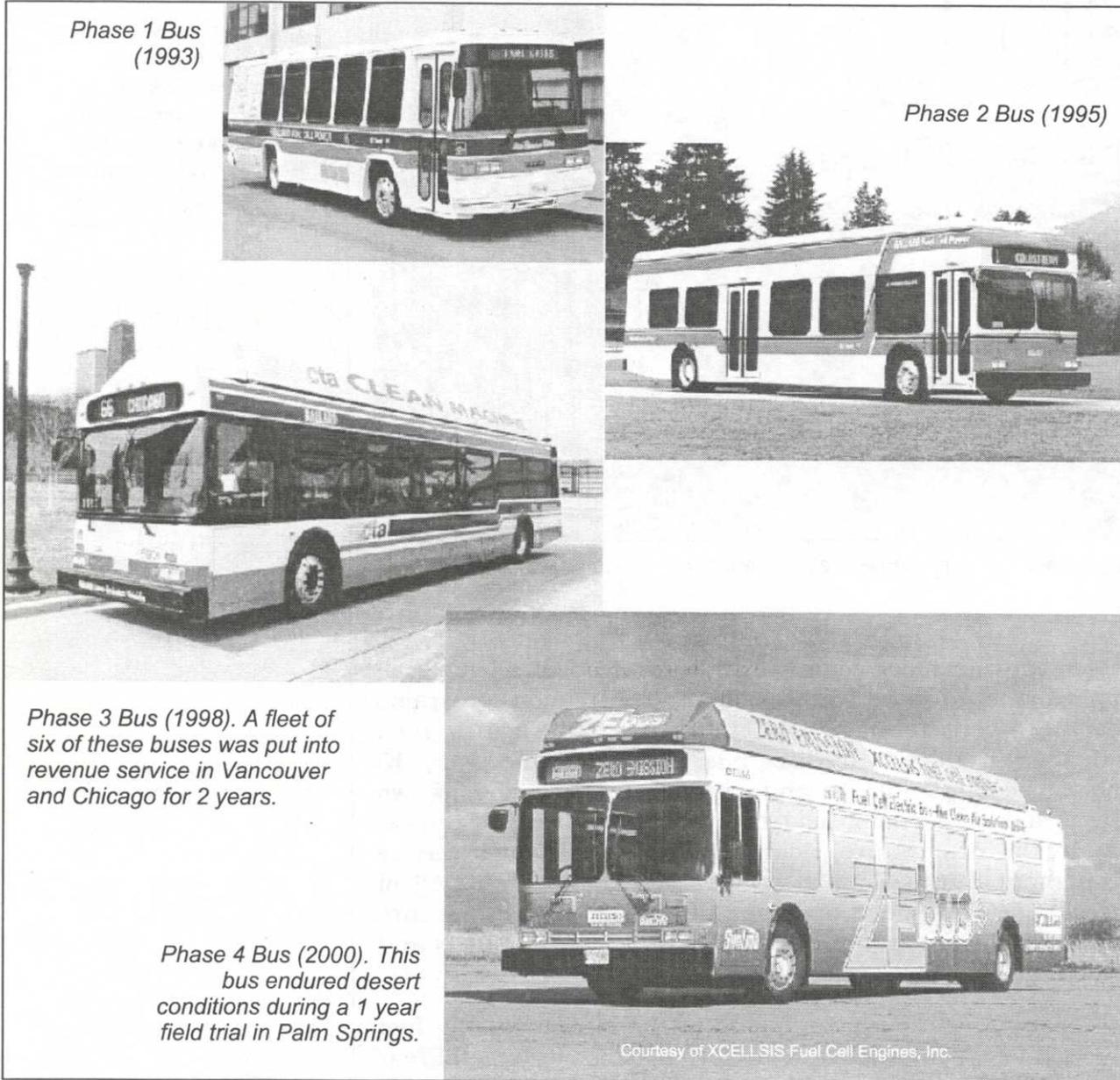


Figure 4-6 XCELLSiS Fuel Cell Bus Prototypes

Key Points & Notes

Cars

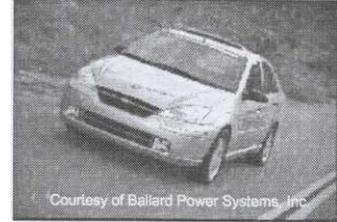
Cars represent the ultimate market for fuel cell manufacturers due to the quantities involved worldwide. While cars provide the major stimulus for fuel cell development, as they are a major contributor to air pollution, they also pose some of the greatest challenges to commercialization. These challenges include their relatively small size, the vast fueling infrastructure required, and the inconsistent maintenance habits of the public at large. In addition, performance and reliability expectations are high, while cost expectations are low.

Many major car companies are engaged in automotive fuel cell programs including Daimler-Chrysler, Ford, General Motors, Nissan, Mazda, Subaru, Toyota, Honda and Hyundai. Some of these companies have built prototype vehicles using fuel cells with or without auxiliary batteries, and fueled using either pure (gaseous or liquid) hydrogen or reformate.

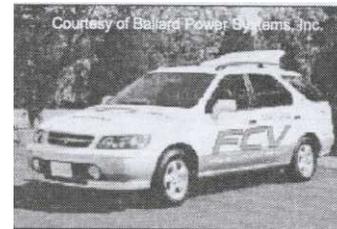
Lack of an existing hydrogen infrastructure is a serious deterrent to automotive fuel cell use. To this end, many current prototypes use an on-board reformer with methanol as the preferred fuel, although gasoline systems are also under investigation. Although this alleviates some of the fuel availability and storage problems, it increases the amount of hardware that must be installed in the vehicle (thereby increasing cost and complexity), and introduces control and performance problems associated with reformers. Of course, use of a reformer does not completely eliminate harmful emissions, and does little or nothing to reduce dependence on fossil fuels.

Some automotive manufacturers have made commitments to introduce fuel cell vehicles to the market in the early years of the first decade of this century. It is likely that these vehicles will make their debut within fleet operations so that fueling and maintenance issues can be minimized.

Key Points & Notes



Ford THINK 2000 Fuel Cell Car



Nissan Fuel Cell Vehicle



Honda Fuel Cell Vehicle



Figure 4-7 Daimler-Chrysler Nekar Fuel Cell Vehicle Prototypes

Key Points & Notes

Portable Power Systems

Key Points & Notes

Portable fuel cell systems can potentially be used in many applications that currently rely on batteries. Commercial units that provide up to 1.2 kW (4100 Btuh) of electrical power are now available.

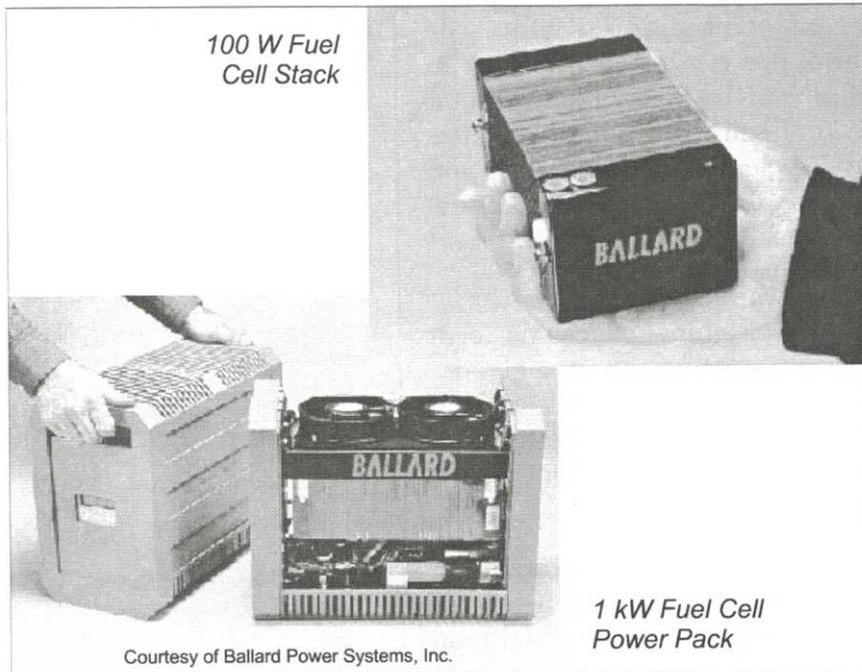


Figure 4-8 Portable Fuel Cell Systems

4.2 Principle of Operation

Key Points & Notes

A fuel cell is an energy conversion device that converts the chemical energy of a fuel directly into electricity without any intermediate thermal or mechanical processes.

Energy is released whenever a fuel reacts chemically with the oxygen in air. In an internal combustion engine, the reaction occurs *combustively* and the energy is released in the form of heat, some of which can be used to do useful work by pushing a piston. In a fuel cell, the reaction occurs *electrochemically* and the energy is released as a combination of low-voltage DC electrical energy and heat. The electrical energy can be used to do useful work directly while the heat is either wasted or used for other purposes.

In *galvanic* (or "voltaic") cells, electrochemical reactions form the basis in which chemical energy is converted into electrical energy. A fuel cell of any type is a galvanic cell, as is a battery. In contrast, in *electrolytic* cells, electrical energy is converted into chemical energy, such as in an electrolyzer or electroplater.

A basic feature of fuel cells is that the electric current load determines the consumption rate of hydrogen and oxygen. In an actual systems application, a variety of electrical loads may be applied to the fuel cell.

4.2.1 Galvanic Cells

In principle, all galvanic cells consist of two electrodes — an anode and a cathode — and an electrolyte. The anode, or negative (fuel) electrode, is made of a substance that is readily *oxidized* (releases electrons). The cathode, or positive (oxidant) electrode, is made of a substance that is readily *reduced* (accepts electrons). When used together, the anode and cathode are two halves of a spontaneous *oxidation-reduction* reaction. In other words, the anode and cathode are at a high energy state and wish to combine to achieve a lower energy state.

For a chemical reaction to occur, the reactive elements must be in contact with each other so that electrons can be exchanged and bonds formed. If the anode and cathode are in direct contact, a reaction can occur where their surfaces touch. No useful work results as the electrons pass between the electrodes directly; all of the energy of reaction manifests itself as heat.

In order to take advantage of the available electrical energy, the electrodes must be separated in such a way that elec-

The term cathode always applies to the electrode at which reduction (a gain of electrons) takes place and the term anode always applies to the electrode at which oxidation (a loss of electrons) takes place. Thus, during operation of a fuel cell, the cathode is electrically positive and the anode is negative. During the opposite reaction of electrolysis, the cathode is electrically negative and the anode is positive. Electrons flow spontaneously from an electrically negative terminal to an electrically positive terminal.

trons can flow from the anode to the cathode through an external load while still being in some form of contact to enable the reaction to proceed. To achieve this, the anode and cathode are separated by an electrolyte.

An electrolyte is a substance that conducts *ions*. An ion is an atom or group of atoms that has acquired an electrical charge through the loss or gain of one or more electrons. Ions with a positive charge have lost one or more electrons and are known as positive ions or “cations”. Ions with a negative charge have gained one or more electrons and are known as negative ions or “anions”.

For example, when table salt (NaCl) is dissolved in water, it dissociates into a sodium cation (Na^+) and a chlorine anion (Cl^-). When an ion moves through an electrolyte, the charge moves with it. Thus, ionic movement imparts a form of conductivity to the electrolyte. Consequently salty water is more conductive than fresh water.

Although an electrolyte conducts *ions*, it does not conduct *electricity*. Electricity is the flow of free electrons such as through a metal. If the electrolyte were to conduct electricity in addition to ions, the anode and cathode would be short-circuited just as if they were in full contact. It is this duality of ionic conduction and electrical insulation that allows electrolytes to form the essential basis of all practical galvanic cells.

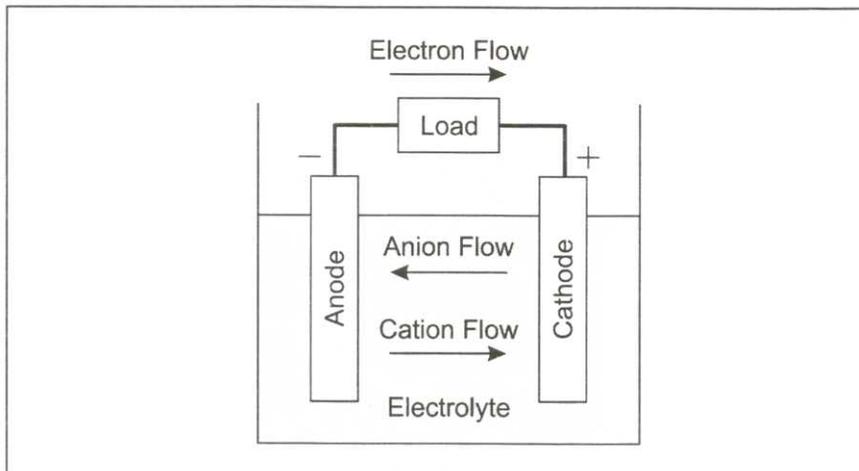


Figure 4-9 Galvanic Cell Operation

In practice, the anode material dissolves into the electrolyte forming positively charged cations and leaves behind a corresponding buildup of free electrons within the anode itself. This buildup of electrons manifests itself as a negative charge. Conversely, the cathode material has a tendency to attract positive cations that originate from either the anode

Key Points & Notes

(with which it reacts) or from the substance of the electrolyte itself.

Key Points & Notes

The accumulation of cations on the cathode manifests itself as a positive charge. Thus, an electrical potential exists between the cathode and the anode since the former is positively charged with respect to the latter. However, this is a static situation since the charge only builds up to a point beyond which there is insufficient chemical attraction to generate additional ions. This charge can be measured as the *open-circuit voltage* (OCV) and is a property of the chosen electrode materials and to some extent on cell temperature.

The chemical reaction between the anode and cathode cannot move to completion as long as the electrons remain trapped within the anode. These electrons are essential to the formation of the final reaction product and to the release of the reaction energy. In order to release the electrons, the electrical circuit between the two electrodes must be completed through an external flow path. If the external flow path includes a load, the electrons do useful work on their way to the cathode.

Once the anode and cathode are connected, the surplus electrons from the anode flow into the cathode, completing the chemical reaction. As the cathode loses its electron excess and therefore its negative charge, more cathode ions dissolve to produce a new excess of electrons. As the cathode gains electrons and loses its positive charge, more positive cations are attracted to the cathode.

In short, electrons flow from the anode to the cathode by way of the external load and then join the positively charged ions that migrate through the electrolyte. This flow continues until the anode is consumed, the electrolyte is unable to furnish further cations, or the load path is removed. The rate of reaction is set by the size of the load.

Overall, the net chemical change that occurs within a galvanic cell is the result of the individual reactions at the anode and the cathode, which always remain balanced in such a way that the same number of electrons are gained and lost. As the reaction completes, a reaction product compound is formed at the cathode. The reaction product depends on the chemical composition of the electrodes and can be a gas, a liquid or a solid. This product compound must be removed as it would otherwise block the reaction sites and thereby impede further reaction.

Practical galvanic cell designs often include a porous barrier between the anode and cathode. This barrier is permeable to

the electrolyte but slows the ion flow and provides mechanical separation between the electrodes.

Key Points & Notes

The electrolyte is the heart of every galvanic cell. Different types of electrolytes account for fundamentally different designs of both batteries and fuel cells. Electrolytes may be liquids or solids and typically include salt, acid or alkali compounds. Regardless of their composition, electrolytes must have good ionic conductivity while being electrically non-conductive, must be non-reactive with the electrode materials, and exhibit little change in properties with changes in temperatures.

4.2.2 Fuel Cells

In a fuel cell, the fuel and the oxidant gases themselves comprise the anode and cathode respectively. Thus, the physical structure of a fuel cell is one where the gases are directed through flow channels to either side of the electrolyte. The electrolyte is the distinguishing feature between different types of fuel cells. Different electrolytes conduct different specific ions.

Electrolytes can be liquid or solid; some operate at high temperature, and some at low temperature. Low-temperature fuel cells tend to require a noble metal catalyst, typically platinum, to encourage the electrode reactions whereas high-temperature fuel cells do not. Most fuel cells suitable for automotive applications use a low temperature solid electrolyte that conducts hydrogen ions as shown in Figure 4-10.

In principle, a fuel cell can operate using a variety of fuels and oxidants. Hydrogen has long been recognized as the most effective fuel for practical fuel cell use since it has higher electrochemical reactivity than other fuels, such as hydrocarbons or alcohols. Even fuel cells that operate directly on fuels other than hydrogen tend to first decompose into hydrogen and other elements before the reaction takes place. Oxygen is the obvious choice of oxidant due to its high reactivity and its abundance in air.

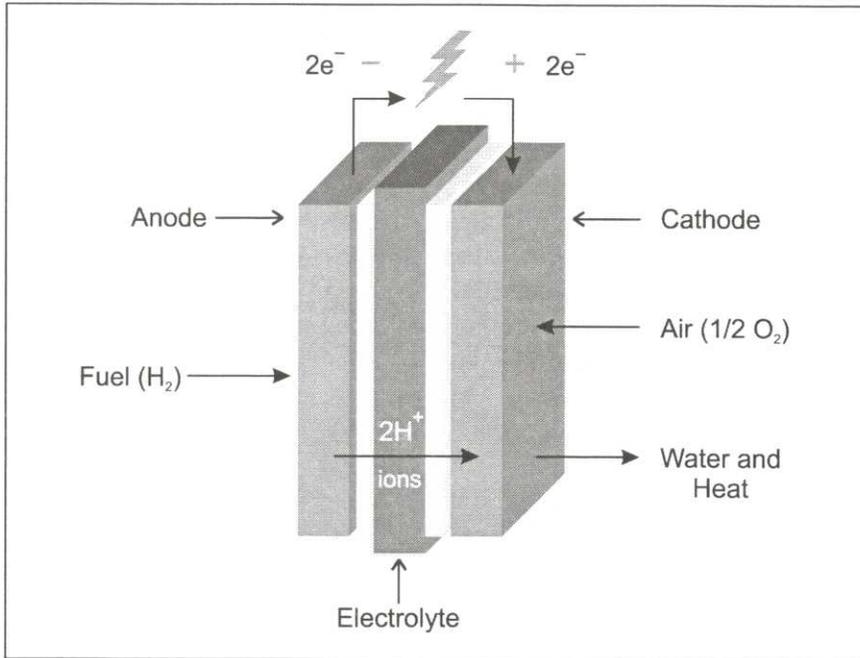


Figure 4-10 Generic Hydrogen Fuel Cell Operation

Key Points & Notes

Comparison of Fuel Cells with Batteries

Fuel cells and batteries are both galvanic cells and therefore have many similarities. Both fuel cells and batteries consist of an anode and a cathode in contact with an electrolyte. Both devices generate electrical energy by converting chemical energy from a high energy state to a lower energy state using an electrochemical reaction.

These reactions occur at the anode and cathode with electron transfer forced through an external load in order to complete the reaction. Individual cells of both batteries and fuel cells generate only small DC voltages, which are then combined in series to achieve substantial voltage and power capacities.

Fuel cells differ from batteries in the nature of their anode and cathode. In a battery, the anode and cathode are metals; zinc or lithium is typically used for the anode and metallic oxides for the cathode. In a fuel cell, the anode and cathode are composed of gases often in contact with a platinum catalyst to promote the power generating reaction. Hydrogen or a hydrogen-rich gas mixture is typically used as the anode and oxygen or air as the cathode.

Fuel cells also differ from batteries in the fundamental method in which the chemical reactants are stored. In a battery, the anode and cathode form an integral part of the battery structure and are consumed during use. Thus, a

battery can only operate until these materials are fully consumed after which it must either be replaced or recharged, depending on the nature of the materials.

Key Points & Notes

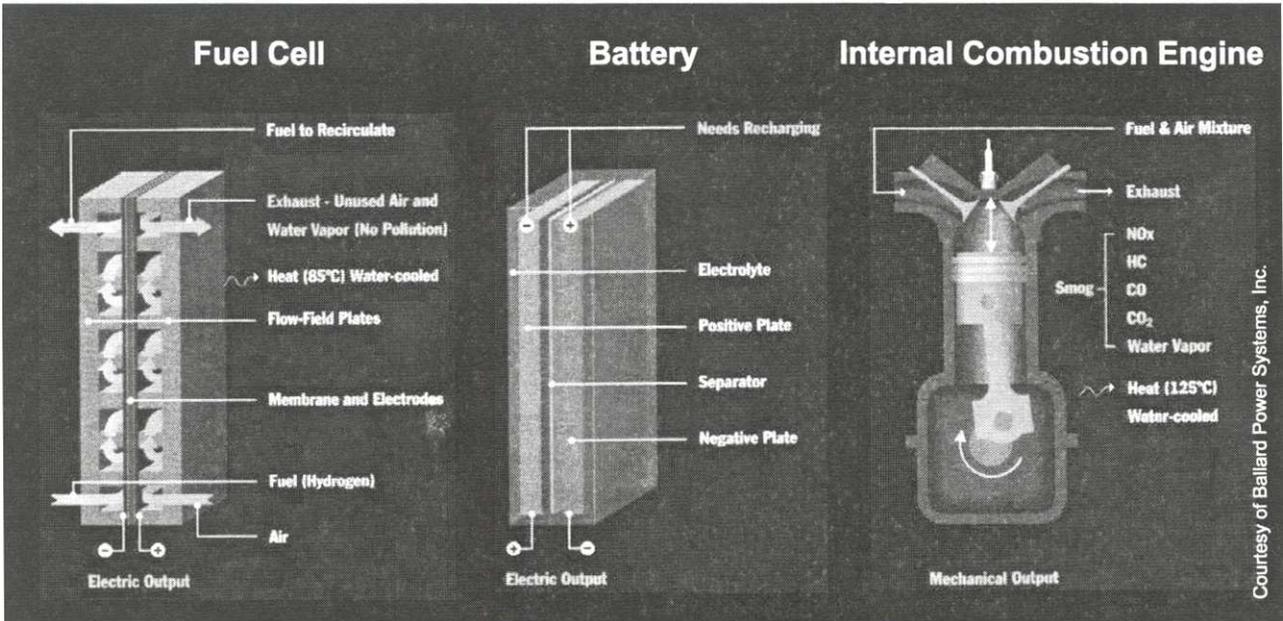
In a fuel cell, the chemical reactants are supplied from an external source so that its materials of construction are never consumed and do not need to be recharged. A fuel cell continues to operate as long as reactants are supplied and the reaction products are removed.

Comparison of Fuel Cells with Internal Combustion Engines

Fuel cells and internal combustion engines share similarities of form. Both fuel cells and internal combustion engines use gaseous fuel, drawn from an external fuel storage system. Both systems use hydrogen-rich fuel. Fuel cells use pure hydrogen or a reformat gas mixture. Internal combustion engines typically use hydrogen-containing fossil fuels directly, although they could be configured to operate using pure hydrogen.

Both systems use compressed air as the oxidant; in a fuel cell engine the air is compressed by an external compressor. In an internal combustion engine, the air is compressed internally through piston action. Both systems require cooling, although engines operate at higher temperatures than fuel cells.

In some respects, fuel cells and internal combustion engines are fundamentally different. Fuel cells react the fuel and oxidant electrochemically whereas internal combustion engines react the fuel and oxidant combustively. Internal combustion engines are mechanical devices that generate mechanical energy while fuel cells are solid state devices that generate electrical energy (although the systems used to support fuel cell operation are not solid state).



Key Points & Notes

Figure 4-11 Fuel Cell, Battery and Internal Combustion Engine Comparisons

Pollution is related to the fuel composition and the reaction temperature. Fuel cell engines operating on pure hydrogen produce no harmful emissions; those that operate on hydrogen-rich reformat produce some harmful emissions depending on the nature of the process. Internal combustion engines operating on pure hydrogen can be designed to produce almost zero harmful emissions; those that run on conventional fuels produce significantly more pollution.

4.3 Types of Fuel Cells

Key Points & Notes

Types of fuel cells differ primarily by the type of electrolyte they employ. The type of electrolyte, in turn, determines the operating temperature, which varies widely between types.

High-temperature fuel cells operate at greater than 1100 °F (600 °C). These high temperatures permit the spontaneous internal reforming of light hydrocarbon fuels — such as methane — into hydrogen and carbon in the presence of water. This reaction occurs at the anode over a nickel catalyst provided that adequate heat is always available. This is essentially a steam reforming process (see Section 2.1.2.2).

Internal reforming eliminates the need for a separate fuel processor, and can use fuels other than pure hydrogen. These significant advantages lead to an increase in overall efficiency by as much as 15%. During the electrochemical reaction that follows, the fuel cell draws on the chemical energy released during the reaction between hydrogen and oxygen to form water, and the reaction between carbon monoxide and oxygen to form carbon dioxide.

High-temperature fuel cells also generate high-grade waste heat, which can be used in downstream processes for co-generation purposes.

High-temperature fuel cells react easily and efficiently without an expensive noble metal catalyst, such as platinum. On the other hand, the amount of energy released by the electrochemical reaction degrades as the reaction temperature increases.

High-temperature fuel cells suffer from severe materials problems. Few materials can work for extended periods without degradation within a chemical environment at high temperature. Furthermore, high-temperature operation does not lend itself easily to large-scale operations and is not suitable where quick startup is required. As a result, current high-temperature fuel cells applications have focused on stationary powerplants where the efficiencies of internal reforming and co-generative capabilities outweigh the disadvantages of material breakdown and slow startup.

The most prominent high-temperature fuel cells are:

- molten carbonate
- solid oxide

Low-temperature fuel cells typically operate below 480 °F (250 °C). These low temperatures do not permit internal re-

forming, and therefore require an external source of hydrogen. On the other hand, they exhibit quick startup, suffer fewer materials problems and are easier to handle in vehicle applications.

Key Points & Notes

The most prominent low-temperature fuel cells are:

- alkaline
- phosphoric acid
- proton exchange membrane (or solid polymer)

4.3.1 Molten Carbonate Fuel Cells

Molten carbonate fuel cells use an electrolyte that conducts carbonate (CO_3^{2-}) ions from the cathode to the anode. This is the opposite of many other types of fuel cells, which conduct hydrogen ions from the anode to the cathode.

The electrolyte is composed of a molten mixture of lithium and potassium carbonates. This mixture is retained by capillary forces within a ceramic support matrix of lithium aluminate. At the fuel cell operating temperature, the electrolyte structure is a thick paste, and the paste provides gas seals at the cell edges.

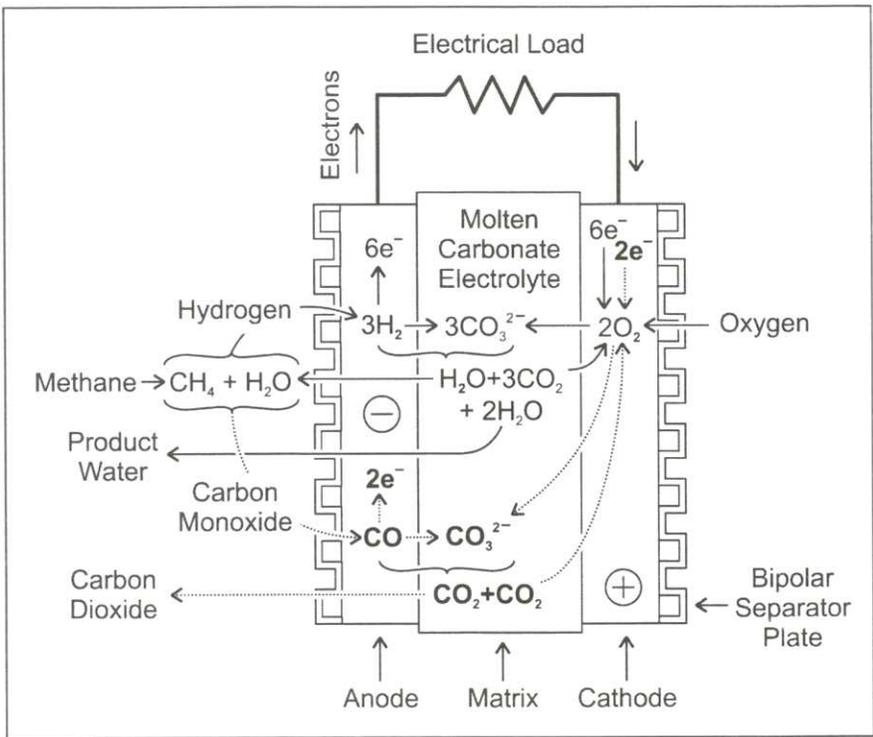


Figure 4-12 Molten Carbonate Fuel Cell

Molten carbonate fuel cells operate at about 1200 °F (650°C) and a pressure of 15 to 150 psig (1 to 10 barg). Each cell can produce up to between 0.7 and 1.0 VDC.

Key Points & Notes

Advantages and Disadvantages

The advantages of molten carbonate fuel cells are that they:

- support spontaneous internal reforming of light hydrocarbon fuels
- generate high-grade waste heat
- have fast reaction kinetics (react quickly)
- have high efficiency
- do not need noble metal catalysts

The disadvantages are that they:

- require the development of suitable materials that are resistant to corrosion, are dimensionally stable, have high endurance and lend themselves to fabrication.

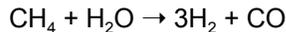
Corrosion is a particular problem and can cause nickel oxide from the cathode to dissolve into the electrolyte, loss of electrolyte, deterioration of separator plates, and dehydration or flooding of the electrodes. All of these corrosion effects result in a decline in performance, limit cell life, and can culminate in cell failure. Use of a platinum catalyst overcomes some of these problems, but eliminates an important cost-saving advantage.

Dimensional instability can cause electrode deformation that alters the active surface area and may cause loss of contact and high resistances between components.

- have a high intolerance to sulfur. The anode in particular cannot tolerate more than 1-5 ppm of sulfur compounds (primarily H₂S and COS) in the fuel gas without suffering a significant performance loss.
- have a liquid electrolyte, which introduces liquid handling problems
- require a considerable warmup period

Reaction

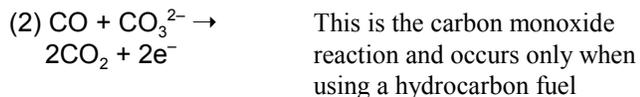
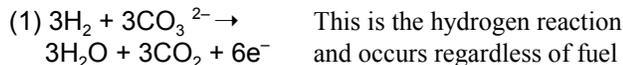
Molten carbonate fuel cells can operate using pure hydrogen or light hydrocarbon fuels. When a hydrocarbon, such as methane, is introduced to the anode in the presence of water, it absorbs heat and undergoes a steam reforming reaction:



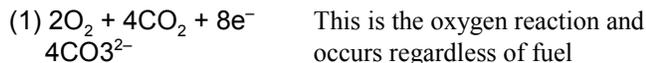
Key Points & Notes

When using other light hydrocarbon fuels, the number of hydrogen and carbon monoxide molecules may change but in principle the same products result.

The reactions at the anode are:

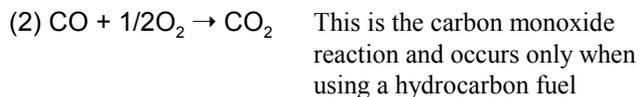
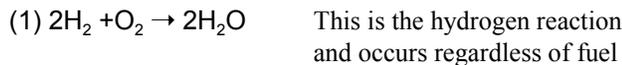


The reaction at the cathode is:



The CO_3^{2-} ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen and carbon monoxide to oxygen, while electrons are forced through an external circuit from the anode to the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:



Thus, the fuel cell produces water, regardless of fuel, and carbon dioxide if using a hydrocarbon fuel. Both product water and carbon dioxide must be continually removed from the cathode to facilitate further reaction.

4.3.2 Solid Oxide Fuel Cells

Solid oxide fuel cells use an electrolyte that conducts oxide (O^{2-}) ions from the cathode to the anode. This is the opposite of most types of fuel cells, which conduct hydrogen ions from the anode to the cathode.

The electrolyte is composed of a solid oxide, usually zirconia (stabilized with other rare earth element oxides like yttrium), and takes the form of a ceramic.

Solid oxide fuel cells are built like computer chips through sequential deposition of various layers of material. Common configurations include tubular and flat (planar) designs. The

designs differ in the extent of dissipative losses within cells, in the manner of sealing between the fuel and oxidant channels, and in the manner that cell-to-cell electrical connections are made in a stack of cells. Metals such as nickel and cobalt can be used as electrode materials.

Solid oxide fuel cells operate at about 1830 °F (1000 °C) and a pressure of 15 psig (1 barg). Each cell can produce between 0.8 and 1.0 VDC.

Key Points & Notes

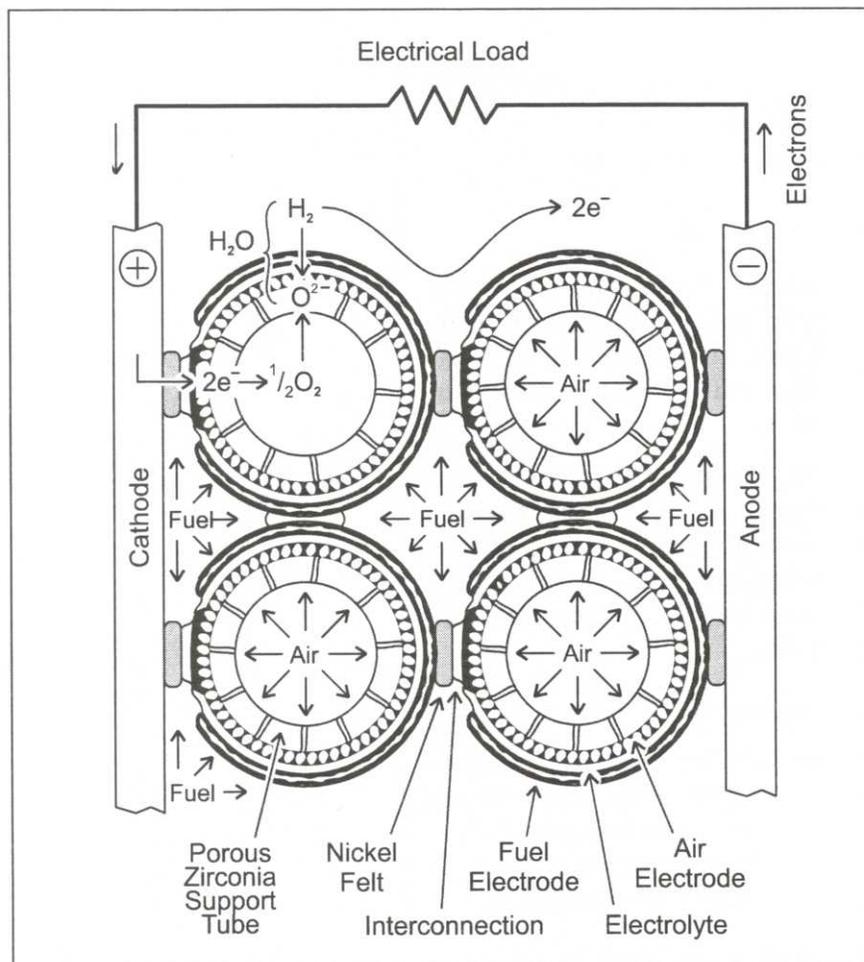


Figure 4-13 Solid Oxide Fuel Cell (Tubular Design)

Advantages and Disadvantages

The advantages of solid oxide fuel cells are that they:

- support spontaneous internal reforming of hydrocarbon fuels.

Since oxide ions — rather than hydrogen ions — travel through the electrolyte, the fuel cells can in principle be used to oxidize any gaseous fuel.

- operate equally well using wet or dry fuels
- generate high-grade waste heat
- have fast reaction kinetics
- have very high efficiency
- can operate at higher current densities than molten carbonate fuel cells
- have a solid electrolyte, avoiding problems associated with handling liquids
- can be fabricated in a variety of self-supporting shapes and configurations
- do not need noble metal catalysts

The disadvantages are that they:

- require the development of suitable materials that have the required conductivity, remain solid at high temperatures, are chemically compatible with other cell components, are dimensionally stable, have high endurance and lend themselves to fabrication.

Few materials can operate at high temperatures and remain solid over long periods of time. Furthermore, the selected materials must be dense to prevent mixing of the fuel and oxidant gases, and must have closely matched thermal expansion characteristics to avoid delamination and cracking during thermal cycles.

- have a moderate intolerance to sulfur

Solid oxide fuel cells are more tolerant to sulfur compounds than are molten carbonate fuel cells, but overall levels must still be limited to 50 ppm. This increased sulfur tolerance makes these fuel cells attractive for heavy fuels. Excess sulfur in the fuel decreases performance.

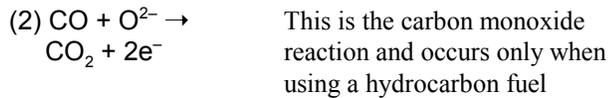
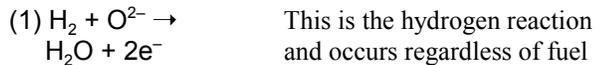
- do not yet have practical fabrication processes
- the technology is not yet mature

Reaction

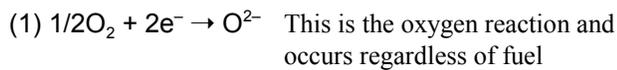
Solid oxide fuel cells can operate using pure hydrogen or hydrocarbon fuels, just like molten carbonate fuel cells. This results in an inlet fuel stream comprised of hydrogen with or without carbon monoxide.

The reactions at the anode are:

Key Notes & Notes

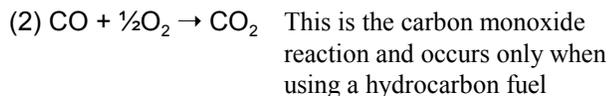
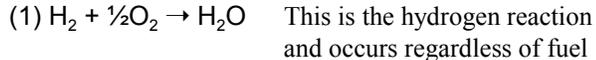


The reaction at the cathode is:



The O^{2-} ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen and carbon monoxide to oxygen, while electrons are forced through an external circuit from the anode to the cathode. Since the ions move from the cathode to the anode, this is the opposite of most types of fuel cells, the reaction products accumulate at the anode rather than the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:



Thus, the fuel cell produces water — regardless of fuel — and carbon dioxide if using a hydrocarbon fuel. Both product water and carbon dioxide must be continually removed from the cathode to facilitate further reaction.

4.3.3 Alkaline Fuel Cells

Alkaline fuel cells use an electrolyte that conducts hydroxyl (OH^-) ions from the cathode to the anode. This is opposite to many other types of fuel cells that conduct hydrogen ions from the anode to the cathode.

The electrolyte is typically composed of a molten alkaline mixture such as potassium hydroxide (KOH). The electrolyte can be mobile or immobile.

Mobile alkaline electrolyte fuel cells use a fluid electrolyte that continuously circulates between the electrodes. The product water and waste heat dilute and heat the liquid electrolyte but are removed from the cell as the electrolyte circulates.

Immobile alkaline electrolyte fuel cells use an electrolyte that consists of a thick paste retained by capillary forces within a porous support matrix such as asbestos. The paste itself provides gas seals at the cell edges. Product water evaporates into the source hydrogen gas stream at the anode from which it is subsequently condensed. The waste heat is removed by way of a circulating coolant.

Alkaline fuel cells operate at about 150 to 430 °F (65 to 220 °C) and a pressure of about 15 psig (1 barg). Each cell can produce up to between 1.1 and 1.2 VDC.

Key Points & Notes

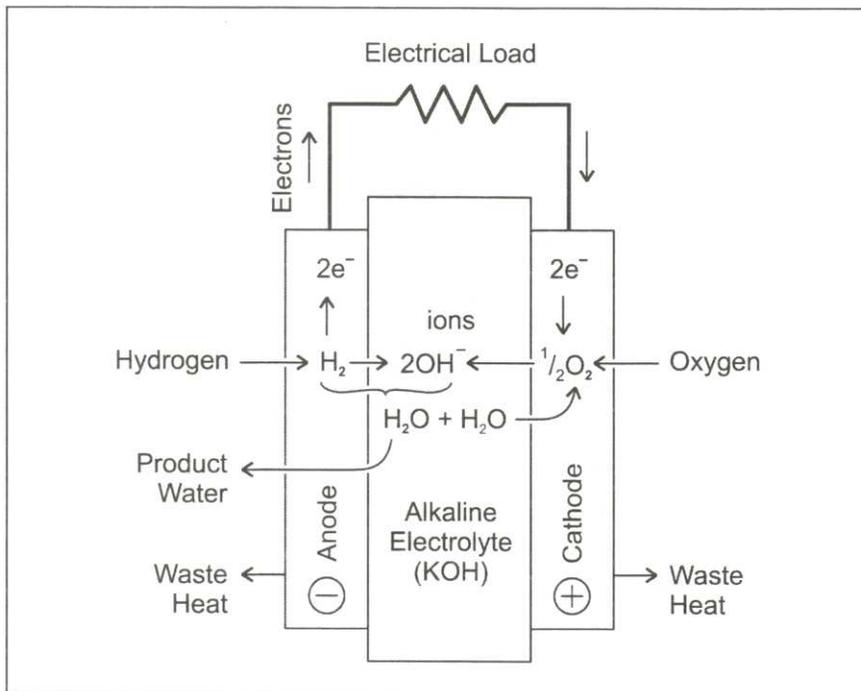


Figure 4-14 Alkaline Fuel Cell

Advantages and Disadvantages

The advantages of alkaline fuel cells are that they:

- operate at low temperature
- have fast startup times (50% rated power at ambient temperature)
- have high efficiency
- need little or no expensive platinum catalyst
- have minimal corrosion
- have relative ease of operation
- have low weight and volume

The disadvantages are that they:

Key Points & Notes

- are extremely intolerant to CO_2 (about 350 ppm maximum) and somewhat intolerant of CO

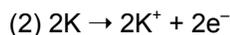
This is a serious disadvantage and limits both the type of oxidant and fuel that can be used in an alkaline fuel cell. The oxidant must be either pure oxygen or air that has been scrubbed free of carbon dioxide. The fuel must be pure hydrogen due to the presence of carbon oxides in re-formate.

- have a liquid electrolyte, introducing liquid handling problems
- require complex water management
- have a relatively short lifetime

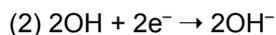
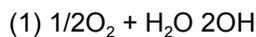
Reaction

Alkaline fuel cells must operate using pure hydrogen free of carbon oxides.

The reactions at the anode are:

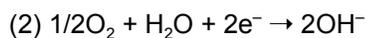
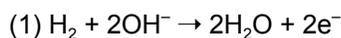


The reactions at the cathode are:



The OH^- ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit from the anode to the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:



Thus, the fuel cell produces water that either evaporates into the source hydrogen stream (in an immobile system) or is flushed out of the cells along with the electrolyte (in a mobile system). This water must be continually removed to facilitate further reaction.

4.3.4 Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells use an electrolyte that conducts hydrogen ions (H^+) from the anode to the cathode. As its name implies, the electrolyte is composed of liquid phosphoric acid within a silicon carbide matrix material. (Some acid fuel cells use a sulfuric acid electrolyte.)

Phosphoric acid fuel cells operate at about 300 to 400 °F (150 to 205 °C) and a pressure of about 15 psig (1 barg). Each cell can produce up to about 1.1 VDC.

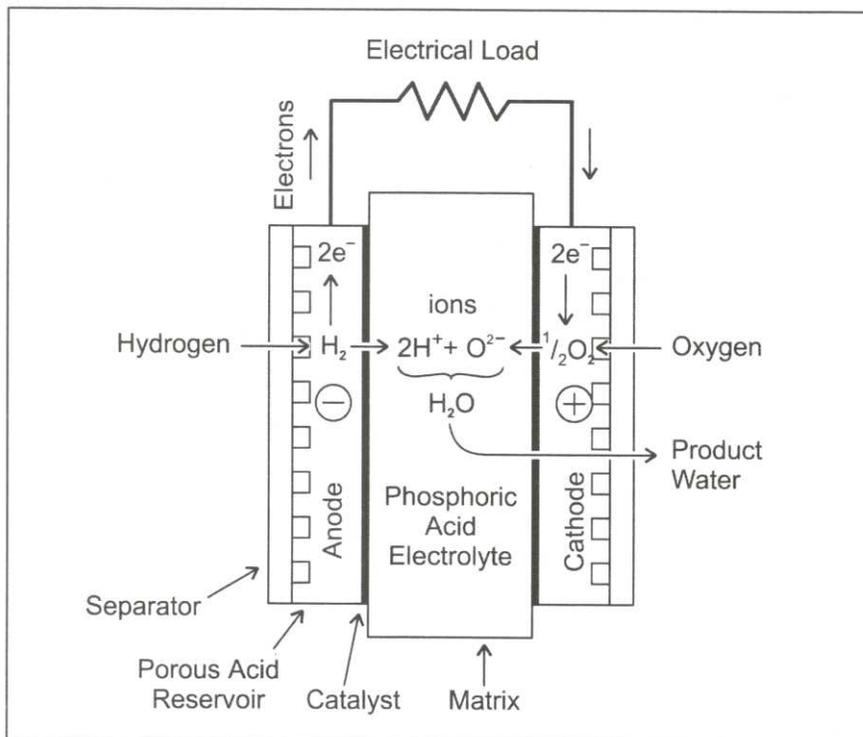


Figure 4-15 Phosphoric Acid Fuel Cell

Advantages and Disadvantages

The advantages of phosphoric acid fuel cells are that they:

- are tolerant of carbon dioxide (up to 30%). As a result, phosphoric acid fuel cells can use unscrubbed air as oxidant, and reformat as fuel.
- operate at low temperature, but at higher temperatures than other low-temperature fuel cells. Thus, they produce higher grade waste heat that can potentially be used in co-generation applications.
- have stable electrolyte characteristics with low volatility even at operating temperatures as high as 392 °F (200°C)

Key Points & Notes

A new form of acid fuel cell currently under development uses a solid acid electrolyte. These cells are made of compounds such as $CsHSO_4$ and operate at temperatures up to 480 °F (250 °C) with open circuit voltages of 1.11 V. These cells offer the advantages of operation without humidity, moderate carbon monoxide tolerance, and support auto-reforming of methanol. They suffer from disadvantages of sulfur degradation, high ductility at temperatures above 257 °F (125 °C), and water solubility. Practical manufacturing techniques have not yet been developed.

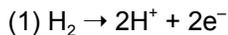
The disadvantages are that they:

- can tolerate only about 2% carbon monoxide
- can tolerate only about 50 ppm of total sulfur compounds
- use a corrosive liquid electrolyte at moderate temperatures, resulting in material corrosion problems
- have a liquid electrolyte, introducing liquid handling problems. The electrolyte slowly evaporates over time.
- allow product water to enter and dilute the electrolyte
- are large and heavy
- cannot auto-reform hydrocarbon fuels
- have to be warmed up before they are operated or be continuously maintained at their operating temperature

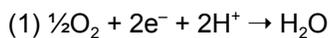
Reaction

Phosphoric acid fuel cells react hydrogen with oxygen.

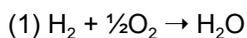
The reactions at the anode are:



The reaction at the cathode is:



The H^+ ion is drawn through the electrolyte from the anode to the cathode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit. Combining the anode and cathode reactions, the overall cell reaction is:



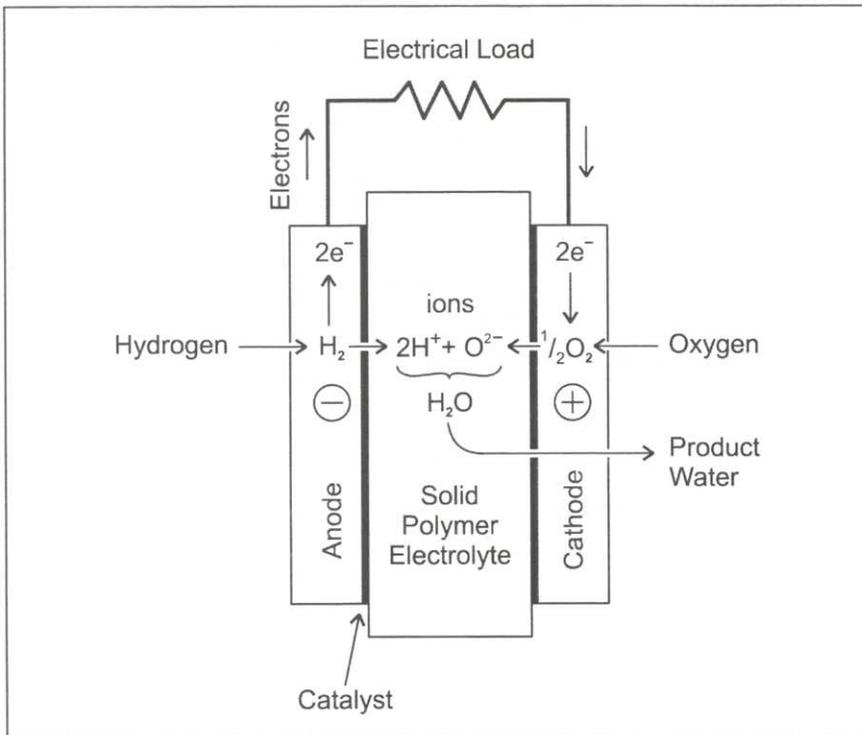
Thus, the fuel cell produces water that accumulates at the cathode. This product water must be continually removed to facilitate further reaction.

4.3.5 Proton Exchange Membrane (PEM) Fuel Cells

Proton exchange membrane (PEM) (or “solid polymer”) fuel cells use an electrolyte that conducts hydrogen ions (H^+) from the anode to the cathode. The electrolyte is composed of a solid polymer film that consists of a form of acidified Teflon.

PEM fuel cells typically operate at 160 to 195 °F (70 to 90 °C) and a pressure of 15 to 30 psig (1 to 2 barg). Each cell can produce up to about 1.1 VDC.

PEM fuel cells are currently the most promising types of fuel cell for automotive use and have been used in the majority of prototypes built to date. As a result, the remainder of this course will focus exclusively on PEM fuel cells.



Key Points & Notes

Figure 4-16 PEM Fuel Cell*Advantages and Disadvantages*

The advantages of PEM fuel cells are that they:

- are tolerant of carbon dioxide. As a result, PEM fuel cells can use unscrubbed air as oxidant, and reformat as fuel.
- operate at low temperatures. This simplifies materials issues, provides for quick startup and increases safety.
- use a solid, dry electrolyte. This eliminates liquid handling, electrolyte migration and electrolyte replenishment problems.
- use a non-corrosive electrolyte. Pure water operation minimizes corrosion problems and improves safety.
- have high voltage, current and power density
- operate at low pressure which increases safety
- have good tolerance to differential reactant gas pressures
- are compact and rugged
- have relatively simple mechanical design
- use stable materials of construction

The disadvantages are that they:

Key Points & Notes

- can tolerate only about 50 ppm carbon monoxide
- can tolerate only a few ppm of total sulfur compounds
- need reactant gas humidification

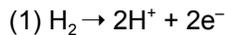
Humidification is energy intensive and increases the complexity of the system. The use of water to humidify the gases limits the operating temperature of the fuel cell to less than water's boiling point and therefore decreases the potential for co-generation applications.

- use an expensive platinum catalyst
- use an expensive membrane that is difficult to work with

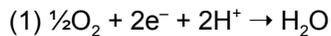
Reaction

PEM fuel cells react hydrogen with oxygen.

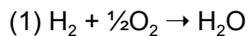
The reactions at the anode are:



The reaction at the cathode is:



The H^+ ion is drawn through the electrolyte from the anode to the cathode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit. Combining the anode and cathode reactions, the overall cell reaction is:

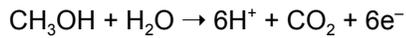


Thus, the fuel cell produces water that accumulates at the cathode. This product water must be continually removed to facilitate further reaction.

Direct Methanol PEM Fuel Cells

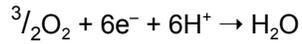
PEM fuel cells can also run using methanol fuel directly, rather than hydrogen. Although the energy released during this reaction is less than when using pure hydrogen, it results in a much simpler fuel storage system and circumvents the need to produce hydrogen.

In a direct methanol PEM fuel cell, the cells are supplied with a liquid mixture of methanol and water at the anode, and air at the cathode. At 266 °F (130 °C), a noble catalyst immediately decomposes the methanol according to the reaction:



Key Points & Notes

Oxygen, from the air, ionizes and reacts with the hydrogen to form water:



Combining the anode and cathode reactions, the overall cell reaction results in pure water and carbon dioxide. This technology is still in its infancy, but holds great promise for the future.

4.4 PEM Fuel Cell Stack Construction

Key Points & Notes

Individual fuel cells have an maximum output voltage on the order of 1 VDC. Substantial voltages and power outputs are obtained by connecting many cells electrically in series to form a fuel cell stack, much like a loaf of sliced bread. Different designs of fuel cell stacks use fuel cells of varying dimensions and in varying quantities.

Physically, each fuel cell consists of a membrane electrode assembly (MEA), which consists of the anode, cathode, electrolyte and catalyst, sandwiched between two flow field plates made of graphite. The plates channel the fuel and air to opposite sides of the MEA. The MEA and flow field plates are presented in greater detail in the next section.

Coolant is used to regulate the fuel cell reaction temperature. To facilitate this, cooling plates are placed between each fuel cell. These cooling plates channel the coolant past the fuel cells to absorb or supply heat as required. Seals between the graphite plates ensure that the oxidant, fuel and coolant streams never mix within the fuel cells.

Electrical endplates are placed at either end of the series of flow field plates. These endplates are connected to the terminals from which the output power is extracted, and typically include the fluid and gas interface connections. The entire sequence of plates is held together by a series of tie rods or other mechanical means.

Practical fuel cell design focuses on achieving a high power output per area of membrane, scaling the active membrane area to a useful size, and making the overall stack suitably compact for its intended use. Critical areas of concern are seals, flow field pattern tolerances and cell alignment. As with any commercial product, the resulting design must be reliable, manufacturable, economically viable and have a significant operating life.

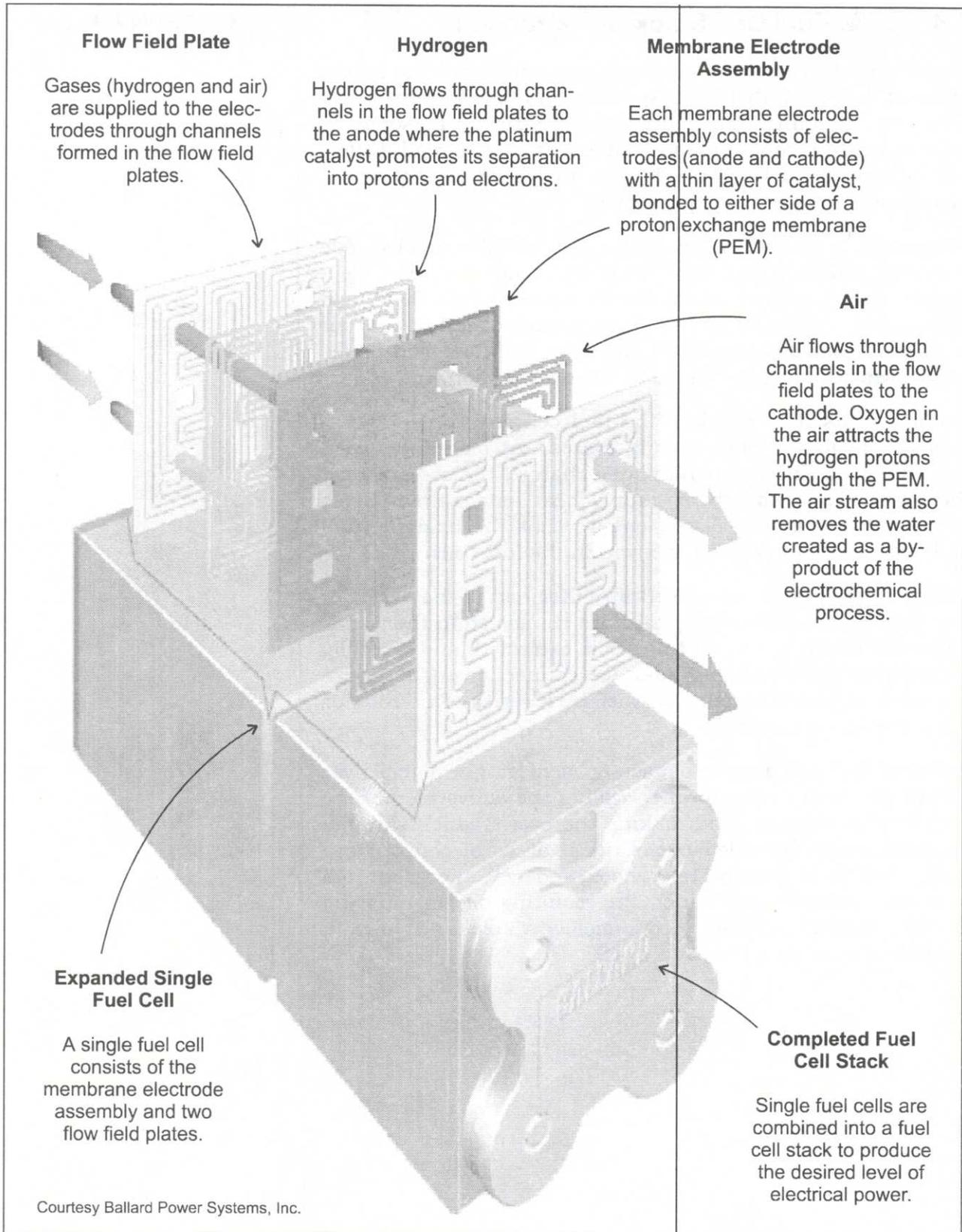


Figure 4-17 Basic PEM Fuel Cell Stack Arrangement

4.4.1 Membrane Electrode Assembly (MEA)

Key Points & Notes

The MEA is the heart of the fuel cell. The MEA consists of a solid polymer electrolyte membrane sandwiched between two porous carbon electrodes. A platinum catalyst is integrated between the membrane and the electrodes. The electrode assemblies often include integral seals where they contact adjacent components.

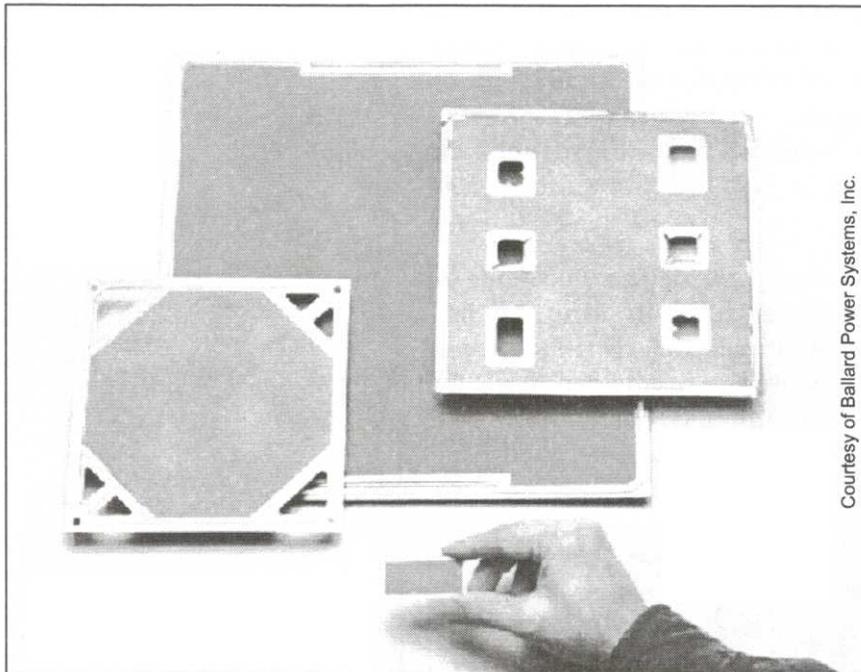


Figure 4-18 PEM Membrane Electrode Assemblies

Electrodes

The electrodes provide the interface between the reactant gases and electrolyte. As such they must allow wet gas permeation, provide a reaction surface where they contact the electrolyte, be conductive to the free electrons that flow from anode to cathode, and be constructed of compatible materials. Carbon fiber paper is typically used for this purpose since it is porous, hydrophobic (non-wettable), conductive and non-corrosive. The electrode material is very thin to maximize gas and water transport.

A catalyst is added to the surface of each electrode where it contacts the electrolyte in order to increase the rate at which the chemical reaction occurs. A catalyst promotes a chemical reaction by providing ready reaction sites but is not consumed in the process. Platinum is typically used for this purpose due to its high electro-catalytic activity, stability and electrical conductivity. Platinum is very expensive, so the amount used (known as the catalyst loading) is a signifi-

cant factor in the cost of a fuel cell. Fuel cell designers strive to minimize the amount of platinum used while maintaining good cell performance.

Key Points & Notes

Electrolyte

The solid polymer electrolyte is the ultimate distinguishing characteristic of a PEM fuel cell.

The electrolyte is a thin membrane of a plastic-like film that ranges in thickness from 50 to 175 $\text{\textcircled{m}}$ (microns). These membranes are composed of perfluorosulfonic acids, which are Teflon-like fluorocarbon polymers that have side chains ending in sulfonic acid groups ($-\text{SO}_3^{2-}$). Thus, PEM fuel cells ultimately use an acidic electrolyte just like phosphoric acid fuel cells.

All acidic solid polymer electrolytes require the presence of water molecules for hydrogen ion conductivity since hydrogen ions move together with water molecules during the ion exchange reaction. The ratio of water to hydrogen ions for effective conductivity is typically about 3:1. For this reason, the gases in contact with the membrane must be saturated with water for effective fuel cell operation.

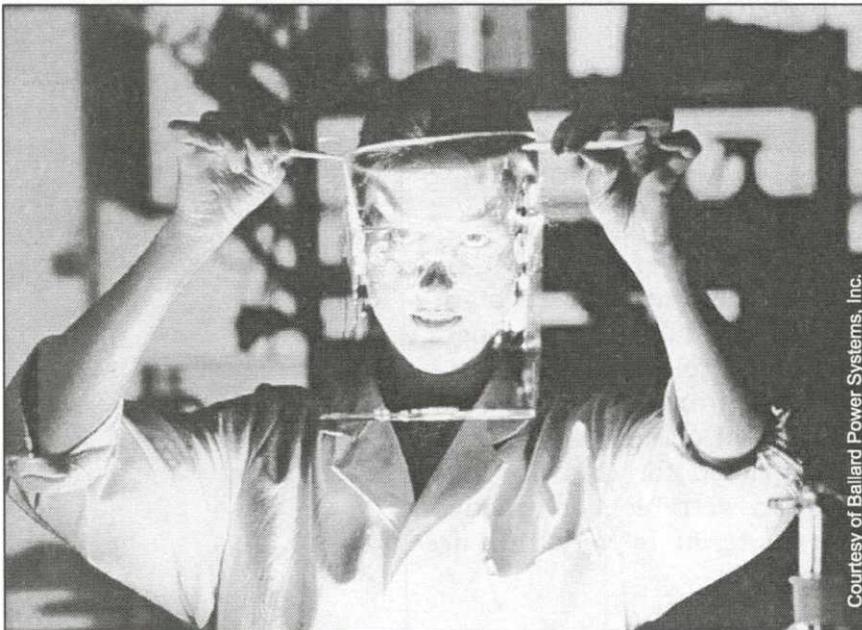


Figure 4-19 A Solid Electrolyte Membrane For Ballard's PEM Fuel Cells

At the molecular level, the polymer has a tubular structure in which the sulfonic acid groups are on the inner surface of the tubes. These groups provide the hydrophilic (readily wettable) conduits for conduction. The outer parts of the tubes are hydrophobic fluorinated material. The tubular structures

shrink and rearrange as the water content decreases. As these tubes contract during dehydration, the conductivity drops sharply resulting in higher contact resistance between the membrane and the electrode. This can lead to cracks or holes in the membrane.

A number of commercial membranes are available such as Nafion, produced by Dupont, and others by the Dow Chemical Company. In addition, fuel cell manufacturers like Ballard Power Systems have developed their own proprietary membranes.

All electrolytes must perform the fundamental functions of being a proton conductor, an electron insulator and a gas separator. In addition, manufacturers strive to produce membranes that have reasonable mechanical strength, dimensional stability (resistance to swelling), high ionic conductivity, low equivalent weight (the weight of polymer relative to the number of acid sites), and that are easily manufacturable. To some extent, mechanical and dimensional stability of the polymer is provided through its integration into a membrane electrode assembly which adds a supporting structure.

4.4.2 Flow Field Plates

The flow field plates channel fuel and oxidant to opposite sides of the MEA.

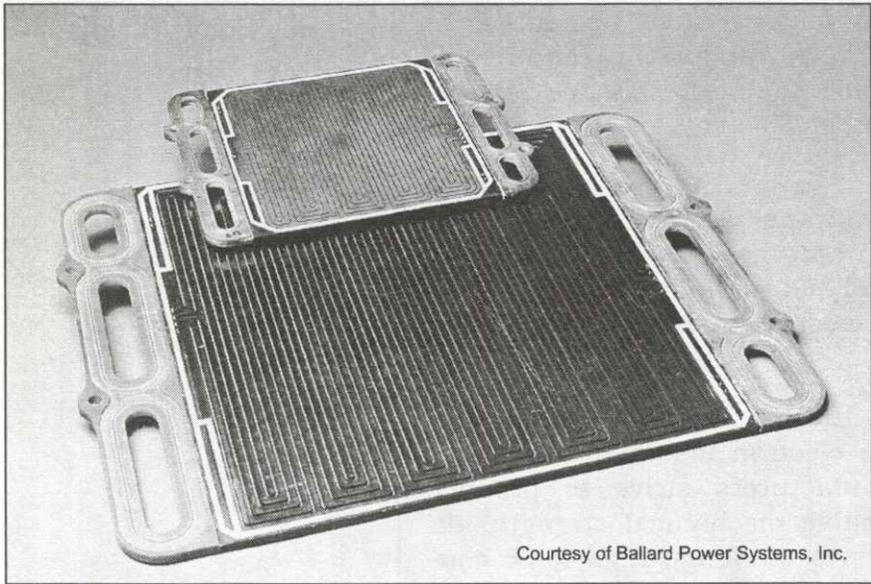
Each flow field plate contains a single gas channel of serpentine design that maximizes gas contact with the MEA. The specific shape of the gas channels is critical for uniform power generation, stable cell performance and correct product water management. Different flow field plate designs are tailored to various fuel cell applications.

Each plate must be electrically conductive so that the current released during the electrochemical reaction can flow from one cell to the next, and ultimately to the electrical endplates from which the stack power is drawn.

The plates are typically made of graphite into which the flow channels are either machined or pressed. Graphite is the preferred material due to its excellent conductivity, low contamination and relatively low cost.

Coolant plates, placed between each fuel cell, are of similar design and construction to the gas flow field plates. Coolant flow channels are designed for effective heat management.

Key Points & Notes

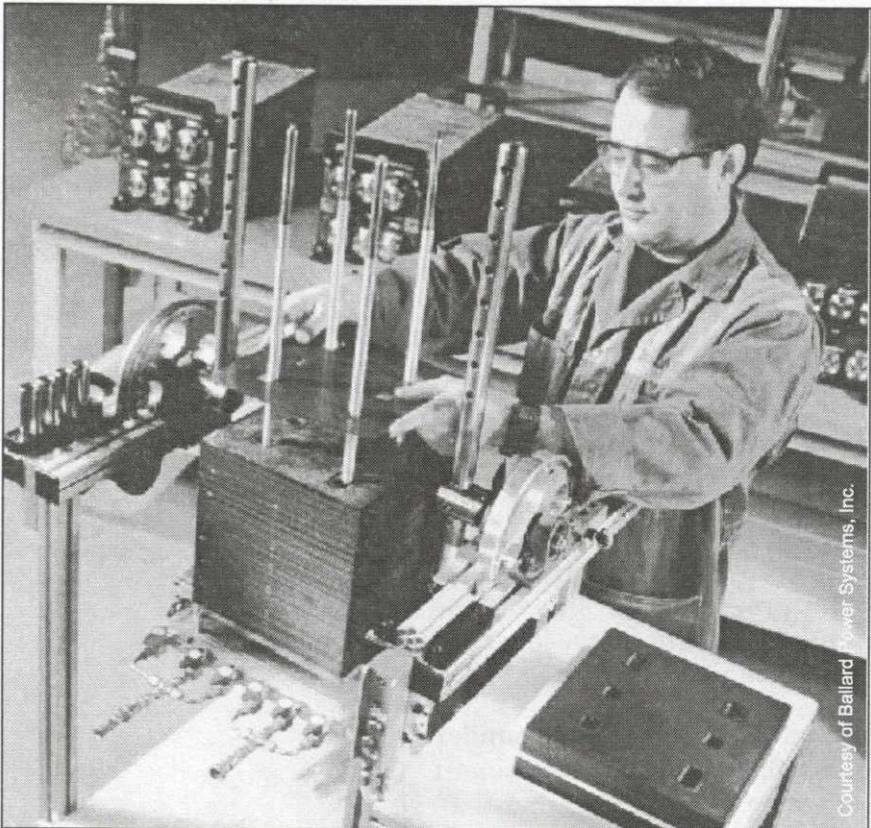


Courtesy of Ballard Power Systems, Inc.

Figure 4-20 PEM Flow Field Plates

Flow field and coolant plates incorporate gas and water ports used to distribute evenly the fuel, oxidant and coolant that enter and exit the stack. Seals between the graphite plates ensure that these flow streams do not mix.

Key Points & Notes



Courtesy of Ballard Power Systems, Inc.

Figure 4-21 Assembling a PEM Fuel Cell Stack

4.4.3 Humidifiers

Key Points & Notes

Humidification of the reactant gases is an important aspect of PEM fuel cell operation. Without adequate humidification, ion conduction cannot occur and fuel cell damage can result.

The amount of water that a gas can absorb is highly dependent on the humidification temperature — particularly at low pressure. Hotter gases can hold more water than colder gases.

Since the goal of humidification is to saturate the reactant gases with as much water as possible, the gases must be humidified at or near the fuel cell operating temperature (as set by the stack coolant temperature). If humidified at a lower temperature, the gas would no longer be saturated once it reached the operating temperature. If humidified at a higher temperature, some water would condense into the gas paths once it dropped to the operating temperature.

On some fuel cell stacks, humidifiers are integrated into the stack itself. On other fuel cell stacks, humidifiers are separate, external components.

Internal humidifiers consist of an additional series of graphite plates assembled into the fuel cell stack. This separates the stack into an active section, which contains the fuel cells, and an inactive section, which contains the humidifier plates. The humidification plates are similar to flow field plates and are used to channel gas and water to either side of a hydrophilic membrane. The water migrates across the membrane and saturates the adjacent gas. A variety of membranes are commercially available for this purpose.

Internal humidifiers draw water directly from the stack coolant stream and results in a simple, well integrated system with excellent temperature matching characteristics. However, this arrangement precludes the use of anything other than pure water as coolant. Pure water exacerbates cold weather starting problems as the cooling water would freeze. In addition, the combined stack/humidifier tends to be bulky and complicates service since both components must be repaired concurrently.

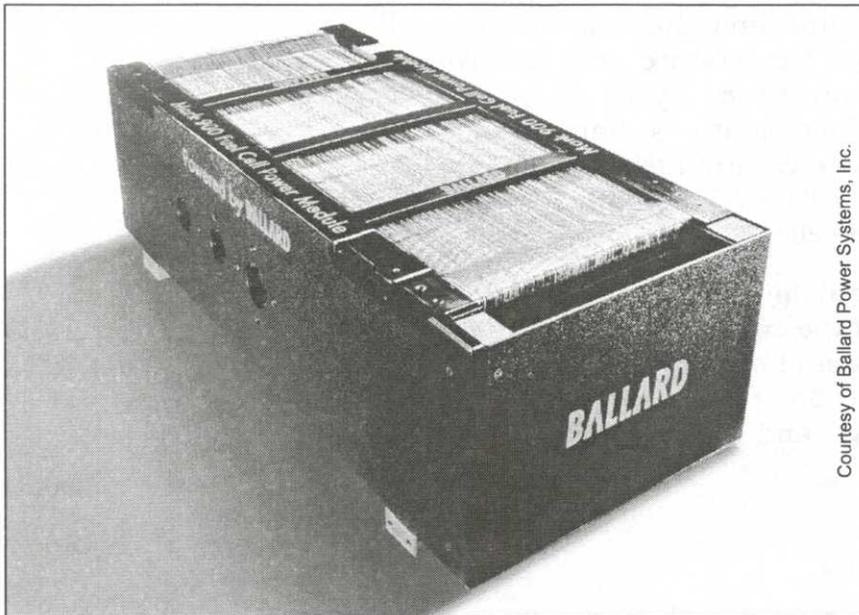
External humidifiers are most commonly of either a membrane or a contact design. Membrane humidifiers operate in the same fashion as internal humidifiers although they are packaged separately. Contact humidifiers operate by spraying humidification water onto a hot surface or into a chamber of high surface area through which one of the reactant

gases flows. The water then evaporates directly into the gas causing it to saturate.

Key Points & Notes

External humidifiers draw water either from the stack coolant stream or from a separate humidification water circuit. The advantages and disadvantages of drawing water from the coolant stream are the same as with an internal humidifier. When using a separate humidification water circuit, a stack coolant with superior low-temperature characteristics than water may be used, although the humidifier and stack temperature matching process becomes more complicated. Regardless of the water source, use of external humidifiers results in individual components that are less bulky and potentially more robust, especially on a contact design.

4.5 PEM Fuel Cell Performance



Ballard's Mk900 fuel cell stack generates 80 kW of power from a volume of only 61 L when run on pure hydrogen.

Figure 4-22 Ballard's State-of-the-Art Mk900 PEM Fuel Cell Module

Key Points & Notes

4.5.1 Efficiency

The efficiency of fuel cells is often touted as one of the primary benefits of the technology. Although this is true in principle, it is important to distinguish between *fuel cell stack* efficiency and *fuel cell system* efficiency.

Fuel Cell Stack Efficiency

Fuel cell stack efficiency is commonly taken to mean the actual efficiency of the electrochemical reaction. This efficiency can be derived as follows.

The amount of energy released when hydrogen and oxygen combine to form water according to the reaction $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$ is quantified as the "enthalpy of reaction" (ΔH°). This value is measured experimentally and depends on whether the water is formed as a gas or a liquid. For fuel cells, the water forms as a gas and the enthalpy of reaction is known to be:

$$\Delta H_{(\text{gas})}^\circ = -230 \frac{\text{BTU}}{\text{mole}_{\text{Water}}} = -242 \frac{\text{kJ}}{\text{mole}_{\text{Water}}}$$

Where:

$$\text{mole}_{\text{Water}} = 6.023 \times 10^{23} \text{ molecules of water}$$

The negative sign denotes that the energy is released during the reaction, and not absorbed.

This value of the enthalpy of reaction is only strictly correct at 77 °F (25 °C) and 1 atmosphere. The effect of temperature is more significant than pressure, and the amount of released energy decreases as the temperature goes up. This change in available energy only varies by a few percent within PEM fuel cell operating temperatures, but can be as much as 30% lower for high-temperature fuel cells. For this reason, high-temperature fuel cells are inherently less powerful than low-temperature fuel cells.

Unfortunately, not all of the enthalpy of reaction is available to do useful work. A portion of the enthalpy adds to the disorder of the universe in the form of entropy and is lost; the remainder is known as the "Gibbs free energy" (ΔG°). For gaseous water (at 77 °F/25 °C and 1 atmosphere) this is known to be:

$$\Delta G^\circ_{(gss)} = -217 \frac{\text{BTU}}{\text{mole}_{\text{Water}}} = -229 \frac{\text{kJ}}{\text{mole}_{\text{Water}}}$$

The voltage of each cell ($\mathcal{E}_{\text{Cell}}$) is related to the Gibbs free energy according to the equation:

$$\mathcal{E}_{\text{Cell}} = -\frac{\Delta G^\circ}{n \mathcal{F}}$$

Where:

n = Number of electrons involved in the reaction. This is most conveniently expressed as "mole of electrons" (or mole e^-) where each mole e^- is equal to 6.023×10^{23} electrons.

From the anode and cathode reactions ($\text{H}_2 \rightleftharpoons 2\text{H}^+ + 2e^-$ and $\frac{1}{2}\text{O}_2 + 2e^- + 2\text{H}^+ \rightleftharpoons \text{H}_2\text{O}$), two electrons are involved in the formation of each water molecule. Thus, $n = 2$ mole e^- for every 1 mole_{Water} formed.

\mathcal{F} = Faraday's constant, equal to 96,500 coulombs/mole e^- . Coulombs are a unit of electric charge.

Substituting values into the equation (using imperial units):

$$\begin{aligned} \mathcal{E}_{\text{Cell}} &= -\frac{-217 \text{ BTU}}{\text{mole}_{\text{Water}}} \times \frac{1055.7 \text{ J}}{\text{BTU}} \times \frac{\text{mole}_{\text{Water}}}{2 \text{ mole } e^-} \times \frac{\text{mole } e^-}{96,500 \text{ coul}} \\ &= \frac{1.187 \text{ J}}{\text{coul}} = 1.187 \text{ V} \end{aligned}$$

Key Points & Notes

The amount of hydrogen and oxygen consumed is directly related to the operating current:

- 0.43 in³ (7.0 cm³) of hydrogen are consumed per minute per ampere per cell
- 0.21 in³ (3.5 cm³) of oxygen are consumed per minute per ampere per cell

Actual gas flow rates may be higher depending on stoichiometry and dilution of the fuel and oxidant with non-reactive gases.

Similarly, using metric units:

$$\begin{aligned} \mathcal{E}_{\text{Cell}}^{\circ} &= -\frac{-229 \text{ kJ}}{\text{mole}_{\text{water}}} \times \frac{1000 \text{ J}}{\text{kJ}} \times \frac{\text{mole}_{\text{water}}}{2 \text{ mole } e^{-}} \times \frac{\text{mole } e^{-}}{96,500 \text{ coul}} \\ &= \frac{1.187 \text{ J}}{\text{coul}} = 1.187 \text{ V} \end{aligned}$$

Thus each cell can generate a maximum theoretical voltage of 1.187 V (at 77 °F/25 °C and 1 atmosphere). The fuel cell efficiency is therefore simply the proportion of the actual voltage the cell produces with respect to this theoretical maximum:

$$\text{Efficiency}_{\text{Cell}} = \frac{V_{\text{Actual}}}{\mathcal{E}_{\text{Cell}}^{\circ}} \approx \frac{V_{\text{Actual}}}{1.2 \text{ V}}$$

For a real fuel cell, typical voltages are between 0.5 and 0.6 V at normal operating loads and can reach 1.1 V at open circuit conditions. The electrochemical efficiency is therefore typically between approximately 40 and 50% with open circuit conditions reaching 90%.

Key Points & Notes

Fuel Cell System Efficiency

Fuel cell system efficiency relates to the overall performance of a fuel cell powerplant.

A fuel cell stack can only operate if provided with pressurized air and hydrogen and flushed with coolant. Practical fuel cell systems require additional equipment to regulate the gas and fluid streams, provide lubrication, operate auxiliary equipment, manage the electrical output and control the process. Some systems include reformers for fuel processing. All of this equipment introduces losses and reduces the total efficiency of the system from its theoretical ideal.

In order to make meaningful efficiency comparisons between fuel cell and other power generating systems, each powerplant must be defined in a similar way.

When comparing a fuel cell powerplant to an internal combustion engine for an automotive application, it is convenient to define each as a device that inputs fuel and air and delivers mechanical output power to a driveshaft. In either case, fuel is drawn from a tank in either gaseous or liquid form that has been stored after refining or other processing.

Both systems compress atmospheric air; the internal combustion engine uses piston action whereas the fuel cell powerplant uses an external compressor. The internal com-

bustion engine delivers mechanical power to the driveshaft directly while the fuel cell powerplant uses an inverter and electric motor. Both systems reject waste heat to the ambient surroundings using a coolant pump, radiator and other heat management equipment. Both systems supply equal auxiliary vehicle loads.

The overall efficiency of an internal combustion engine is often quoted as between 15 and 25%. These values are representative of the output efficiency at the *wheels* of a vehicle; efficiencies at the *output of the flywheel* are more typically between 30 to 35% and even higher for diesel engines.

For a fuel cell powerplant operating on pure hydrogen, the comparable efficiency breakdown at the *output of the flywheel* is roughly as follows:

Fuel cell efficiency:	40 to 50%
Air compression:	85% (uses 15% of gross power)
Inverter efficiency:	95%
Electric motor efficiency:	97%

Multiplying each of these values together yields an overall system efficiency of roughly 31 to 39%.

For a fuel cell system that operates using a reformer, these efficiencies are further reduced by 65 to 75% (depending on the type of reformer) for an overall system efficiency of roughly 20 to 29%.

More difficult to quantify is the effect of overall system weight. Fuel cell systems (including fuel storage) are heavier than internal combustion engine systems of comparable power and range, and therefore use more power on an ongoing basis.

Batteries have electrochemical efficiencies comparable to fuel cells. When used as an automotive powerplant, battery systems also require an inverter and electric motor, although they do not require air compression, complex cooling equipment or reformers. Batteries as a means of power storage are heavier than fuel cells although this is offset somewhat by the elimination of other components.

When stepping back further, the source of fuel becomes an essential component of the overall efficiency. With an internal combustion engine, this usually involves refining hydrocarbon fuels. With a fuel cell, this involves producing hydrogen from fossil fuels or through water electrolysis, or the production of secondary fuels such as methanol for use with

Key Points & Notes

an on-board reformer. With a battery system, this involves a source of electrical power for charging.

Analysis of these factors is complex and depends on the source fuel, processing method, handling and transportation difficulty, and other factors such as the energy required to compress or liquefy the final fuel. In the end, these factors reduce the overall fuel cost although this cost may not take into account the cost associated with long-term damage of the environment.

4.5.2 Polarization Characteristics

In an ideal world, the theoretical optimum fuel cell voltage of 1.2 V would be realized at all operating currents. In reality fuel cells achieve their highest output voltage at open circuit (no load) conditions and the voltage drops off with increasing current draw. This is known as polarization and is represented by a polarization curve as shown in Figure 4-23.

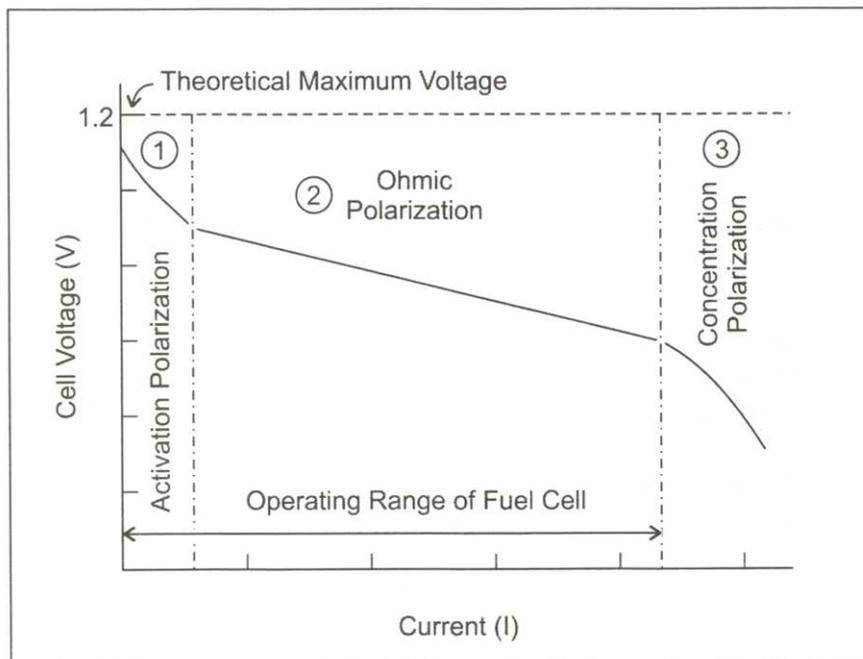


Figure 4-23 Typical PEM Fuel Cell Polarization Curve

The polarization curve characterizes the cell voltage as a function of current. The current, in turn, depends on the size of the electrical load placed across the fuel cell. In essence the polarization curve shows the electrochemical efficiency of the fuel cell at any operating current since the efficiency is the ratio of the actual cell voltage divided by the theoretical maximum of 1.2 V (see Section 4.5.1)

Fuel cell designers often use "current density" rather than current when characterizing fuel cell performance. Current density is calculated as the current divided by the active area of the fuel cell with units of A/cm². Current density indicates how effectively the MEA materials are being utilized; high current density indicated greater utilization than low current density.

Key Points & Notes

Batteries have polarization curves very much like fuel cells. Both batteries and fuel cells exhibit excellent partial load performance since the voltage increases as the load decreases. In contrast, internal combustion engines operate most efficiently at full load and exhibit a rapid decrease in efficiency at part load.

Key Points & Notes

Polarization is caused by chemical and physical factors associated with various elements of the fuel cell. These factors limit the reaction processes when current is flowing. There are three basic regions affecting the overall polarization:

- activation polarization
- ohmic polarization (or resistance polarization)
- concentration polarization

The deviation of cell potential from ideal behavior is a direct result of the sum of these factors over the entire load range.

Activation Polarization

Activation polarization is related to the energy barrier that must be overcome to initiate a chemical reaction between reactants. At low current draw, the electron transfer rate is slow and a portion of the electrode voltage is lost in order to compensate for the lack of electro-catalytic activity.

Ohmic Polarization

Ohmic polarization (or “resistance polarization”) occurs due to resistive losses in the cell. These resistive losses occur within the electrolyte (ionic), in the electrodes (electronic and ionic), and in the terminal connections in the cell (electronic). Since the stack plates and electrolyte obey Ohm’s law ($V=IR$), the amount of voltage lost in order to force conduction varies linearly throughout this region.

Concentration Polarization

Concentration polarization results when the electrode reactions are hindered by mass transfer effects. In this region, the reactants become consumed at greater rates than they can be supplied while the product accumulates at a greater rate than it can be removed. Ultimately these effects inhibit further reaction altogether and the cell voltage drops to zero.

4.5.3 Power Characteristics

Electrical power is the product of its voltage and current ($P=VI$). Since a fuel cell’s polarization curve indicates the relationship between voltage and current at all operating

conditions, it can be used to derive a corresponding power curve. At any point along the curve the instantaneous power is represented graphically as the rectangular area that just touches the curve. A typical power curve is shown in Figure 4-24.

Maximum power occurs at approximately 0.5 to 0.6 V, which corresponds to relatively high current. At the peak point, the internal resistance of the cell is equal to the electrical resistance of the external circuit. However, since efficiency drops with increasing voltage, there is a tradeoff between high power and high efficiency. Fuel cell system designers must select the desired operating range according to whether efficiency or power is paramount for the given application. It is never desirable to operate in the range beyond where the power curve drops off.

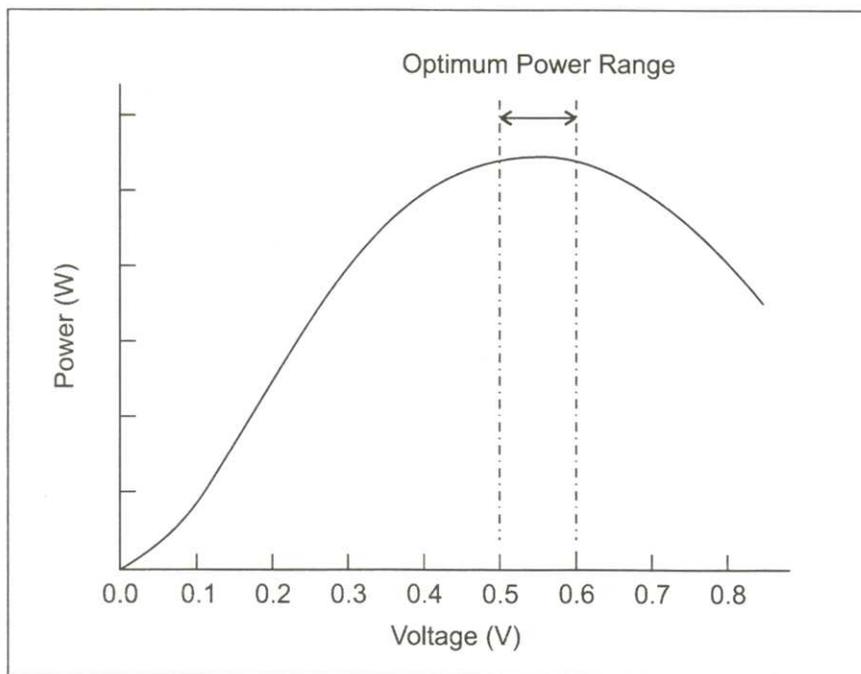


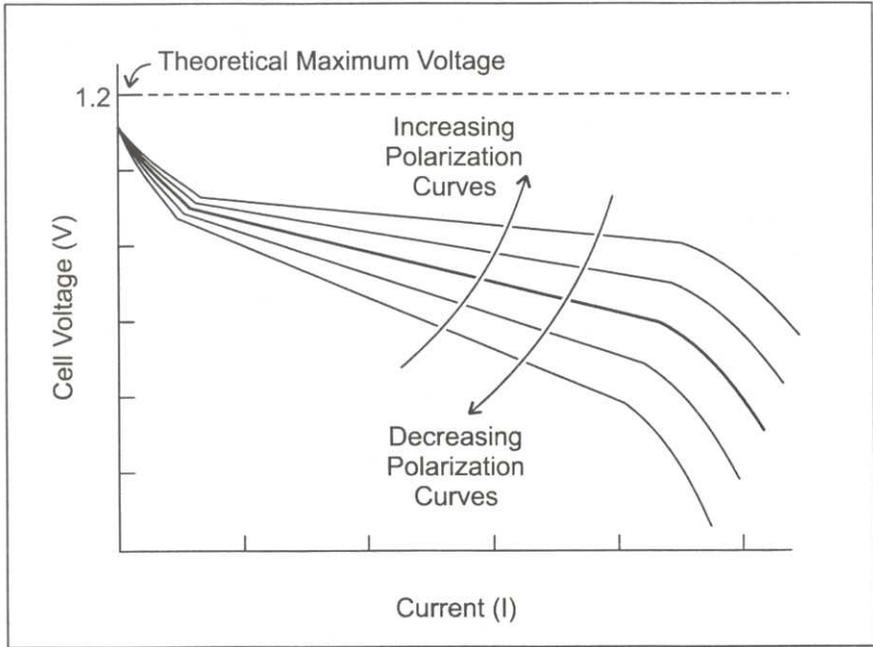
Figure 4-24 Typical PEM Fuel Cell Power Curve

4.5.4 Temperature and Pressure Effects

The shape of a polarization curve depends on the operating temperature and pressure of the stack. In general, a family of polarization curves can be drawn that characterize the stack performance over its entire operating envelope.

Key Points & Notes

Fuel cell designers assess the overall effectiveness of a fuel cell stack in terms of its volumetric power density. This is calculated as its maximum power divided by its physical volume with units of W/L. High power density indicates that much power is being drawn from a small unit. Power density for state-of-the-art PEM fuel cells exceeds 1350 W/L; a decade ago power density was on the order of 90 W/L.



Fuel cell polarization curves tend to drop as the fuel cells age.

Figure 4-25 Polarization Curve Variations

In general, any parameter variation that causes the polarization curve to go up is beneficial since this results in greater power and higher electrochemical efficiency. The converse is also true.

Pressure

Fuel cell polarization curves typically increase with increasing operating pressure. Conversely, the polarization curves decrease with decreasing operating pressure.

The reason for this is that the rate of the chemical reaction is proportional to the partial pressures of the hydrogen and the oxygen. (Each gas within a gas mixture contributes a partial pressure, the sum of which makes up the total pressure.) Thus, the effect of increased pressure is most prominent when using a dilute oxidant (like air) or a dilute fuel (like reformat). In essence, higher pressures help to force the hydrogen and oxygen into contact with the electrolyte. This sensitivity to pressure is greater at high currents.

Although an increase in pressure promotes the electrochemical reaction, it introduces other problems. Fuel cell stack flow field plates work better at low pressure since they exhibit smaller flow-induced pressure losses. Fuel cell seals operate under additional stress. Additional air compression is required, which absorbs more of the gross power. Other system components must be re-designed accordingly; some gases components must increase in size and cost.

Key Points & Notes

Use of a pure fuel (like hydrogen) or oxidant (like oxygen) increases stack polarization curves. This effect is essentially one of partial pressure: when no other gases are present, all of the available pressure helps force the hydrogen and oxygen into contact with the electrolyte and none is lost pressurizing other gases.

Ultimately, increases in pressure achieve diminishing returns when considering both stack efficiency and overall system consequences. Because of these factors, PEM fuel cells are typically operated at pressures no greater than a few atmospheres.

Temperature

Fuel cell polarization curves increase with increasing operating temperature. Conversely, the polarization curves decrease with decreasing operating temperature.

The reason for this is that higher temperatures improve mass transfer within the fuel cells and results in a net decrease in cell resistance (as the temperature increases, the electronic conduction in metals decreases but the ionic conduction in the electrolyte increases). Together, these effects improve the reaction rate.

The accumulation of product water within the oxidant stream effectively limits operating temperatures to below 212 °F (100 °C). At this temperature, the water boils and the resulting steam severely reduces the partial pressure of the oxygen. This, in turn, drastically reduces cell performance due to oxygen starvation. This can damage the fuel cells and reduce their life.

To some extent, higher temperatures can be achieved by operating at higher pressures since this increases the water boiling point accordingly. However, this effect is slight at the practical PEM fuel cell operating pressures.

The net effect is that fuel cell voltage increases with temperature until the temperature approaches the boiling point of water at which point the voltage begins to decline. The optimum temperature occurs near 175 °F (80 °C) where the two effects balance each other as shown in Figure 4-26. Typically operating temperatures are 158 to 194 °F (70 to 90 °C).

Key Points & Notes

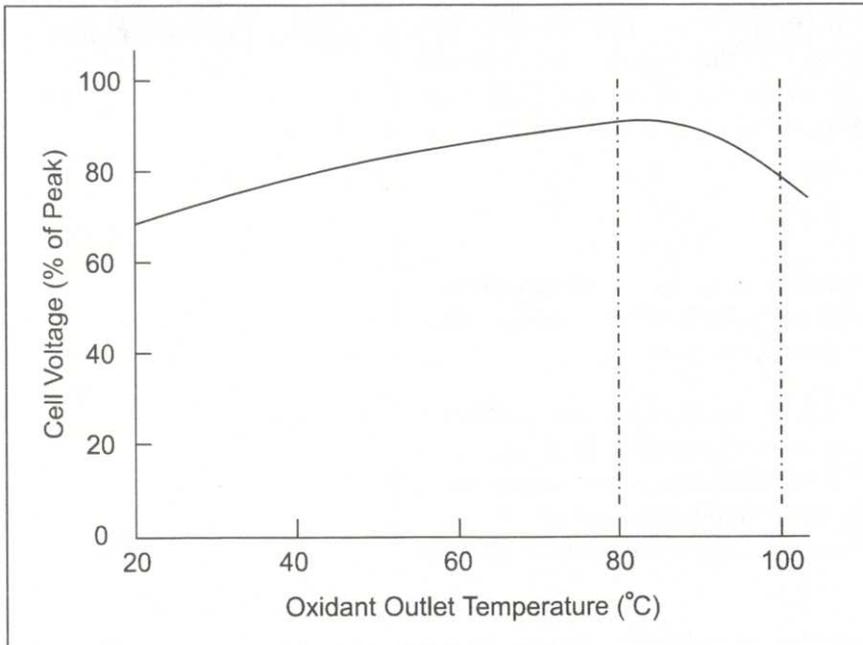


Figure 4-26 Effect of Temperature on Fuel Cell Voltage

As with high pressure operation, operation at elevated temperatures affects all system components, some of which must be re-designed accordingly.

4.5.5 Stoichiometry Effects

Fuel cell polarization curves increase with increasing reactant gas stoichiometry. Conversely, the polarization curves decrease with decreasing reactant gas stoichiometry.

The reason for this is that higher stoichiometry increases the chance that sufficient numbers of hydrogen and oxygen molecules interact with the electrolyte. Insufficient stoichiometry deprives (or “starves”) the fuel cell stack of sufficient reactants and may cause permanent damage.

Stoichiometry is the ratio of the amount of gas present relative to the amount of that gas that is needed to exactly complete the reaction. This is much like the definition of specific gravity where densities are indicated relative to a reference substance. Thus, a stoichiometric ratio of 1.0 provides exactly the correct number of gas molecules to theoretically complete the reaction. Stoichiometric ratios greater than 1.0 provide excess gas and ratios less than 1.0 provide insufficient gas. A stoichiometric ratio of 2.0 provides exactly twice the number of gas molecules as required.

As gas stream stoichiometric ratio increases, the resulting fuel cell voltage approaches its terminal voltage asymptotically as shown in Figure 4-27. Practical fuel cell stacks are

Key Points & Notes

The stoichiometric ratio provides a fundamental method of comparing the gas utilization of different energy conversion devices. For example, steam plants typically run at an air stoichiometric ratio of about 4.0 and diesel electric generators typically run at a ratio of about 7.0

typically operated at a hydrogen stoichiometric ratio of 1.4 and an air stoichiometric ratio of 2.0 at rated load; additional gas provides little additional benefit. Higher stoichiometric ratios are required when operating at low power.

Key Points & Notes

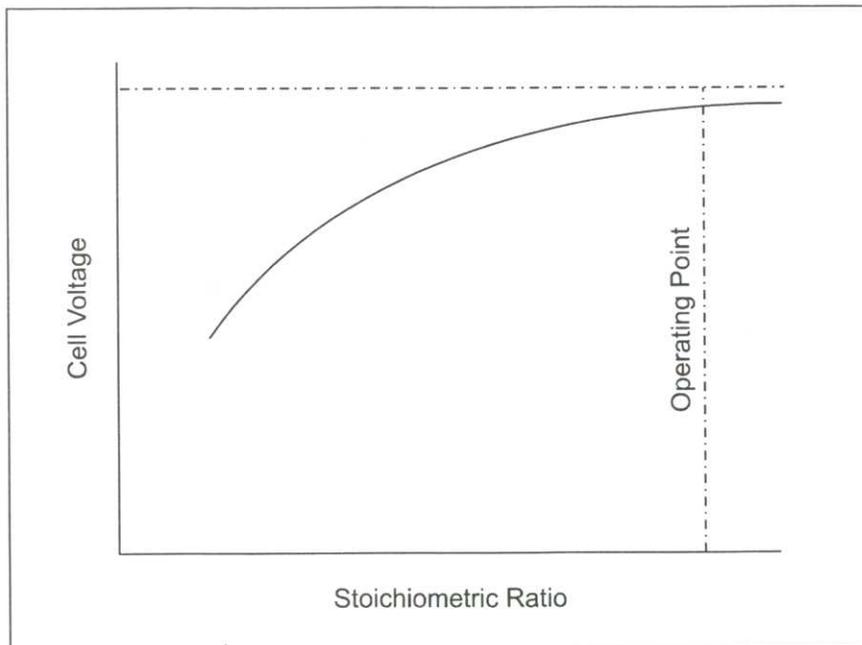


Figure 4-27 Effect of Stoichiometry on Fuel Cell Voltage

4.5.6 Humidity Effects

Sufficient gas stream humidification is essential to PEM fuel cell operation since water molecules move with the hydrogen ions during the ion exchange reaction.

Insufficient humidification water dehydrates the membrane and can lead to cracks or holes in the membrane. This results in a chemical short circuit, local gas mixing, hot spots, and the possibility of fire.

Conversely, excess humidification water leads to condensation and flooding within the flow field plates. This, in turn, can result in a phenomenon known as cell reversal where the affected cells produce a zero or negative voltage. If a large enough negative voltage occurs, the affected fuel cells start to act like an electrolyzer. This produces a lot of heat and can potentially destroy the cell. Cell monitoring systems are typically installed to detect cell reversal before cell damage occurs.

Humidity is typically measured as “relative humidity”; relative since it depends on the pressure and temperature of the gas. When a gas has absorbed as much water as it is physi-

cally able to at a given pressure and temperature, it is said to be saturated and has a relative humidity of 100%. If that saturated gas then becomes hotter (without the addition of more water), the relative humidity drops. (Every degree Celsius increase in temperature drops the relative humidity by approximately 4%.) If the gas cools, some of the water condenses and the gas remains saturated at the new temperature.

Fuel cells are typically operated at or near saturated conditions at the fuel cell operating temperature (as set by the stack coolant temperature). This provides the maximum amount of water possible while preventing flooding.

The use of water for humidification purposes effectively limits fuel operating and storage temperature to between 32 and 212 °F (0 and 100 °C). Outside of these limits, the water freezes and boils respectively.

A further consideration is that the humidifier water must remain non-conductive. Failure to do so causes short circuits and corrosion currents within the fuel cell stack. Water becomes conductive as it absorbs ions from its surroundings. To eliminate these ions, the water must continuously flow through a de-ionizing filter.

Key Points & Notes

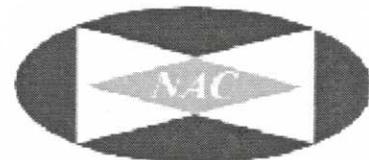
MODULE 5:

Fuel Cell Systems

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

5.1	INTRODUCTION	5-1
5.2	SYSTEM DESCRIPTIONS	5-2
5.2.1	AIR SYSTEM	5-2
5.2.2	FUEL STORAGE SYSTEM	5-4
5.2.3	FUEL DELIVERY SYSTEM	5-9
5.2.4	HUMIDIFICATION SYSTEM	5-11
5.2.5	STACK COOLING SYSTEM	5-12
5.2.6	BUS COOLING SYSTEM	5-14
5.2.7	HVAC SYSTEM	5-17
5.2.8	LUBRICATION SYSTEM	5-18
5.2.9	HYDRAULIC SYSTEM	5-19
5.2.10	ELECTRICAL SYSTEM	5-20
5.2.11	CONTROL SYSTEM	5-23
5.2.12	LEAK DETECTION SYSTEM	5-24
5.2.13	FIRE SUPPRESSION SYSTEM	5-27

OBJECTIVES

At the completion of this module, the technician will understand:

- the systems required to operate a fuel cell engine
- the components and functionality of each fuel cell system

5.1 Introduction

Key Points & Notes

A fuel cell stack requires fuel, oxidant and coolant in order to operate. The composition, pressure and flow rate of each of these streams must be regulated. In addition, the gases must be humidified and the coolant temperature must be controlled. To achieve this, the fuel cell stack must be surrounded by a fuel system, fuel delivery system, air system, stack cooling system and humidification system.

Once operating, the output power generated by the fuel cells must be conditioned and absorbed by a load. Suitable alarms must shut down the process if unsafe operating conditions occur and a cell voltage monitoring system must monitor fuel cell stack performance. These functions are performed by electrical and control systems.

When a fuel cell powerplant is installed in a transit bus, it must interface with the power train, steering circuit, bus cooling system and HVAC system. The power train includes the drive motor, transmission and ancillary components. The steering circuit uses pressurized hydraulic oil to operate the steering mechanism. The bus cooling system removes heat from standard bus and fuel cell components, supplies heat to the HVAC system, and rejects waste heat to the environment. The HVAC system provides coach heat and air conditioning. This equipment requires subsidiary lubrication and hydraulic systems in order to operate.

In addition, the presence of hydrogen on-board a bus requires additional equipment to ensure passenger safety. This takes the form of a leak detection system to detect escaped hydrogen and a fire suppression system to detect and extinguish fires.

5.2 System Descriptions

Key Points & Notes

The following system descriptions pertain to a bus application using pure hydrogen stored as a high pressure gas. These descriptions are based on the Phase 3 and 4 fuel cell buses designed and built by XCELLSiS Fuel Cell Engines, Inc. This information represents the most complete description currently available, although it cannot cover all hardware configurations and variations.

These system descriptions indicate the basic functionality of each system, the type of components required, and their interrelationships. Specific fuel cell buses differ from these descriptions in a variety of details depending on the state of the art at the time of manufacture, constraints imposed by the specific bus chassis, and the level of component integration.

For the purpose of clarity, transducers, switches and other incidental components are not included in the descriptions.

5.2.1 Air System

The air system supplies regulated air to the fuel cells to feed the power generation reaction.

Ambient air enters the air system and passes through a particulate filter to remove debris from the air and a silencer to muffle the downstream compressor noise.

The air is compressed in two stages using an air compressor and a turbocharger. The speed of the air compressor both increases the air pressure and sets the air flow rate. The turbocharger further increases the pressure by recovering energy from the exhaust air stream. Under normal operating conditions, the air pressure entering the fuel cell stacks is nominally 30 psig (2 barg).

Air pressurization greatly increases the temperature of the air stream and may introduce oil particles (a fuel cell poison) from the interaction of the lubrication system with the compressors. To prevent damage to the fuel cells, the hot air stream passes through an intercooler after the air compressor to cool it to the fuel cell operating temperature. The heat is transferred to the bus cooling system.

The cooled air destined for the fuel cell stacks flows through an inlet filter to remove any oil contaminants and a mass flow meter to measure the actual air flow. The air stream then passes through a humidifier, where it is saturated with

water at the stack operating temperature, and enters the fuel cell stacks where it feeds the power generation reaction.

The depleted hot air that exits the fuel cell stacks contains water as a product of the power generation reaction and from humidification. This water is primarily in the vapor state and is largely recovered by passing the air through a condenser and a coalescing air/water separator. The condenser transfers heat to the bus cooling system. Both the condenser and separator pass recovered water to the humidification water tank. Some air flows into the header tank along with the water; this provides positive ventilation of the tank while maintaining a pressure balance between the air and water systems.

Downstream of the water separator, the air turns the turbo-charger turbine, passes through a second silencer, and vents to the atmosphere.

Key Points & Notes

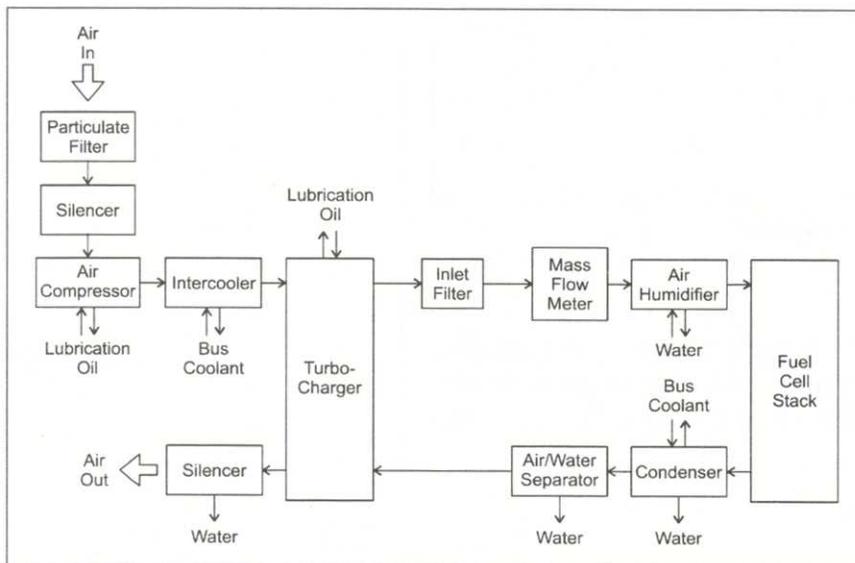


Figure 5-1 Air System Flow Diagram

5.2.2 Fuel Storage System

Key Points & Notes

The fuel storage system receives, stores and dispenses the hydrogen fuel. The fuel storage system consists of a fueling circuit, the storage cylinders, a high pressure circuit and a motive pressure circuit.

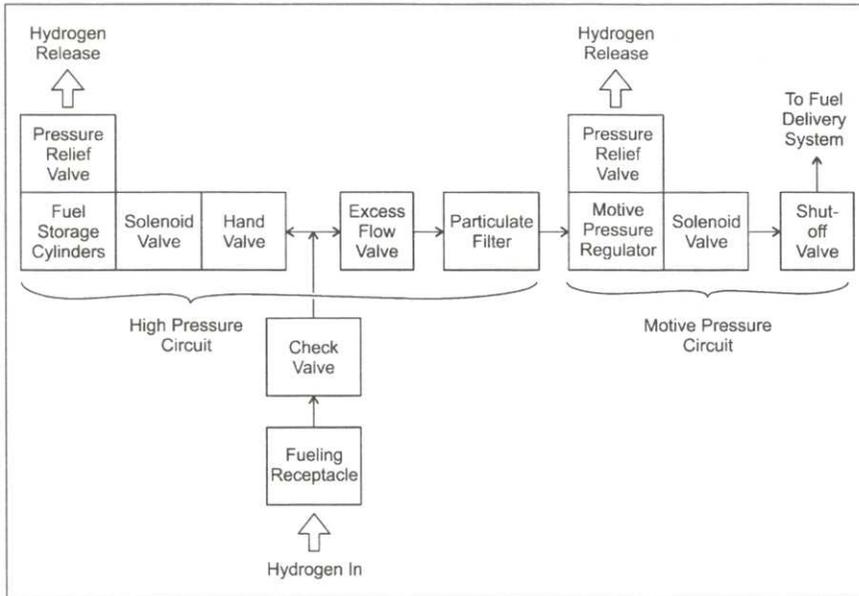


Figure 5-2 Fuel Storage System Flow Diagram

Fueling Circuit

The fueling circuit receives fuel through a fueling receptacle. The fuel then flows through a check valve to prevent back-flow, and into the high pressure circuit which in turn fills the hydrogen storage cylinders.

Hydrogen Storage Cylinders

Key Points & Notes

The hydrogen storage cylinders store the hydrogen fuel as a high pressure gas for consumption by the engine.

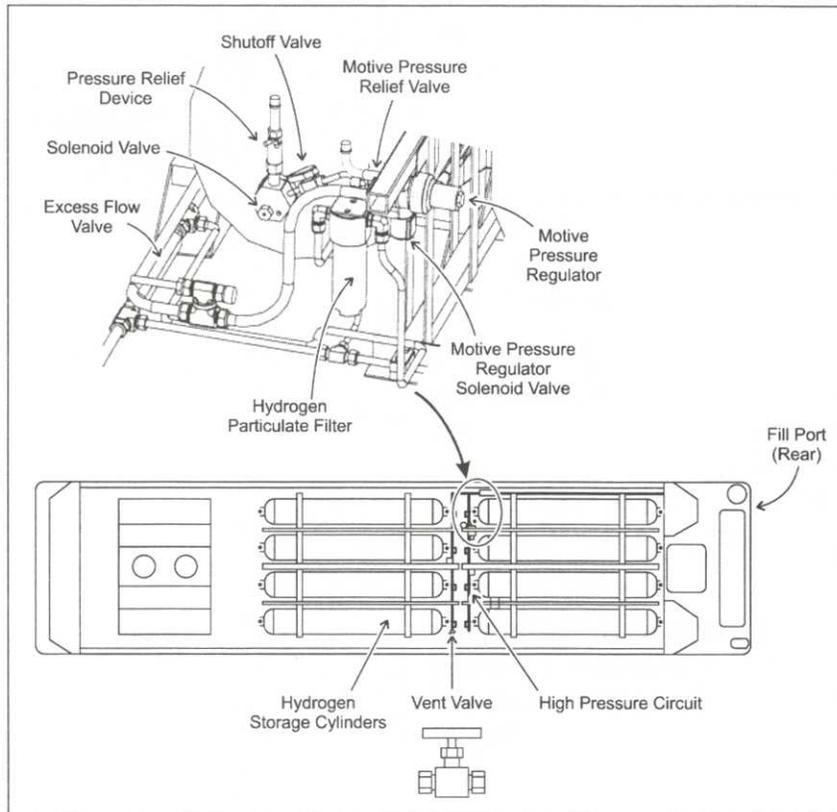


Figure 5-3 Typical Fuel Storage System Layout

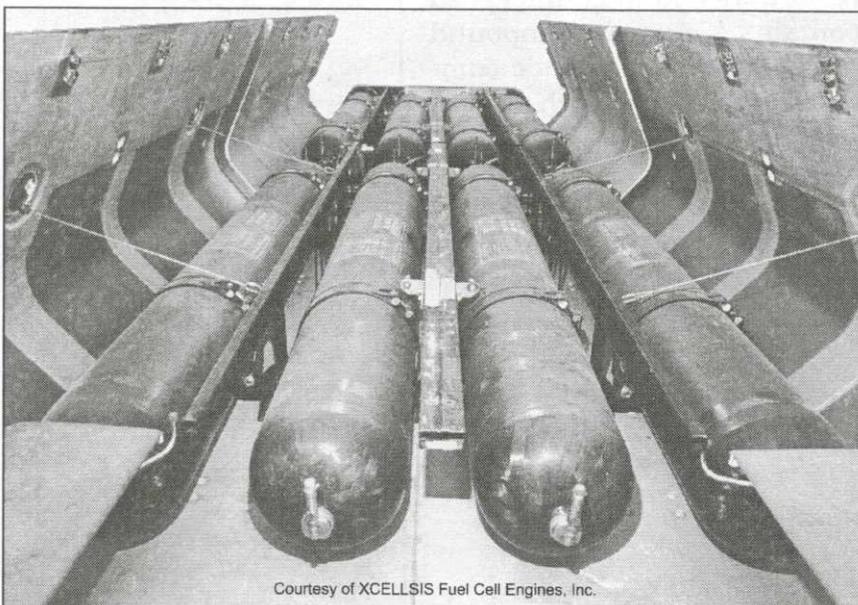


Figure 5-4 Hydrogen Storage Cylinders

The end boss through which the fuel flows into and out of each cylinder includes an integral solenoid valve, check valve, excess flow valve and shutoff valve assembly (or “manual lockdown assembly”).

The solenoid valve automatically closes and isolates the cylinder whenever the bus is off. The check valve permits fueling while the solenoid valve is closed.

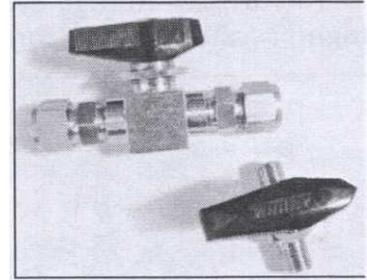
The excess flow valve interrupts the fuel flow out of the cylinder whenever the flow rate is excessive (such as if a pipe bursts or during vigorous venting). When closed, the excess flow valve permits a small amount of leakage so that the outlet and cylinder pressures equalize over a period of time, thereby restoring normal valve function.

The manual lockdown assembly can be used to isolate the cylinder contents, but is normally left fully open. In the event that a solenoid valve fails closed, the manual lockdown assembly can be removed and replaced with a venting tool that forces the solenoid valve open in order to discharge the cylinder contents.

An external hand valve is typically installed in the inlet pipe associated with each cylinder. This valve provides an additional level of safety (in addition to the integral solenoid valve) and is a convenient method of isolating individual cylinders during fueling or venting.

Pressure relief devices are attached to the end bosses at both ends of each cylinder and protect against explosion in the event of a fire. Each pressure relief device is in contact with the internal gas pressure and contains a eutectic compound that acts as a plug. When exposed to fire, the eutectic compound melts and the internal gas escapes through a vent line that passes through the roof canopy.

Key Points & Notes



Hand Valves

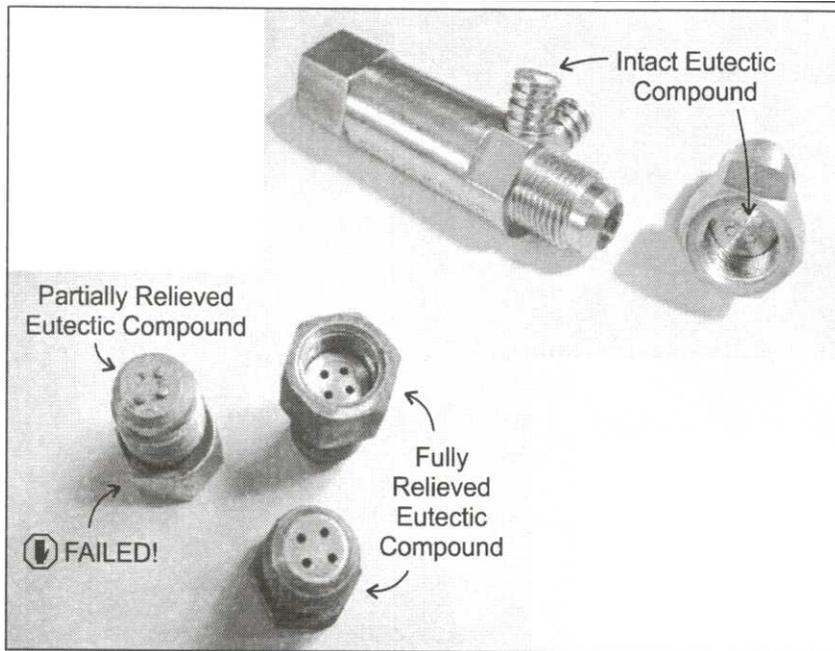


Figure 5-5 Pressure Relief Devices

Key Points & Notes

High Pressure Circuit

The high pressure circuit consists of a common manifold that links the hydrogen storage cylinders with both the fueling circuit and the motive pressure circuit.

During operation, high pressure hydrogen passes from the cylinders into the high pressure circuit where it flows through an excess flow valve to the motive pressure regulator assembly. The excess flow valve closes if excessive flow occurs, providing redundancy to the excess flow valves integrated into each cylinder end boss.

The high pressure circuit includes a hand-operated vent valve, mounted on the common manifold, used when venting and purging the high pressure circuit during maintenance.

Motive Pressure Circuit

The motive pressure circuit supplies intermediate pressure hydrogen to the fuel delivery system.

The motive pressure circuit consists of a pressure regulator assembly, a filter, and a fuel shutoff valve the fuel delivery tube to the engine. The pressure regulator assembly is an integral unit that includes a pressure regulator, a solenoid valve and a pressure relief valve.

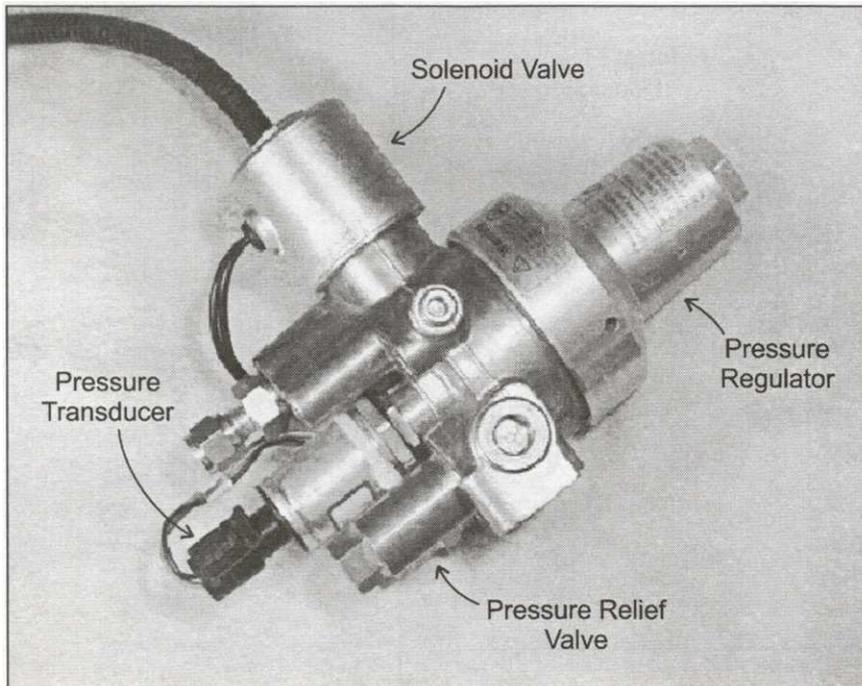


Figure 5-6 Motive Pressure Regulator Assembly

Key Points & Notes

The pressure regulator reduces the hydrogen pressure from its storage pressure to the intermediate (or “motive”) pressure of approximately 175 psig (12 barg). This type of pressure regulator is the same as that used on a CNG bus, where the CNG is supplied at intermediate pressure to the internal combustion engine.

The solenoid valve automatically closes and isolates the high pressure circuit (entering the pressure regulator) whenever the bus is off. This valve operates in tandem with the individual solenoid valves mounted within the end boss of each hydrogen storage cylinder.

The pressure relief valve protects the fuel cell engine and releases hydrogen through a roof vent if the motive pressure exceeds 250 psig (17 barg). This pressure relief valve is of spring-loaded design and remains closed until the pressure in the circuit exceeds the pressure setpoint by a small amount. Once exceeded, the force causes the spring to open and bleed off the excess hydrogen. The spring stays open until the pressure is reduced below the setpoint.

The filter removes particulate debris and liquid from the fuel.

The fuel shutoff valve provides a manual method for interrupting the flow of fuel to the fuel cell engine. This valve is meant for emergency use only, since interrupting the fuel flow to a fuel cell engine while it is operating can cause fuel cell damage. As an alternative, some fuel cell buses include a

fuel shutoff valve that is electrical rather than mechanical in nature. When actuated, this valve immediately shuts down the engine in a controlled manner and closes the cylinder and pressure regulator assembly solenoid valves.

Key Points & Notes

5.2.3 Fuel Delivery System

The fuel delivery system regulates the hydrogen that passes through the fuel cell stacks. The system consists of a fuel delivery circuit and a purge circuit.

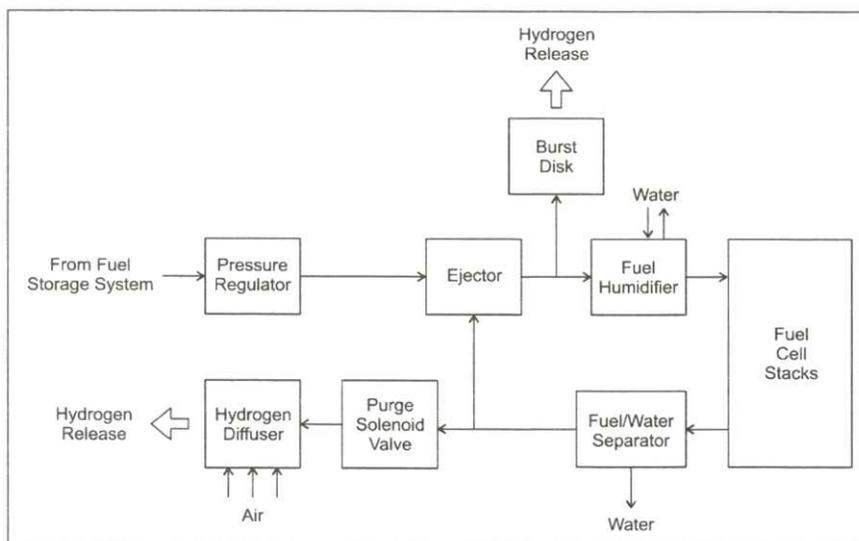


Figure 5-7 Fuel Delivery System Flow Diagram

Fuel Delivery Circuit

The fuel delivery circuit receives intermediate pressure hydrogen from the motive pressure circuit. A pressure regulator at the inlet to the fuel delivery circuit controls the fuel pressure entering the stack module. This regulator receives its feedback signal from the hydrogen inlet to the fuel cell stacks.

The low pressure hydrogen circulates through the fuel cell stacks using an ejector. New hydrogen enters the ejector where it mixes with and drives the recirculating flow by way of suction. A portion of the hydrogen is consumed by the power generation reaction, and the excess is recirculated.

The excess hydrogen contains water from humidification of the fuel stream. This water is in both vapor and liquid states since some of the vapor super-saturates and condenses as the hydrogen is consumed. This water is recovered by a water separator and is either drained through a water trap to the road, or collected for use in the humidification system.

A burst disk protects the fuel delivery circuit and releases hydrogen through a roof vent if the pressure exceeds 46 psig (3.2 barg). The burst disk contains a rupture disk that consists of a membrane of predetermined thickness. The membrane is often scored. The thickness, and scoring, is designed to withstand a certain pressure. At pressures greater than the design pressure, the disk bursts releasing the gas. Ring Rupture disks do not reset and must be replaced once burst. Rupture disks tend to fatigue under normal pressure fluctuations and are therefore prone to premature failure. Rupture point and lifetime are also affected by temperature.

Purge Circuit

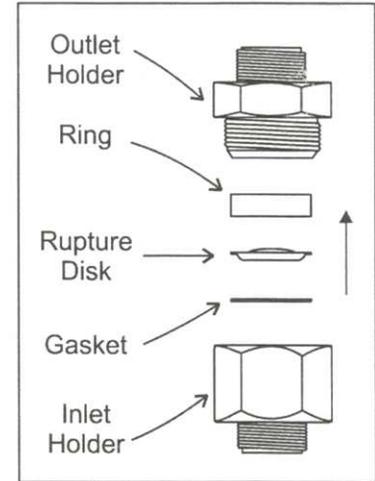
The purge circuit is linked to the fuel delivery circuit and permits periodic fuel discharge to atmosphere. This occurs periodically and automatically in order to drive out any accumulated water or residual non-fuel gases.

A solenoid valve controls the gas discharge. This solenoid valve remains open whenever the engine is shut down and allows the motive and low pressure hydrogen circuits to vent when not in use. This prevents a vacuum from building up within the fuel delivery circuit since any residual hydrogen would slowly react within the fuel cell stacks while the engine is off.

The escaping gas is expelled through a roof-mounted hydrogen diffuser. Residual water is either drained through a water trap to the road, or collected for use in the humidification system.

The diffuser consists of a pair of tubes that pass in front of a ducted fan. One tube carries the purged hydrogen and has a series of holes that release the hydrogen into the forced air stream. The second tube carries coolant (from the bus cooling system) which warms the discharge tube to prevent ice formation. The fan dilutes the hydrogen with sufficient air so that it is non-flammable.

Key Points & Notes



Burst Disk

5.2.4 Humidification System

Key Points & Notes

The humidification system saturates the hydrogen and air with water prior to their use in the fuel cells, and manages the product water that results from the fuel cell reaction.

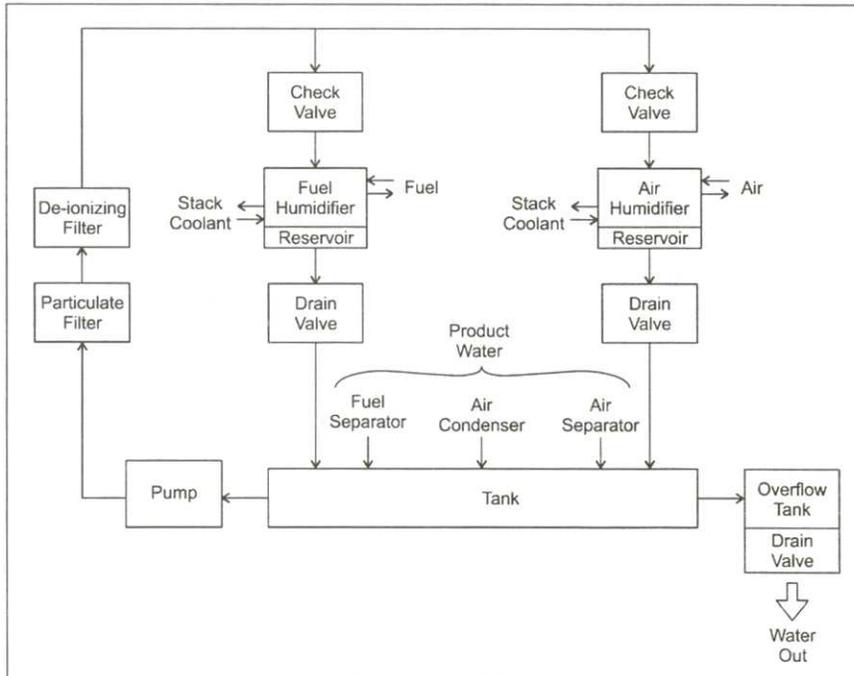


Figure 5-8 Humidification System Flow Diagram

Humidification

Some fuel cell powerplants combine the humidification system with the stack cooling system. This results in a simple, well integrated system with excellent temperature matching characteristics. However, this arrangement precludes the use of anything other than pure water as stack coolant, which exacerbates cold weather starting problems (since the cooling water freezes).

The humidification system consists of a single circuit that draws humidification water from a product water tank, using a pump, and passes the water through a particulate filter and a de-ionizing filter. The particulate filter removes particulate debris from the water. The de-ionizing filter contains a mixed-bed resin to remove anions and cations.

Ions cause fluid conductivity and accumulate during normal operation. Conductivity within any fluid stream that passes through the fuel cell stacks can cause short circuits within the fuel cells. This results in corrosion currents that lower performance and can cause fuel cell damage.

The water leaving the de-ionizing filter splits into two streams; one stream is used for fuel humidification and the other for air humidification. Each stream flows through a check valve and into a humidifier. Some of the water passes into the gas stream and the remainder collects in a reservoir within the humidifier. This excess water passes through a drain valve back into the product water tank.

Source heat for the humidifiers is drawn from the stack coolant. This ensures that both the fuel cells and the humidifier operate at the same temperature so that the maximum amount of water vapor can be carried into the fuel cells. This heat can be used directly, by using the same water in both the stack cooling and humidification circuits, or indirectly by transferring the heat from the stack coolant to the humidification water using a heat exchanger.

5.2.5 Stack Cooling System

The stack cooling system regulates the fuel cell reaction temperature, provides source heat to humidify the reactant gases, serves as a heat sink for an electrical resistor and provides source heat for the HVAC system.

The stack cooling system consists of a main coolant loop and a bypass filtration loop.

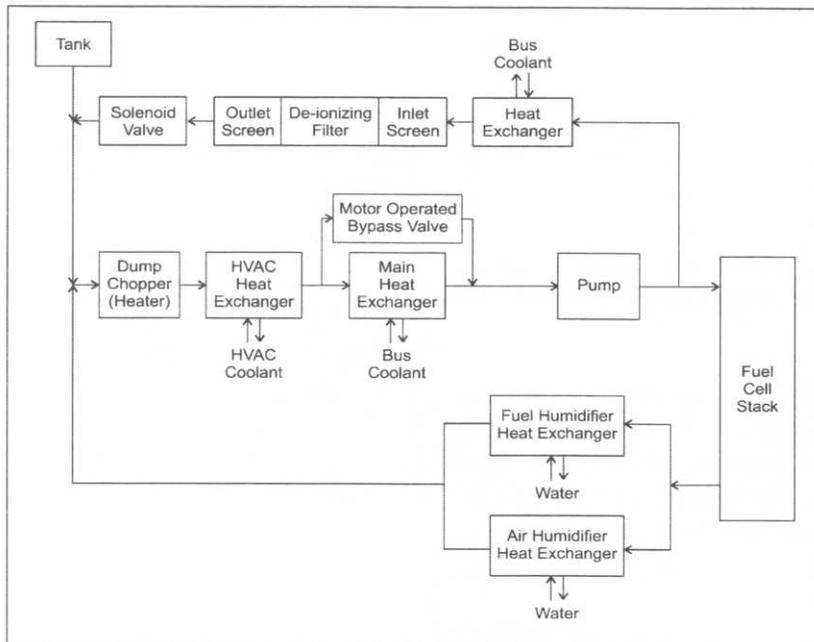


Figure 5-9 Stack Cooling System Flow Diagram

Main Coolant Loop

The main coolant loop circulates the stack coolant through the fuel cell stacks where it absorbs heat and maintains the fuel cells at their optimum operating temperature. As the coolant leaves the stacks, it flows through the air and hydrogen humidifiers where it supplies the heat required to vaporize the humidification water. The coolant then enters the dump chopper.

The dump chopper consists of a chamber through which the stack coolant flows and into which is suspended a resistor. The resistor transfers heat to the stack cooling system both during initial startup, to quickly raise the coolant and thereby the fuel cells to their operating temperature, and whenever the bus is off, to deplete residual reactants from the fuel cell stacks.

Coolant leaving the dump chopper passes through a heat exchanger that transfers heat to the heating/air conditioning circuit as required.

A motor operated control valve then splits the coolant flow into two streams. One stream passes through the main heat exchanger (which transfers heat to the bus cooling system) and the second stream bypasses it. The two streams re-mix after the heat exchanger with a resulting final temperature that depends on the relative flow within each path.

Coolant leaving the main heat exchanger enters a pump and passes back into the fuel cell stacks.

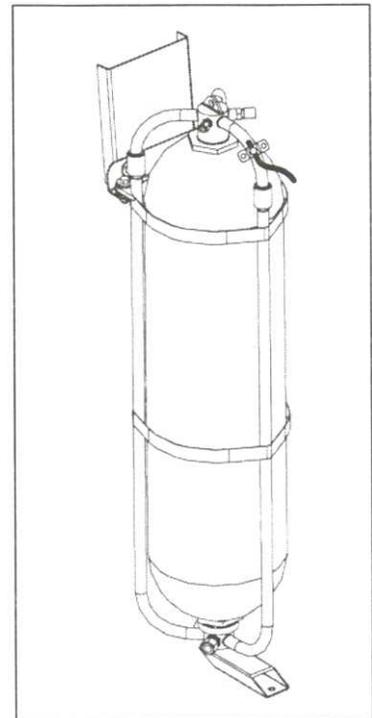
Additional coolant is fed into the main coolant loop from a header tank as required.

Bypass Filtration Loop

As with the humidification water, the stack coolant must be non-conductive in order to prevent internal short circuits as it passes through the fuel cells. The stack coolant can therefore be either pure de-ionized water, or a mixture of 50% pure de-ionized water with 50% pure ethylene glycol (the glycol must be free of additives that could damage the fuel cells).

When pure water is used, the stack cooling system can be merged with the humidification system reducing overall complexity (since the stack cooling water can be used directly to humidify the reactant gases). However, the use of water complicates cold weather operation since it freezes at 32 °F (0 °C). Conversely, using a water/glycol mixture im-

Key Points & Notes



De-Ionizing Filter

proves cold weather performance but necessitates the use of a separate humidification system.

Key Points & Notes

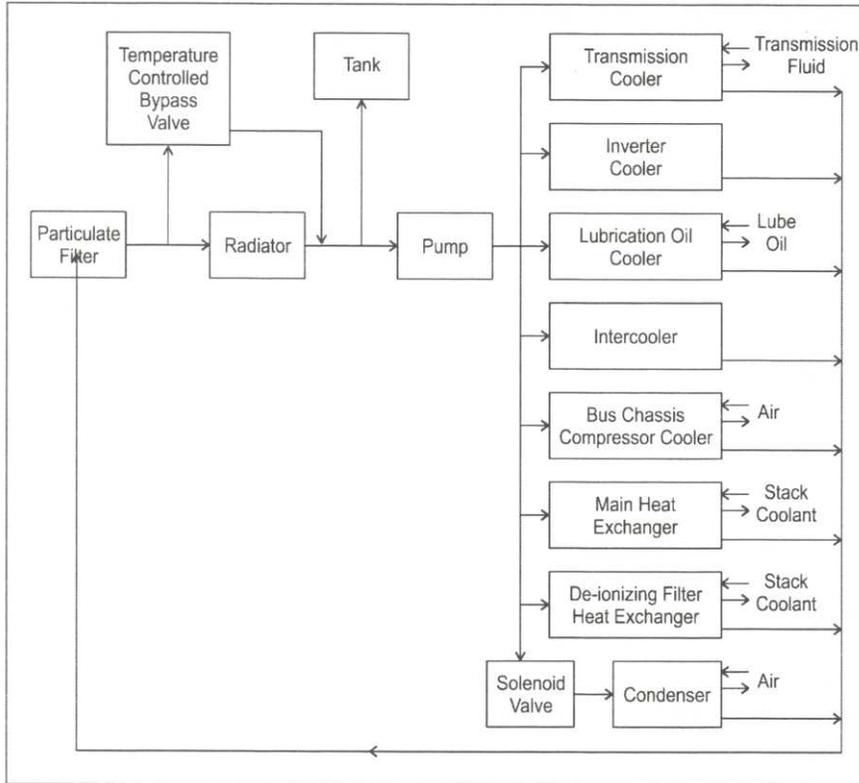
Regardless of the coolant composition, it must remain non-conductive just like the humidification water. This is accomplished by diverting a portion of the stack coolant flow through a bypass filtration loop that includes a de-ionizing filter.

Coolant for the bypass filtration loop is drawn from the main coolant loop at the pump outlet. The coolant passes in succession through a heat exchanger, a strainer, the de-ionizing filter, a second strainer and a solenoid valve before re-joining the main coolant loop at the inlet to the dump chopper.

The de-ionizing filter contains a mixed-bed resin to remove anions and cations. The heat exchanger reduces the filtration coolant temperature in order to protect the de-ionizing filter resin, transferring the heat to the bus cooling system. The strainers remove particulate debris from before and after the filter assembly to protect the fuel cell stacks from escaped filter resin or other particulate matter. The solenoid valve controls the coolant flow through the filter loop.

5.2.6 Bus Cooling System

The bus cooling system absorbs heat from various systems associated with the fuel cell engine and expels excess heat to the atmosphere.



Key Points & Notes

Figure 5-10 Bus Cooling System Flow Diagram

The bus cooling system circulates coolant, using a pump, through the following components:

Key Points & Notes

- inverter
- condenser
- intercooler
- bus chassis air compressor
- main heat exchanger
- de-ionizing filter heat exchanger
- lubrication oil cooler
- transmission fluid cooler

The coolant absorbs heat from each component except the hydrogen diffuser, which it heats in order to prevent ice formation. The manner in which the individual components are plumbed together (whether in parallel or series) depends on the nature of each cooling load and the physical location of each component within the bus chassis. Some components, such as the condenser, may include a solenoid valve or other flow control device to regulate the amount of coolant flow.

After passing through the various components, the bus coolant streams merge and flow through a filter to remove particulate debris. A temperature controlled bypass valve then splits the coolant flow, causing some to flow through a radiator and some to bypass it. The two streams re-mix after the radiator with a resulting final temperature that depends on the relative flow within each path. The radiator expels the heat to the atmosphere using fans driven by the hydraulic system.

Additional coolant is fed into the coolant circuit from a header tank as required.

Since the bus coolant does not come into direct contact with the fuel cells, it does not need to be de-ionized and consists of a standard solution of 50% ethylene glycol with 50% clean water.

5.2.7 HVAC System

Key Points & Notes

The HVAC system provides source heat to warm the passenger compartment.

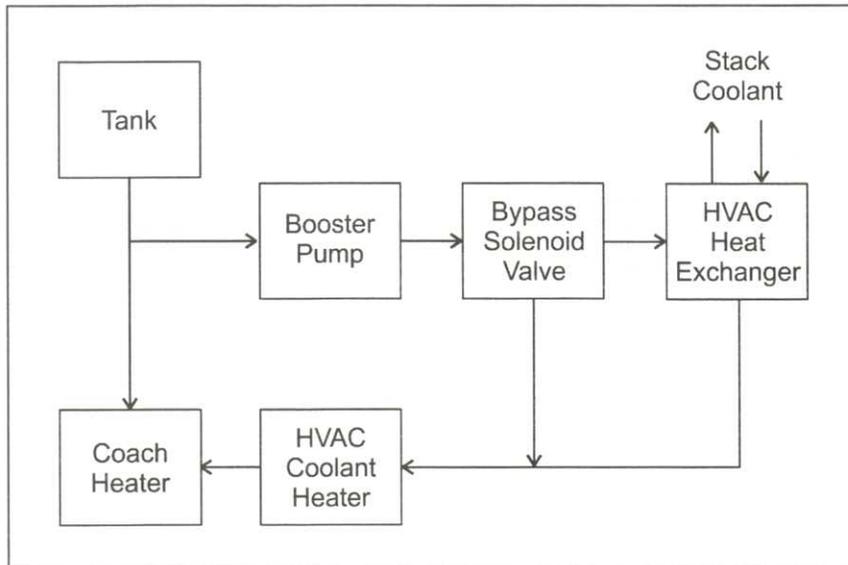


Figure 5-11 HVAC System Flow Diagram

Source heat for the HVAC system is drawn from the stack coolant stream by way of the HVAC heat exchanger. A bypass solenoid valve is used to regulate whether the HVAC coolant flows through the heat exchanger or around it depending on the heating demand. The hot coolant then flows through a heater, which adds additional electrical heat if required, and passes into the coach heater, which distributes the heat throughout the passenger compartment. The coolant then flows back to the booster pump and the circulation repeats.

Additional coolant is fed into the HVAC circuit from a header tank as required.

Since the HVAC coolant does not come into direct contact with the fuel cells, it does not need to be de-ionized and consists of a standard solution of 50% ethylene glycol with 50% clean water.

5.2.8 Lubrication System

Key Points & Notes

The lubrication system provides lubrication and cooling to key rotating components.

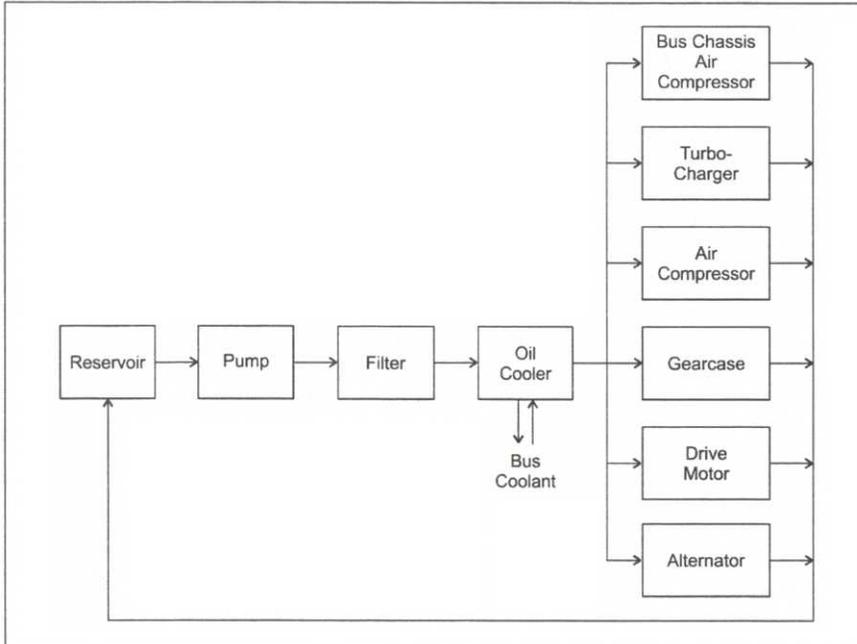


Figure 5-12 Lubrication System Flow Diagram

Lubrication oil resides within the sump of the drive motor. A pump, located within the sump, forces the oil through a particulate filter and into a distribution manifold. The manifold first directs the oil through the lubrication oil cooler, where it expels heat to the bus cooling system, and then distributes the oil flow through the following components:

- bus chassis air compressor
- turbocharger
- air compressor
- gearcase (used to drive ancillary components)
- drive motor
- alternator

The manner in which the individual components are plumbed together (whether in parallel or series) depends on the nature of each lubricating load and the physical location of each component within the bus chassis.

The lubrication system uses synthetic oil with a low vapor pressure in order to minimize the amount of oil that diffuses into the air stream within the air compressor and turbo-charger. This decreases the risk of fuel cell contamination.

5.2.9 Hydraulic System

Key Points & Notes

The hydraulic system powers the radiator fans and power steering system. The hydraulic system consists of a radiator fan circuit and a power steering circuit.

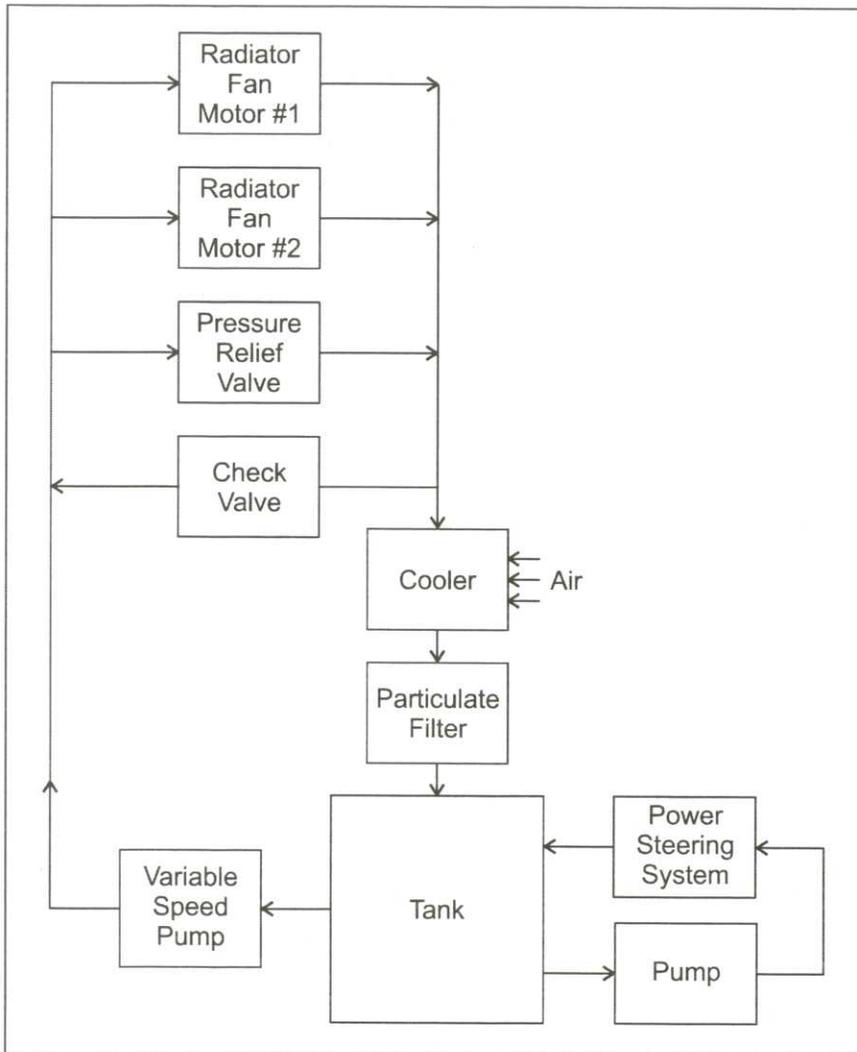


Figure 5-13 Hydraulic System Flow Diagram

Radiator Fan Circuit

The radiator fan circuit draws hydraulic fluid from a tank using a variable speed pump. The fluid then splits into three streams. Two of the streams pass directly through respective radiator fan motors. The third stream flows to a pressure relief valve. The pump speed, and therefore fan speeds, varies according to heat rejection requirements.

Each of the two radiator fan motors is connected to a fan that draws air through the radiator in order to expel heat from the bus cooling system to atmosphere.

The pressure relief valve protects the variable speed pump from damage by providing a flow path should the fan motors offer too great a flow resistance.

A check valve links the motor outlets to inlets and acts as a pressure relief during system shutdown.

The hydraulic streams re-combine after the fan motors and flow through a fluid cooler and a filter before returning to the tank. The fluid cooler is exposed to the air stream that flows through the radiator and expels waste heat to atmosphere. The filter removes particulate debris from the fluid.

Key Points & Notes

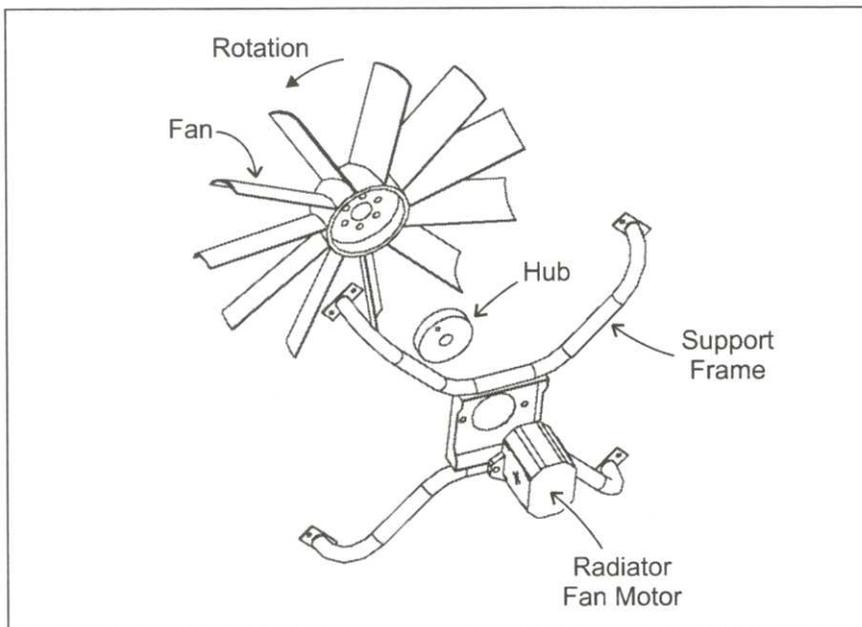


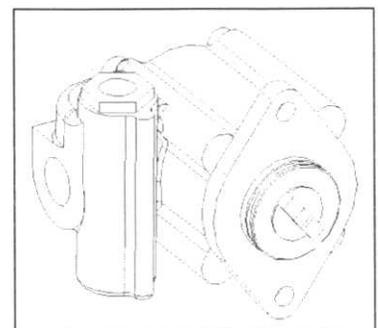
Figure 5-14 Radiator Fan Assembly Components

Power Steering Circuit

The power steering circuit draws hydraulic fluid from a tank using a pump. In some systems this tank is the same as that used in the radiator fan circuit; in others, a separate tank is used. The fluid leaving the pump enters the vehicle's power steering system where it drives standard bus manufacturer's components. The fluid returns to the tank.

5.2.10 Electrical System

The electrical system regulates, conditions and distributes the power generated by the fuel cell stacks.



Power Steering Pump

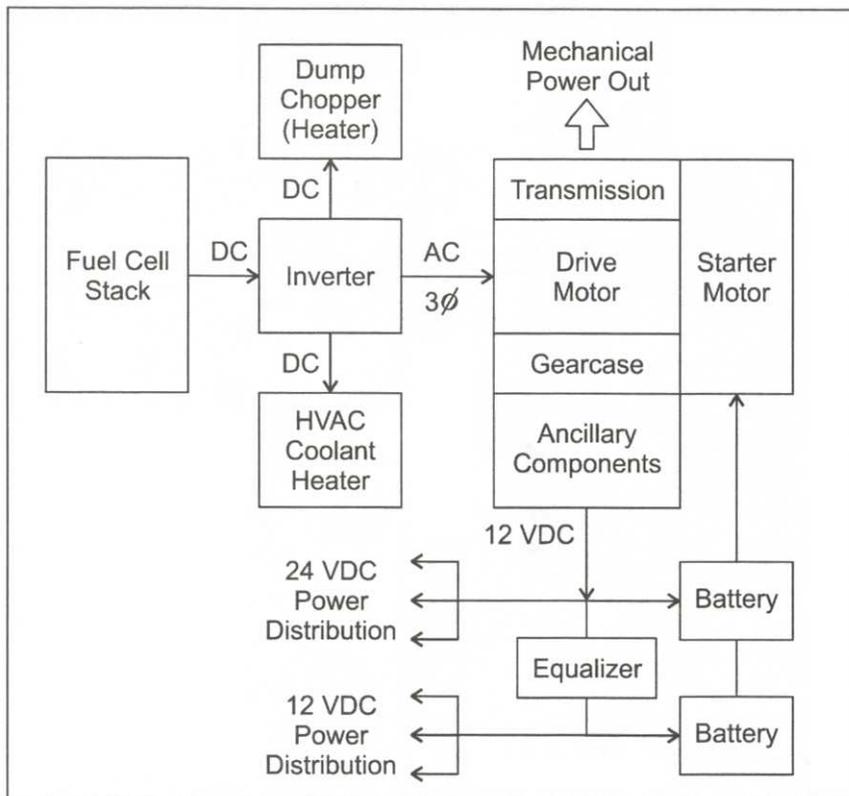
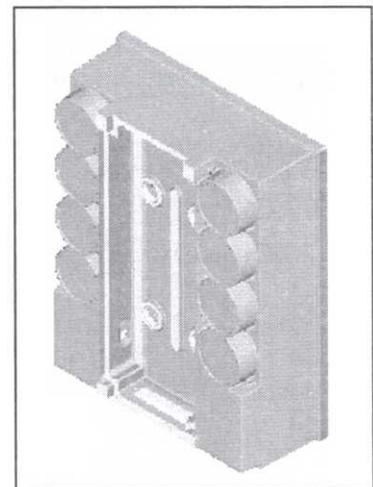


Figure 5-15 Electrical System

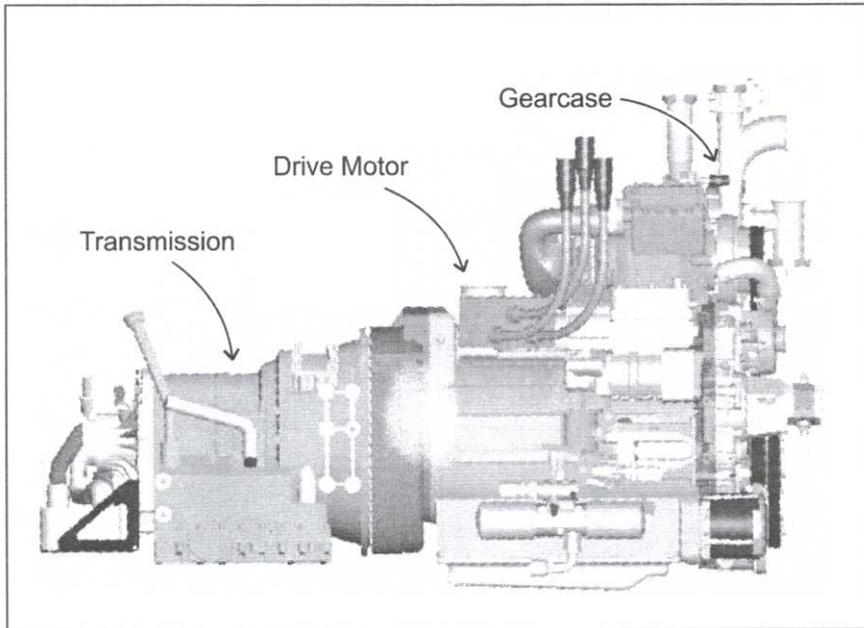
The DC electrical power generated by the fuel cell stacks passes directly into an inverter. The inverter generates a variable frequency 3-phase AC waveform to operate the drive motor in response to torque commands from the control system. The inverter assembly also energizes the resistor within the dump chopper during engine warmup to quickly raise the stack coolant temperature and energizes the HVAC coolant heater as required. The inverter includes a ground fault detector that triggers a warning if a leakage current exists between the stack module power connections and the bus chassis. Waste heat generated by the inverter assembly is transferred to the bus cooling system.

The drive motor transfers mechanical power to the bus driveshaft and to a gearcase. The gearcase drives ancillary components including the alternator, air compressor, stack coolant pump, bus coolant pump, radiator fan motors pump, power steering pump, lubrication oil pump, HVAC refrigerant compressor and the bus chassis air compressor. A starter motor rotates the drive motor and ancillary components during startup.



Inverter

Key Points & Notes

**Figure 5-16** Power Train

The alternator generates 24 VDC electrical power; this output is regulated and charges the bus batteries. An equalizer provides equal charging, resulting in 12 VDC and 24 VDC source power.

This source power is distributed through a series of fuses, circuit breakers and relays to fuel cell engine and standard bus chassis components throughout the bus.

Key Points & Notes

5.2.11 Control System

Key Points & Notes

The control system manages the operation of the fuel cell engine and collects operational data.

Control logic resides in three primary components: the engine controller, the bus controller and the data acquisition system.

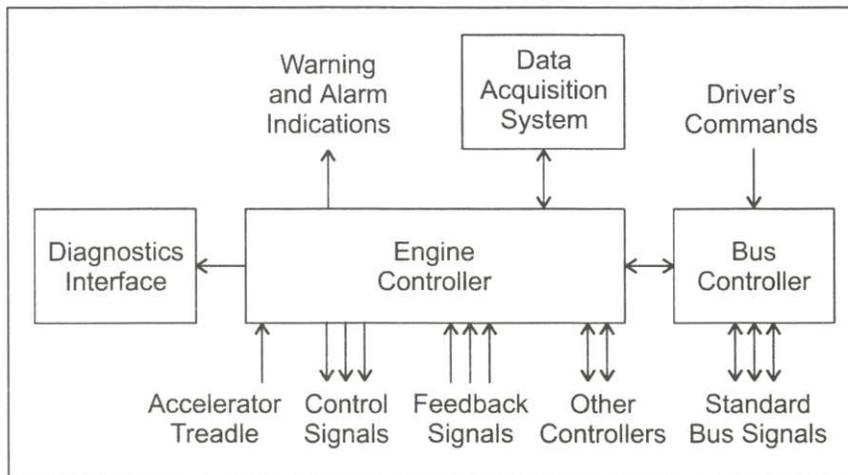


Figure 5-17 Control System

Engine Controller

The engine controller manages fuel cell engine functions such as system startup, shutdown, operating state transitions, and warnings and alarms. The controller inputs driver's commands (by way of the accelerator treadle), receives transducer feedback signals, communicates with other control devices (such as the bus controller and transmission controller), and receives inputs from other systems. The controller's algorithms derive inverter commands, component setpoints, and valve positions using a set of mathematical relationships. Warnings and alarms are indicated by way of dashboard lights, a message display center, or other means. The engine controller relays real-time operating data to the diagnostics interface for diagnostics purposes.

Control system algorithms are proprietary information.

Bus Controller

The bus controller is supplied by the bus chassis manufacturer and manages standard bus functions such as lights, doors and climate control. The bus controller receives driver's commands (from driver's area switches) and feedback from standard bus transducers and components. The bus controller relays commands and communicates with the engine controller.

Data Acquisition System

Key Points & Notes

The data acquisition system (DAC) is an optional component installed on some buses to record operating conditions for future analysis. The DAC stores engine controller and other non-control transducer signals on disk whenever the bus is running. These signals can be viewed using the diagnostics interface or downloaded to a host computer.

5.2.12 Leak Detection System

The leak detection system senses the presence of hydrogen and passes alarm signals to the vehicle's control system. The leak detection system consists of a series of leak sensors, leak indicators, and a junction box.

The leak detection system is powered whenever the bus control system is powered.

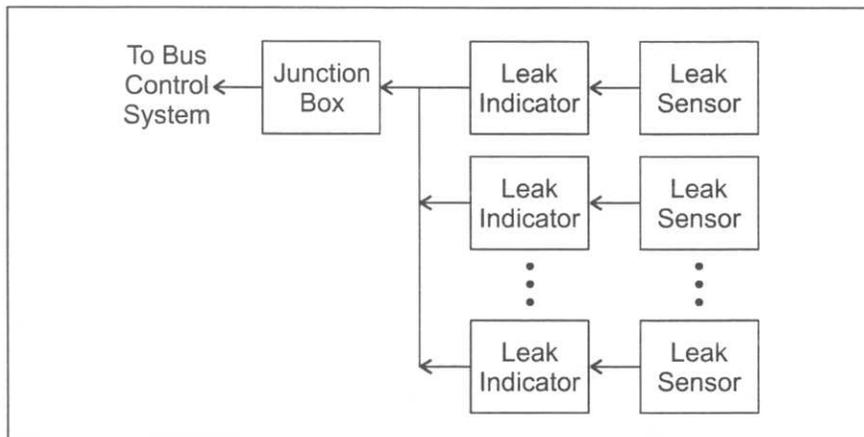


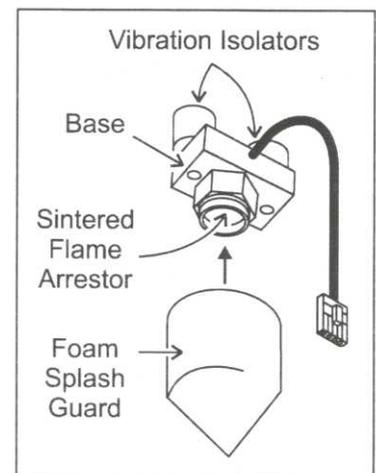
Figure 5-18 Leak Detection System

Leak Sensors

Hydrogen gas leak sensors are calibrated to measure hydrogen gas concentrations.

Each sensor consists of an explosion-proof chamber that contains two elements. Each element is constructed of a small coil of wire sealed in a ceramic substance. One element is coated with a catalyst (which encourages chemical reaction) while the other element is coated with a passivating substance (which deters chemical reaction). Both elements are heated by passing electrical power through their coils.

When a combustible gas/air mixture enters the chamber through the sintered flame arrestor, it burns easily on the catalytic element but not on the passivated element. This combustion further heats the internal coil of the catalytic element, which undergoes a subsequent change in electrical



Leak Sensor

resistance. The hydrogen leak indicator associated with the sensor compensates for this resistance change by altering the electrical power fed to the element until the original coil resistance is restored. This change in electrical power is therefore proportional to the amount of gas present and forms the basis of the gas concentration measurement.

The passivated element acts as a reference to compensate for changes in ambient temperature, humidity and pressure. Since these ambient changes affect *both* elements whereas the combustion affects the catalytic element *only*, the combusive effect is isolated by subtracting the reference element resistance from the catalytic element resistance.

The measured gas concentration accuracy depends on the oxygen concentration and humidity within the chamber. In addition, the measured concentration is accurate for the sensor location only; greater gas concentrations may exist at other locations where no sensor is present.

Sensors are typically installed by the fuel cylinders, within the filling box and in the engine, radiator and battery compartments. The sensors are installed above the hydrogen components or in dead air spaces where hydrogen is likely to accumulate. Sensors are often covered with a foam splash guard to prevent water and dirt ingress, and mounted using rubber vibration mounts to protect against vibration damage.

Hydrogen leak sensors are poisoned by silicones, chlorinated and fluorinated solvents (caulking, sealing and gasketing compounds) halogenated compounds and metallo-organic compounds.

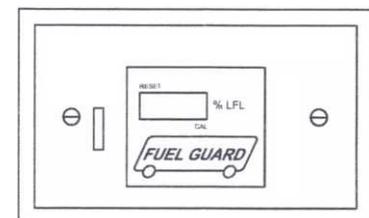
Sensors have a useful life of about 2-3 years and their output drifts with age, or after poisoning. Sensors must be calibrated after installation and regularly thereafter. When a sensor has been unpowered for several days, it may take up to 24 hours of operation to stabilize fully.

Leak Indicators and Junction Box

Each gas sensor is linked to a hydrogen leak indicator. Where multiple sensors are used, multiple indicators are also used. Each hydrogen leak indicator powers a single sensor and displays the gas concentration detected by that sensor.

Gas concentrations are displayed as a percentage of the lower flammability limit of hydrogen, or %LFL (see Section 1.3.3). At gas concentrations above the upper flammability

Key Points & Notes



Leak Indicator

limit (UFL) of hydrogen, there is not enough oxygen in the air/gas mixture for a flame to propagate. Since the sensor operates by burning the gas that enters its explosion-proof chamber, gas concentrations above the UFL cannot be sensed.

When subjected to gas concentrations above the UFL, the sensor quickly indicates a high value (resulting in alarm trigger), but the value drops as the available oxygen depletes. For this reason the high alarm setpoint is latched and does not reset when the gas concentration drops after alarm trigger.

When the gas concentration on any hydrogen leak indicator exceeds an internal threshold, a warning or alarm signal is sent from the indicator through a junction box to the control system. The control system then alerts the driver by way of dashboard lights, a message display center, or other means and shuts down the engine if an alarm concentration occurs.

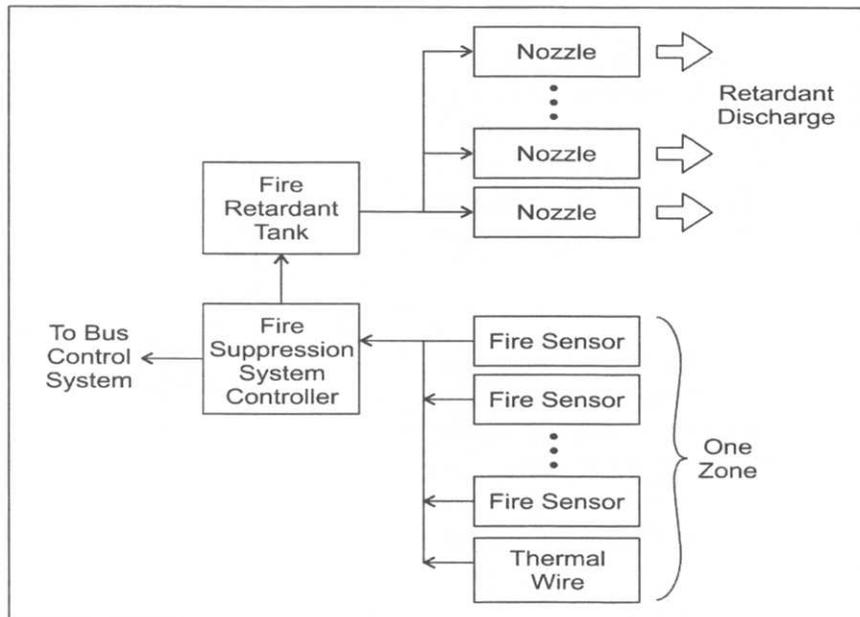
Typical setpoints for leaks are warnings at 5, 10 or 15% and alarm at 25% LFL hydrogen. These setpoints correspond to concentrations of 0.2, 0.4, 0.6 and 1.0% hydrogen in air respectively.

Key Points& Notes

5.2.13 Fire Suppression System

Key Points & Notes

The fire suppression system protects against fire and passes alarm signals to the vehicle's control system. The fire suppression system may be organized in a series of zones that serve specific areas in the bus. Each zone may or may not contain fire sensors, thermal wire, fire retardant tanks and nozzles.



Fire sensors to detect hydrogen fires must use optical (IR-or UV-type) detection principles. Thermal-type fire sensors are not suitable.

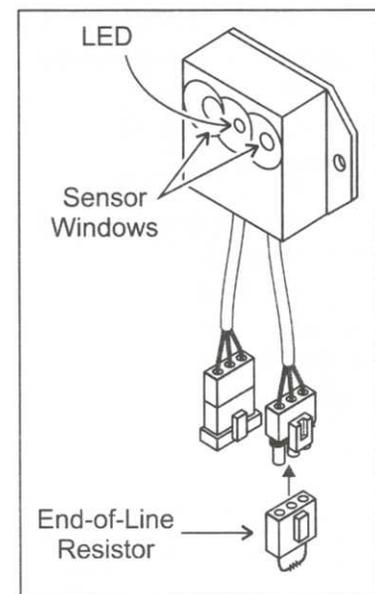
Figure5-19 Fire Suppression System

The fire suppression system is active at all times, unless battery power is interrupted. The bus control system does not need to be active for the fire suppression system to function, although the dashboard lights, message display center, or other driver indicators will not come on when the control system is off.

Fire Sensors and Thermal Wire

Fire sensors are located in areas of highest fire probability and are installed in a particular orientation to cover the area of interest.

Each fire sensor monitors two separate bands of infrared energy throughout a 90° solid cone field of view to a trigger distance of 5 feet (1.5 m). A sensor triggers (within 10 ms) whenever it detects the infrared energy pattern characteristic of a fire. In this way the sensor remains immune to false alarms from sunlight, flashlights, lightning, headlights, incandescent lights (100 W at 2 in; 5 cm) and welding arcs (at greater than 30 in; 76 cm) all of which have different energy patterns. The fire sensors do not detect high tempera-



Fire Sensor

tures, only flames. A green LED on each sensor comes on whenever that sensor has electrical power.

Thermal wire is wound in close contact with the fuel cell stacks. Each wire consists of two separate conductors wound together but separated by insulation. This insulation is designed to melt at 356 °F (180 °C) temperature, causing the conductors to come into contact thereby creating a short circuit.

The sensors and thermal wire within each zone are wired in series and are terminated by an end-of-line resistor attached to the last sensor in the series. If any device trips within a series, a discrete ground signal is sent to the fire suppression system controller resulting in a fire alarm. If a sensor fault occurs or the end-of-line resistor is missing, the controller detects incorrect impedance within the series resulting in a system fault warning.

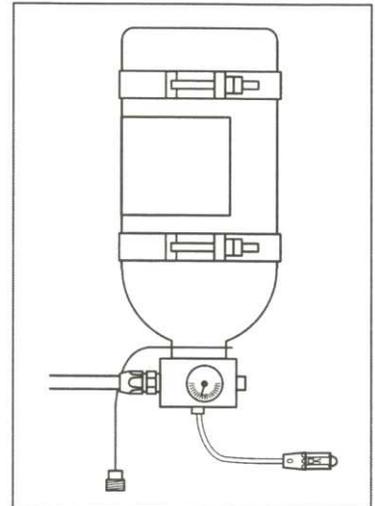
When a warning or alarm occurs, the fire suppression system controller sends a signal to the bus control system. The bus control system then alerts the driver by way of dashboard lights, a message display center, or other means. The bus shuts down automatically in the event of a fire and the fire retardant discharges soon after if the affected area includes a fire retardant tank and nozzles.

Fire Retardant Tanks and Nozzles

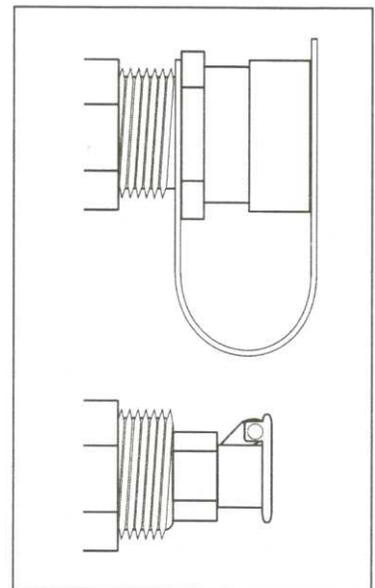
The fire retardant tanks contain the fire retardant that discharges following sensor trip. Individual tanks are associated with individual zones and specific discharge nozzles. Tanks are typically charged with a dry chemical retardant at high pressure although different retardants are sometimes used for different zones. Once triggered, the retardant discharges fully as a single shot and travels through distribution hoses to the nozzles.

The nozzles are located in area of highest fire probability, such as in the engine compartment, near the fuel cylinders, or in the battery compartment. The nozzles are designed for the specific type of retardant used and discharge to provide blanket coverage of the target area. Fire retardants do not discharge into the interior of the bus.

Key Points & Notes



Fire Retardant Tank



Nozzles

MODULE 6:

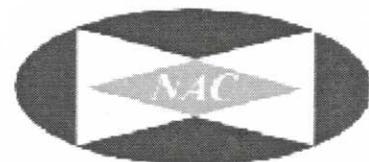
Fuel Cell Engine Safety

College of the Desert

Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

6.1	HYDROGEN	6-1
6.1.1	HYDROGEN LEAKS	6-1
6.1.2	HYDROGEN FIRES	6-5
6.1.3	LOW TEMPERATURE HAZARD	6-8
6.2	HIGH TEMPERATURE	6-10
6.3	HIGH PRESSURE	6-11
6.4	ELECTRICAL SHOCK	6-13
6.5	CHEMICAL	6-15
6.5.1	DE-IONIZING RESIN	6-15
6.5.2	ETHYLENE GLYCOL	6-15
6.5.3	PURPLE K DRY CHEMICAL FIRE RETARDANT	6-17
6.6	PHYSICAL	6-18

OBJECTIVES

At the completion of this module, the technician will:

- Understand the hazards and safety provisions associated with hydrogen and fuel cell engine systems

6.1 Hydrogen

Key Points & Notes

All fuels are dangerous because they are highly chemical reactive. It is this reactivity that makes fuels excellent sources of energy. Hydrogen is not inherently more dangerous than other fuels, such as natural gas or gasoline, but its properties are unique and must be handled with appropriate care. In many ways, hydrogen is safer than other fuels.

Hydrogen leaks form the basis of all gaseous hydrogen hazards, since without a leak there is no opportunity for hydrogen to mix with air, and therefore no basis for flammability or asphyxiation hazards. In addition to leaks, the low temperature of liquid hydrogen forms the basis for frostbite and oxygen condensation hazards.

6.1.1 Hydrogen Leaks

The properties of hydrogen that contribute to its leak hazard are:

- it has the lowest molecular weight, and the smallest molecule, of any element
- it has the lowest density and therefore highest buoyancy of any element
- it can cause embrittlement in some materials
- it is colorless, odorless and tasteless
- it acts as a simple asphyxiant when present in a sufficient concentration to reduce the level of oxygen

These properties are detailed in Section 1.

The small size of hydrogen molecules makes them more difficult to contain than the molecules of other gases. To a large extent, the potential for hydrogen leakage is minimized through design. Materials of construction are designed for hydrogen use and are resistant to metal embrittlement. Fuel lines never pass through the passenger compartment, eliminating the potential for hydrogen to leak into the vehicle.

In a transit bus application, hydrogen is stored on the roof in a series of high-pressure cylinders. Placing the fuel storage cylinders on the roof takes advantage of hydrogen's high buoyancy – any leaked gas dissipates quickly and vertically to the atmosphere with little impedence.

The storage cylinders contain the vast majority of hydrogen on the vehicle. The amount of hydrogen present in the fuel cell or internal combustion engine is very small when operat-

ing, and none while shut down. Furthermore, the hydrogen in the storage cylinders and associated manifold is at high-pressure, whereas the hydrogen within the engine is at low-pressure. The higher the pressure, the more likely that a leak will occur. Fuel lines, unwelded connections, and non-metal seals such as gaskets, O-rings, pipe thread compounds and packings are potential leakage or permeation sites.

When hydrogen is used in a fuel cell engine, the hydrogen and air that pass through the fuel cell stacks are designed to not mix directly. This is accomplished using seals. A heavy-duty fuel cell engine may have thousands of seals. Over time, fuel cell stacks develop leaks either internally (between flow paths) or externally to the ambient environment. To deal with this potential leakage, fuel cell stacks are typically enclosed and the enclosure is vented with forced air in order to prevent hydrogen accumulation. Fuel cell stack leaks often manifest themselves in other ways, such as poor electrical performance of individual fuel cells.

A hydrogen leak in itself is not a hazard, but it poses a potential fire hazard when mixed with air at appropriate concentrations (Section 6.1.2), and poses an asphyxiation hazard when it displaces the oxygen in air.

Sufficient hydrogen to pose an asphyxiation hazard can only accumulate if hydrogen leaks into an enclosed area. Outdoors, the hydrogen diffusion is so rapid that the risk is negligible. **However, since hydrogen is colorless, odorless and tasteless, its presence cannot be detected by humans, and there are no warning symptoms before unconsciousness results.**

Leakage gases may be hot and pose a burn hazard as detailed in Section 6.3. Leakage gases may pose a high-pressure hazard as detailed in Section 6.4.

Detecting Hydrogen Leaks

Hydrogen leaks will occur. Undetected leaks are the cause of the greatest number of hydrogen accidents. To this end, transit bus applications include a leak detection system.

The leak detection system consists of a series of sensors that are linked to the vehicle's control system. The sensors are located at strategic locations around the vehicle (such as the beneath the roof canopies and in the engine compartment) and are typically calibrated to trigger warnings at 5 and 15%, and an alarm at 25% of the LFL of hydrogen. Since the LFL of hydrogen is 4% hydrogen in air, these warning and

Key Points & Notes



alarm thresholds represent hydrogen concentrations of 0.2, 0.6 and 1% respectively. Thus, the leak detection system indicates an alarm before gas concentrations reach a dangerous level.

When a sensor trigger occurs, the control system alerts the driver by way of dashboard lights, a message display center, or other means and shuts down the engine if an alarm concentration occurs. Measured gas concentrations may be concurrently displayed on dedicated leak indicators. A typical leak detection system is described in detail in Section 5.12.

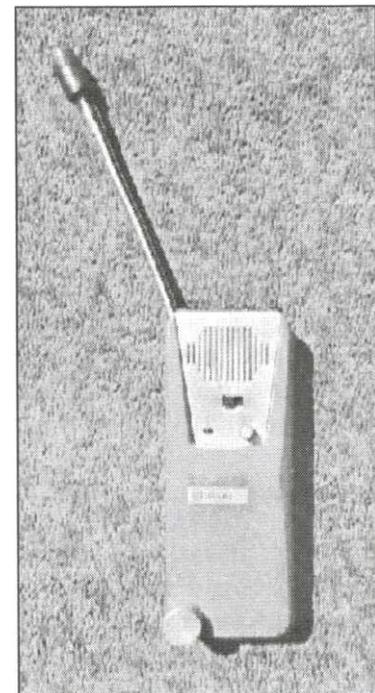
In most cases, the on-board leak detection system is only active whenever the vehicle is on. When the vehicle is off, it is probably unoccupied and so there is little benefit to dashboard annunciation. Accordingly, a supplementary leak detection system is an essential part of any parking or maintenance facility into which the vehicle is driven while fueled. Facility gas leak requirements are further described in Section 10.1.

Hydrogen leaks may be large or small. Leaks may manifest themselves through an audible gas rushing sound, a slow or sudden drop in fuel pressure, or a trigger of the leak detection system. Very slow leaks may not be noticeable through any of these means, and can only be detected through leak tests.

Leak tests are a routine part of fuel system maintenance, and fuel cell stack leak tests are an important part of fuel cell engine maintenance. Leak tests generally take three forms: pressure drop (or “leak-down”) observations over time, use of a hand-held leak detector (or “sniffer”), or application of a leak detection solution. These methods provide increasingly precise means of locating hydrogen leaks and are usually performed in sequence:

- Pressure drop tests indicate whether a leak exists in a large, generalized area.
- Hand-held leak detector tests indicate whether a leak exists within a localized area. Hand-held leak detectors only work on circuits pressurized with a flammable gas; they do not work on circuits pressurized with air or inert gases such as nitrogen.
- Leak detection solution tests indicate whether a leak exists at a precise location. These solutions work on any gas, flammable or not.

Key Points & Notes



Hand-held Leak Detector

Stopping Hydrogen Leaks

Key Points & Notes

In principal, hydrogen leaks are stopped by tightening or replacing the leaking fitting or component.

Leaks must be remedied in a safe area where the hydrogen cannot accumulate and that is free of ignition sources. Ideally, this is outdoors away from overhead obstructions, or inside a hydrogen-safe maintenance facility. Personnel should be limited to those fixing the leak. Smoking is strictly forbidden.

When a leak exists, the remaining hydrogen is safely stored on board the vehicle. The only reasons to vent the remaining fuel are to repair a component on the fuel storage circuit, or to move the bus into a facility that is not certified as hydrogen-safe.

Before a leak can be fixed, it must be located using leak tests and leak detection equipment as indicated above. If the leak occurs on a hydrogen powered vehicle, leak tests normally used during routine maintenance may be employed to help determine the leak location. A leak can only occur when the components are pressurized.

The fuel storage circuit remains pressurized even when the vehicle is off. Other circuits, such as the fuel delivery circuit (that is, downstream of the motive pressure regulator), are only pressurized when the vehicle is on. If the vehicle can be off, open (disconnect) the battery knife switches so that the vehicle is electrically dead while fixing the leak.

Once you locate a leak, tighten the connections, and if the leak persists despite tightening, replace the surrounding components. Tighten fittings only at low or ambient pressure: tightening a fitting while under high-pressure could cause it to shatter with serious personal injury. Thus, if a leak is detected in the high-pressure circuit, vent the circuit to near atmospheric conditions (using prescribed venting procedures and equipment) before tightening the fitting. Similarly, if a component must be replaced, vent the circuit to atmospheric pressure before opening the circuit: loosening a fitting while under pressure could cause it to be propelled with extreme force.

Never *tighten* any fitting while it is under pressure; doing so could cause the fitting to shatter with serious personal injury. Never *loosen* a fitting while under pressure; doing so may cause the fitting or component to be propelled with extreme force.



Once a fuel circuit has been vented to atmospheric pressure and exposed to air, it requires nitrogen and hydrogen purges before fueling. This normally applies to hydrogen storage cylinders only, but may include other components according to manufacturer's instructions. After a leak has been repaired, purge as required using facility equipment and procedures, re-pressurize the component, and repeat the leak test.

Key Points & Notes

6.1.2 Hydrogen Fires

The properties of hydrogen that contribute to its flammability hazard are:

- it has the widest flammability range of any fuel
- it has the lowest ignition energy of any fuel
- it has the greatest energy per weight of any fuel
- it burns invisibly and without smoke
- it can potentially generate electrostatic charges that result in sparks through flow or agitation

These properties are detailed in Section 1.

Once leaked, hydrogen mixes with air and is flammable over a wide range of concentrations. This flammable mixture is very easy to ignite, and, once ignited, burns with great vigor. The flame is nearly invisible in daylight. If hydrogen leaks into an enclosed environment, the risk of combustion and explosion is increased. If hydrogen leaks into an open environment, it rises quickly and is rapidly diffused, reducing the risk of fire. Existing fires burn vertically and generally for short periods of time.

Most mixtures of hydrogen and air are potentially flammable and explosive, and can be easily ignited by a spark or hot surface. Hydrogen flames are almost invisible in daylight.



To some extent, the potential for fire is reduced through design. Materials of construction are fire-resistant and are thoroughly grounded to prevent static charge accumulation. High-pressure fuel storage cylinders include pressure relief devices that are designed to release the cylinder contents when immersed in fire, thus preventing explosive pressure buildup within the cylinders. The pressure relief device discharge is routed to vents that protrude to the top surface of the bus canopy, allowing unimpeded access to the atmosphere.

Particular diligence must be applied by personnel when handling hydrogen directly, such as during venting or fueling. When venting or fueling, facility equipment and procedures must be followed exactly, and all sources of ignition must be eliminated.

The fueling and venting facility must be grounded together with the vehicle to prevent static electrical discharge. Suitable facility fire detection, fire extinguishing equipment and procedures must be in place.

Fueling facility requirements are further described in Section 10.2.

Detecting Hydrogen Fires

The near invisibility of hydrogen fires makes them hard to detect and a serious hazard to personnel.

Hydrogen fires may be large or small. The ferocity of a fire is directly related to the level of pressure behind the underlying leak. Fires may manifest themselves through the presence of flames, smoke from adjacent equipment engulfed in the flames, heat waves, a burning smell, explosion, component damage, or trigger of the fire suppression system. Very small fires may not be noticeable through any of these means.

Some transit bus applications include a fire suppression system in order to detect and extinguish fires. The fire suppression system consists of a series of sensors that are linked to the vehicle's control system. The sensors are located at strategic locations around the vehicle (such as the beneath the roof canopies and in the engine compartment) and are designed to trigger an alarm in the event of fire. Some types of sensors can also detect high heat. Fuel cell applications may include thermal wire wound around the fuel cell stacks that are designed to short when melted, thereby signaling the control system.

When a sensor trigger occurs, the control system alerts the driver by way of dashboard lights, a message display center, or other means and shuts down the engine. After the vehicle is shut off, single-shot fire retardants may be released into one or more zones associated with the triggered sensor. A fire suppression system is described in detail in Section 5-12. Fire retardants do not discharge into the vehicle passenger compartment.

When a retardant discharge occurs, expect a high noise level. A cloud of dry chemical retardant dust may exit

Key Points & Notes



the vehicle from the discharge areas. Avoid breathing the dry chemical dust as it will irritate throat and lungs.

Key Points & Notes

In most cases, the fire suppression system is active at all times unless the vehicle battery knife switches are open (disconnected). Accordingly, a supplementary fire detection system is an essential part of any parking or maintenance facility into which the vehicle is driven. Facility requirements are further described in Section 10. 1.

Extinguishing a Hydrogen Fire

The protocol for fighting a hydrogen fire is similar to fighting any fire fueled by a gas. The main thing to do is eliminate the fuel source. If this is not an option, allow the fuel to burn itself out under controlled conditions. The object is to minimize the risks of injury and danger to people, and risk of damage to equipment in the surrounding area. As with any fire, evacuate all personnel except those fighting the fire, contact local fire authorities if needed, and fight the fire from as great a distance as possible.

Large fires can only be extinguished by shutting off the fuel supply. Small fires can be fought with a dry powder retardant (recommended), carbon dioxide or halon extinguisher. Carbon dioxide extinguishers, modified by sawing off the fog nozzle, may be used to blow out the fire rather than smother it. A fire blanket may also be used. However, if a hydrogen fire is extinguished without shutting off its fuel supply, an explosive or flammable mixture may re-form and can re-ignite from surrounding hot surfaces or other ignition sources.

When the source of hydrogen cannot be shut off, the standard fire fighting practice is to prevent the fire from spreading while it burns out. Use copious amounts of water to cool surrounding equipment; and continue the water flow until well after the fire is out. Remove flammable materials from the surrounding area if it is safe to do so. When fighting a hydrogen fire, stay away from storage cylinder ends. Withdraw immediately in case of a rising sound from a venting safety device or any discoloration of a storage cylinder due to the fire.

For massive fires, use an unmanned hose holder or monitor nozzles, or withdraw from the area and let the fire burn. Keep upwind and avoid breathing the vapors. Evacuate to a radius of 1500 ft (450 m) for uncontrollable fires. Consider evacuation of the downwind area.

If a fire occurs on board a hydrogen powered vehicle, shut it down as soon as it is safe to do so. This closes the solenoid valves associated with each cylinder and the high-pressure solenoid, effectively isolating the fuel in the fuel storage system. An alarm shutdown by the fire suppression system should automatically discharge retardants within the fire area. If the fire continues, use standard fire fighting techniques as described above. Once the fire is out, tow the vehicle back to the maintenance facility and notify the manufacturer.

Key Points & Notes

6.1.3 Low Temperature Hazard

The property of hydrogen that causes a low temperature hazard is:

- it has second lowest boiling point of all substances, after helium.

This property is detailed in Section 1.

Low temperature hazards only exist when hydrogen is stored in liquid form. The extremely low temperature of liquid hydrogen results in severe frostbite danger and secondary fire danger.

Liquid hydrogen is stored below $-423\text{ }^{\circ}\text{F}$ ($-253\text{ }^{\circ}\text{C}$; 20 K) in vacuum-lined vessels. Liquid hydrogen vessels must be completely insulated with specified materials to prevent any contact with the vessel.

A severe frostbite hazard danger occurs whenever skin comes into contact with liquid hydrogen, liquid hydrogen vapors or surfaces directly in contact with liquid hydrogen. Any skin contact can cause extensive tissue damage, burns, freezing or tearing.

Any surface in contact with liquid hydrogen poses a severe frostbite danger.

A secondary fire danger occurs whenever air comes directly into contact with cryogenic surfaces that contain liquid hydrogen. The temperature of liquid hydrogen is low enough to liquefy air and thereby concentrate the air's constituent components. Among these, liquid oxygen poses an explosion or flammability hazard if it drips onto combustible materials such as asphalt.

To minimize these low temperature hazards, all pipes, vessels and other equipment that contain liquid hydrogen must be completely insulated with appropriate materials. Liquid hydrogen must be removed from the vehicle or otherwise



isolated during maintenance. Maintenance facility surfaces should be of concrete or be covered with suitable drip pans.

Air must not be allowed to liquefy on pipes, vessels or other components that contain liquid hydrogen.

Key Points & Notes



6.2 High Temperature

Key Points & Notes

Water, glycol solutions, oils and gases circulate through pipes and other vessels within a transit bus. The maximum temperature achieved by any of these streams is the turbo-charger compressor outlet, which can exceed 400 °F (200 °C). Exposed surfaces can cause serious burns if touched.

During normal operation, engine compartment covers prevent exposure to hot surfaces; however, the engine may be operated with the engine covers open. If the covers are open, such as during maintenance procedures, contact with any internal surfaces containing circulating liquids or gases must be avoided. Internal components may remain hot for a long time after the engine has been shut down.

Avoid contact with internal surfaces that are In contact with liquids or gases. Heed all warning decals.



6.3 High Pressure

Key Points & Notes

Hydrogen to fuel a transit bus is typically stored in roof-mounted cylinders at an operating pressure of up to 3600 psig (250 barg), and potentially as high as 5000 psig (345 barg). Personnel handle hydrogen at high-pressure when fueling these cylinders. This high-pressure is extremely dangerous and could result in an explosive force if a leak or component rupture occurred. Even when depleted, the hydrogen cylinders are often at a residual pressure of 300–500 psig (21–35 barg).

Never crack open or loosen the fitting of any high-pressure component; doing so may cause the fitting or component to be propelled with extreme force. Never tighten a high-pressure fitting while under pressure; doing so could cause the fitting to shatter with serious personal injury. Follow fueling and venting procedures exactly.



All high-pressure components are certified pressure vessels and must be inspected regularly and replaced if any damage or fault occurs. Hydrogen storage cylinders must survive a battery of tests to obtain certification as described in Section 2.2.1.

Hydrogen storage cylinders have multiple safety features. Each cylinder contains a solenoid valve that automatically closes whenever the engine is shut down or when a collision sensor trips as the result of bus impact. Each cylinder also includes an internal excess flow valve that closes whenever the gas flow leaving the cylinder is too great (such as if a pipe bursts). An additional excess flow valve, on the common cylinder manifold, serves the same function. Pressure relief devices mounted at each end of each cylinder release the cylinder contents when exposed to fire.

Refer to warning and cautions in Section 7.1.1 whenever accessing rooftop components.



All high-pressure components reside on the roof and within the filling box. Hydrogen leaving the cylinders is regulated to the intermediate (or “motive”) pressure of approximately 178 psig (12 barg); this is further regulated to pressures up to 30 psig (2 barg) within the fuel delivery circuit.

Additional components protect the motive- and low-pressure circuits against fuel overpressure. A pressure relief valve is mounted downstream of the motive pressure regulator and vents to atmosphere if the pressure exceeds 200 psig (14 barg). A burst disk vents hydrogen from the fuel delivery

circuit to the atmosphere if the pressure within the circuit exceeds 46 psig (3 barg).

Key Points & Notes

Hydrogen, air, water and coolant operate at a maximum pressure of approximately 35 psig (2.4 barg) within the fuel cell engine. The lubrication oil and hydraulic fluid operate at a maximum pressure of approximately 90 psig (6.2 barg). The bus chassis air system (air brakes) operates at up to 125 psig (9 barg). These pressures are potentially dangerous and caution must be exercised when dealing with any pressurized component.

When a fuel cell engine shuts down, the following circuits vent or depressurize:

- motive pressure fuel circuit
- fuel delivery circuit
- air delivery circuits
- humidification water circuits
- hydraulic circuits
- lubrication circuits

When a fuel cell engine shuts down, the following circuits remain pressurized for some time, but depressurize slowly:

- stack coolant circuit
- bus coolant circuit

When the a fuel cell engine shuts down, the following circuits do not depressurize:

- fuel storage cylinders
- high-pressure fuel circuit
- bus chassis air system

The hydrogen cylinders and high-pressure circuit are pressurized even when the engine is shut down.



In addition, fuel cell vehicles that include a fire suppression system contain fire retardant tanks that remain pressurized at all times.

6.4 Electrical Shock

Key Points & Notes

A fuel cell powered transit bus contains a variety of high and low voltage components.

Fuel cell stacks produce voltage in proportion to the number of fuel cells, and overall levels can exceed 1000 VDC (open circuit voltage) for a heavy-duty engine such as for a transit bus. This is converted to AC power within an inverter to operate the drive motor. The inverter adjusts the AC output frequency and current to achieve a prescribed torque set-point and the output voltage floats as required, but can reach levels as high as 460 VAC.

At times, some of this AC power is diverted into one or more water- or coolant-cooled bleed resistors (or “dump choppers”) where it is converted to heat. These high voltage components pose a severe shock or electrocution danger and can remain charged for up to five minutes even after the engine has shut down.

Fuel cell engines contain high DC and AC voltages. Exercise caution when accessing electrical components to prevent shock or electrocution.



The fuel cell stacks, inverter and other high voltage components are individually enclosed and located within the engine compartment. During normal operation, these barriers offer protection against shock and electrocution, and must be in place.

Do not operate a fuel cell engine unless all high voltage barriers are in place.



Whenever the engine is shut down, the reactant gases are automatically vented and one or more dump choppers are engaged. These dump choppers continuously absorb any power generated by residual reactant gases within the stacks. If groups of fuel cell stacks or individual stacks have been removed from the vehicle, the dump chopper is no longer connected and a residual voltage may build up in as little as several minutes. Furthermore, a reading of zero volts (0 V) across an entire fuel cell stack does not guarantee that all cells are uncharged.

Always assume that the fuel cell stacks are electrically charged. Do not touch the fuel cell stack, its graphite cells, or the cell voltage monitoring wires until you confirm that no voltage exists.



The bleed resistor is located on the bus chassis. When the stacks are removed from the chassis or electrically disconnected, the bleed resistor is no longer connected.

Jewelry (such as rings, necklaces, bracelets and watches) may concentrate an electric current when it comes into contact with charged components, or when a shock passes through the human body. These concentrations can cause serious heat burns.

Do not wear jewelry near the fuel cell engine. To minimize conductivity, your hands and clothes should be dry.

The vehicle control system and other components operate on 12 and/or 24 VDC. This power derives from one or more batteries while the engine is off, and from an alternator when the engine is on. These low voltage components are located in many places throughout the vehicle and do not pose a shock hazard. Some of these components may remain charged even when the engine is shut down.

Vehicle Ground Fault Monitor

High voltage components are electrically isolated from the vehicle chassis. In order to guard against inadvertent charge leakage onto the vehicle chassis, a ground fault monitor is incorporated into the inverter that constantly monitors the approximate electrical resistance between the two planes. A high resistance indicates that there is little or no current leakage onto the chassis (as it should be), and a low resistance indicates that a leakage current exists.

A leakage current, or ground fault, occurs wherever an electrical short-circuit occurs and usually derives from ion accumulation in the humidification water or stack coolant. If the resistance is too low, the ground fault monitor generates a warning or alarm.

Key Points & Notes



6.5 Chemical

A fuel cell powered transit bus does not pose any serious chemical hazards although caution should be exercised when handling the following substances.

6.5.1 De-Ionizing Resin

De-ionizing filters contain a mixed-bed de-ionizing resin used to remove anions and cations from the humidification water or stack coolant. De-ionizing resin is inert and considered safe, but can cause mechanical eye irritation. **As a preventative measure, wear safety glasses when handling the filters or resin.** Respirators and ventilation are not required under normal conditions.

Store new de-ionizing resin above freezing and below 120 °F (49 °C). Keep containers sealed to prevent drying. Dispose of used resin by incineration or landfilling according to local regulations.

Refer to the manufacturer's Material Safety Data Sheet for comprehensive safety information.

6.5.2 Ethylene Glycol

The stack and bus coolant circuits contain solutions that include ethylene glycol. (*Ethylene glycol* is different from *propylene glycol*, which is essentially non-toxic. Propylene glycol is not used as it is incapable of sufficient heat absorption.)

Ethylene glycol is toxic. Ingestion can lead to central nervous system, cardiovascular and kidney effects, including kidney failure and death. Symptoms of ethylene glycol ingestion are numerous and include slight inebriation, eye problems, depressed reflexes, convulsions, mild hypertension, rapid heartbeat and increased respiration among others.

Ethylene glycol is toxic if ingested, or if its vapors are inhaled.

Ethylene glycol vapors pose little hazard due to low vapor pressure, however, when heated or misted they present a significant health hazard. Irritation, cough and headache may occur from repeated exposure to vapors, and more severe symptoms including coma can occur from inhalation of heated or misted vapors.

Heated or misted ethylene glycol is a significant health hazard.

Key Points & Notes

Process fluids and cleaning solutions can also pose chemical hazards if ingested, inhaled or absorbed. Always refer to manufacturer's instructions and Materials Safety Data Sheet prior to use.



Skin absorption occurs, although toxic amounts have not been reached in human cases.

As preventative measures: wear safety glasses or chemical safety goggles, wear chemically protective gloves, boots, aprons and gauntlets made of natural or nitrile rubber or of Neoprene to prevent skin contact. Do not eat, drink or smoke in the work area. Follow OSHA respirator regulations and if necessary, wear a MSHA/NIOSH approved respirator. Provide general and local ventilation or local exhaust ventilation to minimize ethylene glycol vapors.

Wash hands after contact with ethylene glycol, and before eating, drinking, smoking, using the toilet or applying cosmetics. Separate contaminated clothing from street clothes and launder before re-use. Clean contaminated boots.

Heated or misted ethylene glycol is a moderate fire and explosion hazard. The auto-ignition temperature of ethylene glycol is approximately 748 °F (398 °C).

Avoid exposing ethylene glycol to heat and ignition sources.

Ethylene glycol fires can be extinguished with carbon dioxide, dry chemical, water spray or alcohol-resistant foam fire extinguishers. To fight ethylene glycol fires, wear self-contained breathing apparatus (pressure-demand MSHA/NIOSH approved or equivalent) with a full facepiece operated in pressure-demand or positive-pressure mode. Apply cooling water to sides of containers until well after the fire is out.

Ethylene glycol is chemically incompatible with many chemicals and causes ignition at 212 °F (100 °C) with others. Refer to the MSDS for the complete list of incompatibles. **Avoid exposing ethylene glycol to incompatible chemicals.**

Ethylene glycol can absorb twice its weight in water at 100% relative humidity. Avoid exposing new ethylene glycol to water or high humidity.

Used ethylene glycol may be contaminated with trace amounts of lead or other metals and should be disposed of in accordance with local regulations.

Refer to the manufacturer's Material Safety Data Sheet for comprehensive safety information.

Key Points & Notes



6.5.3 Purple K Dry Chemical Fire Retardant

Key Points & Notes

Fire suppression system retardant tanks contain Purple K dry chemical fire retardant. Purple K dry chemical is a powder consisting of a mixture of chemicals and is generally non-hazardous, except when present in sufficient concentration to cause asphyxiation by oxygen displacement.

During normal operation, Purple K dry chemical is contained under pressure within the fire suppression system retardant tanks. In the event of a fire sensor trigger, the dry chemical mixture is discharged through nozzles into each of the affected zones.

When a retardant discharge occurs, expect a high noise level. A cloud of dry chemical retardant dust may exit the vehicle from the discharge areas. Avoid inhalation of Purple K dry chemical. Skin does not absorb Purple K dry chemical. It is slightly irritating to skin or eyes. Prolonged or repeated skin contact may cause irritation, drying and cracking.

Avoid inhalation and contact with Purple K powder.

If ingestion of Purple K dry chemical occurs, do not induce vomiting, rinse mouth with water and contact a physician or poison control center. Purple K dry chemical reacts violently with lithium.



As preventative measures: wear safety glasses (or goggles) and gloves when handling the Purple K dry chemical; wash hands with soap and water and flush for 15 minutes after contact. Do not eat, drink or smoke during handling.

Dispose of used Purple K dry chemical or its containers according to local regulations. Purple K dry chemical is known to contribute to ozone depletion in the upper atmosphere - recycling is either required or encouraged by local authorities.

Refer to the manufacturer's Material Safety Data Sheet for comprehensive safety information.

6.6 Physical

Key Points & Notes

Physical hazards include rotating equipment and weight hazards.

Rotating Equipment

The fuel cell engine contains fans and belt-driven rotating equipment that may be partially exposed, or could become exposed if protective guards are removed.

During normal operation, engine and radiator compartment covers prevent exposure to these rotating components; however, the engine may be operated with these covers open. If the covers are open, such as during maintenance procedures, contact with rotating equipment is possible and must be avoided. **Loose clothing may become entrained in rotating equipment and should not be worn.**



Weight

A fuel cell powered transit bus is very heavy and weighs approximately 2200 lb (1000 kg) more than a CNG bus. **Hoisting equipment capable of safely lifting this weight is required during some maintenance procedures.**



Individual fuel cell engine components, such as the power train, stack modules and other components can weigh as much as 2200 lb (1000 kg) and require either a crane or hoist to lift, and special cradles to handle. To prevent slippage, properly secure the components to the lifting equipment.

Wear appropriate safety equipment, such as steel-toed boots when handling heavy components.



MODULE 7:

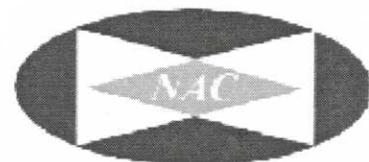
Fuel Cell Bus Maintenance

College of the Desert

Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

7.1	GENERAL	7-1
7.1.1	WARNINGS AND CAUTIONS	7-1
7.1.2	WORK PROCEDURES	7-3
7.1.3	FITTINGS	7-4
7.1.4	VALVES	7-8
7.1.5	MATERIALS	7-10
7.1.6	CLEANING	7-11
7.1.7	FLUIDS	7-12
7.1.8	HOISTING AND JACKING	7-14
7.1.9	TOWING AND PULLING	7-14
7.1.10	WELDING AND HEATING	7-15
7.1.11	PARKING AND STORAGE	7-16
7.1.12	PRE-MAINTENANCE PREPARATION	7-18
7.1.13	POST-MAINTENANCE CHECKS	7-19
7.2	FUEL SYSTEM OPERATIONS	7-21
7.2.1	FUELING	7-21
7.2.2	VENTING	7-29
7.2.3	PURGING	7-34
7.3	ROUTINE MAINTENANCE	7-39
7.4	FUEL CELL ENGINE PROCEDURES	7-43
7.4.1	GROUND FAULT MONITOR CHECK AND CONDITIONAL DE-IONIZING FILTER REPLACEMENT	7-43
7.4.2	WATER TRAP INSPECTIONS	7-44
7.4.3	AIR SYSTEM OIL DETECTOR INSPECTION	7-45
7.4.4	HYDROGEN DIFFUSER INSPECTION	7-46
7.4.5	STACK VENT FANS CHECK	7-46
7.4.6	CELL VOLTAGE MONITOR CHECK	7-46
7.4.7	FUEL CELL ENGINE LEAK TESTS	7-48
7.4.8	POWER CABLE CONNECTION CHECK	7-72
7.4.9	GLYCOL SYSTEM INTEGRITY TEST	7-72
7.4.10	DUMP CHOPPER RESISTANCE CHECK	7-73
7.5	FUEL SYSTEM PROCEDURES	7-75
7.5.1	FUEL CIRCUIT LEAK TESTS	7-75
7.5.2	FUEL SYSTEM INSPECTIONS	7-78
7.5.3	HYDROGEN PARTICULATE FILTER REPLACEMENT	7-80
7.5.4	MOTIVE PRESSURE REGULATOR SOLENOID VALVE CHECK	7-81
7.5.5	GROUND INTEGRITY CHECK	7-82
7.5.6	FUEL CYLINDER INSPECTIONS	7-83
7.5.7	PRESSURE REGULATOR DIAPHRAGM, SEAL AND SEAT REPLACEMENT	7-92
7.6	CONVENTIONAL PROCEDURES	7-93
7.6.1	GENERAL INSPECTIONS	7-93
7.6.2	LEAK DETECTION SYSTEM CHECKS AND CONDITIONAL CALIBRATION	7-94
7.6.3	FLUID LEVEL CHECKS, SAMPLES AND ASSESSMENTS	7-98
7.6.4	TURBOCHARGER OIL TRAP DRAIN	7-103

7.6.5	FIRE SUPPRESSION SYSTEM INSPECTIONS AND TESTS	7-104
7.6.6	MECHANICAL INSPECTIONS	7-110
7.6.7	FILTER INSPECTIONS AND REPLACEMENT	7-114
7.7	DIAGNOSTICS	7-120
7.7.1	DIAGNOSTICS INTERFACE	7-120
7.7.2	DIAGNOSTIC INTERFACE SCREENS	7-121
7.8	FAULTS	7-128
7.8.1	WARNINGS	7-128
7.8.2	ALARMS	7-128
7.8.3	FAULT MESSAGES	7-129

OBJECTIVES

Upon completion of this module, the technician will be able to:

- understand general maintenance procedures
- understand fuel system fueling, venting and purging procedures
- understand fuel cell engine routine service requirements
- understand the principles of the fuel cell engine service procedures
- understand the principles of the fuel system service procedures
- understand the principles of the conventional service procedures as they pertain to a fuel cell bus
- understand and interpret fuel cell engine diagnostics and fault information

7.1 General

Key Points & Notes

Apply the following general service instructions during maintenance. Many of the instructions are just as applicable to the maintenance of a conventional powered bus as they are to a fuel cell powered bus. These instructions are not meant to be exhaustive, or as a substitute for common sense or basic maintenance skills.

7.1.1 Warnings and Cautions



General Warnings and Cautions

- Be familiar with the safety information, hazards and emergency procedures prior to maintaining the bus.
- Always follow lockout procedures prior to servicing the bus. Lockout procedures vary, but must prevent inadvertent engine start even where various personnel are working independently.
- Be familiar with the location and operation of emergency shutdown switches. A bus normally contains two emergency shutdown switches, one mounted in the motor control center and the other at the rear of the engine compartment. These switches enable the engine to be shut down from either location, and may allow engine start from the rear of the bus.
- When elevating the bus, beware of the limitations of the blocking equipment, and always ensure that the jarring and shaking created by component removal and installation procedures do not overload the blocks, or cause the bus to become unstable.
- Always depressurize air lines prior to disconnection. Failure to do so will cause the hose end to whip uncontrollably as the air is expelled and solid particles deposited in the line to be propelled.
- Do not tamper with any control system communication signals while the bus is operating. Doing so may result in unsafe operating modes, equipment damage, or injury to personnel in or near the bus. Repair all faulty sensors or wiring before operating the bus.
- Open (disconnect) the battery knife switches prior to removing or installing electrical components.
- Understand the conditions under which the fire suppression system is active (if installed). In many buses, the fire suppression system is disabled if the batteries are discharged or if battery knife switches are open (discon-

ected). The fire suppression system may need to be disabled during some maintenance procedures (such as during welding) to prevent false trigger.

- After torquing a bolt, add a spot of paint to the interface between the bolt head and its mating surface to indicate that torquing is complete.
- Always use a hand-held voltmeter to ensure that no voltage exists prior to servicing any electrical component.

Fuel Cell Engine Warnings and Cautions

- Always wait at least five minutes after the engine is shut down prior to servicing any fuel cell engine component in order to discharge any residual electrical charge from the fuel cell stacks and/or electrical components.
- Always ensure that stack voltmeters indicate 0 VDC prior to servicing any fuel cell engine component.
- Always use a hand-held voltmeter to ensure that a given stack is at 0 VDC prior to servicing that stack.
- Take care when handling fuel cell engine components to prevent damage.
- Some fuel cell stack components are fragile. Follow documented procedures when handling stacks to prevent damage.
- Keep foreign objects, materials, petroleum-based products, oil and grease away from the fuel cell stacks or any fuel cell engine components that pass fuel, air or coolant to or from the fuel cell stacks. Doing so may destroy the fuel cell stacks. Clean these components only as described in Section 7.1.6.
- Never introduce any leak inhibitors or other foreign substances into the water system. Doing so may destroy the fuel cell stacks.
- Replace all non-rubber gaskets once used. Replace rubber gaskets during maintenance if they have been in service for six months or if damaged.



Fuel Storage System (Rooftop) Warnings and Cautions

- Whenever possible, access rooftop components while parked indoors. If outdoors, latch the canopies open. Canopies can suddenly close when exposed to wind.
- Access rooftop components by opening one canopy and standing on the opposite (closed) canopy.



Key Points & Notes

- Where available, wear a personal safety harness and attach it to an overhead safety cable when on the bus roof.
- Never open or tighten any high-pressure fitting or component without first venting the hydrogen *and* verifying that *all* high-pressure gauges or displays indicates 10 psig or less. This ensures that the high-pressure circuit is depressurized even if one of the gauges or displays indicates an incorrect value.
- All personnel working with hydrogen storage components must have high pressure gas training or high pressure gas certification, if available.
- Close the fuel shutoff valve that supplies fuel to the engine only in case of emergency. Closing the valve during operation can damage the fuel cell stacks. Instead, turn off the engine in order to automatically close the solenoid valves associated with each hydrogen cylinder and the high-pressure manifold; this isolates all fuel within the fuel storage system.
- Take care when handling fuel storage system components to prevent damage.
- Do not walk on cylinders. Do not expose cylinders to any form of abrasion. Protect cylinders from tool impact. Do not expose cylinders to corrosive acids or bases, or add coatings.
- Do not leave tools or other items on the roof.
- Do not step on roof covers or hatches.

Key Points & Notes

7.1.2 Work Procedures

- Make a sketch of component installation prior to removal and keep parts in order during disassembly to facilitate re-assembly.
- Keep parts clean, and clean them before re-assembly.
- When disconnecting unlabeled hoses or connectors, use tags to identify how they should be reconnected. After completing a repair, check wiring and hose connectors to ensure that they are properly connected and secure.
- Cover open ends of lines, hoses and fittings with caps, tape or clean plastic bags to prevent the entry of foreign objects, substances or dirt.
- To disconnect vacuum hoses, pull on the end, not the middle of the hose.

- To uncouple electrical connectors, pull on the connector itself, not the wires.
- Replace used lock nuts. Do not substitute a regular nut for a lock nut.
- Use stainless steel hardware unless otherwise specified.
- When replacing fuses or breakers, be sure that the new fuse or breaker has the correct amperage rating.
- Understand electrical circuits prior to diagnosis and connecting the test equipment.
- Do not drop electrical components such as sensors or relays as they may become damaged. If they are dropped on a hard floor, they should be verified or replaced.
- Label replacement parts in an identical fashion to the components they replace. Install wires so that their labels are easily readable wherever possible.
- Always replace warning labels (such as for high voltage, high pressure, high temperature or hydrogen).
- When unfastening fittings, ensure that there is no pressure in the circuit before opening and open the fitting slowly so that any trapped gas can escape safely.

Key Points & Notes

7.1.3 Fittings

Fuel cell engines use a variety of fittings for attaching hoses, tubes and other components. Some of the most common are described in the following sections.

7.1.3.1 Flared Tube Fittings

Flared tube fittings are commonly used on hydraulic fluid, oil, coolant and bus chassis air hoses. Each fitting consists of a tube or hose, a support sleeve and a nut that is free to turn, and a fitting body that includes male threads.

When fastening pre-swaged flared tube fittings:

1. Ensure that all parts are clean and undamaged, and that the sealing surfaces are round and smooth and free of all nicks, scratches, spiral tool marks, splits or weld beads in the seal area.
2. Align the tube flair against the nose of the fitting body. Do not apply Teflon tape or other thread compounds to the threads of fittings, sleeve or nut.
3. Tighten the nut by hand, then tighten the nut with a wrench either to the specified torque or by the specified

number of flats (as shown in Table 7-1). When using the flats method, hand tighten, mark one of the nut flats with a vertical line, and tighten. When tight, mark the body hex in line with the line on the nut.

Key Points & Notes

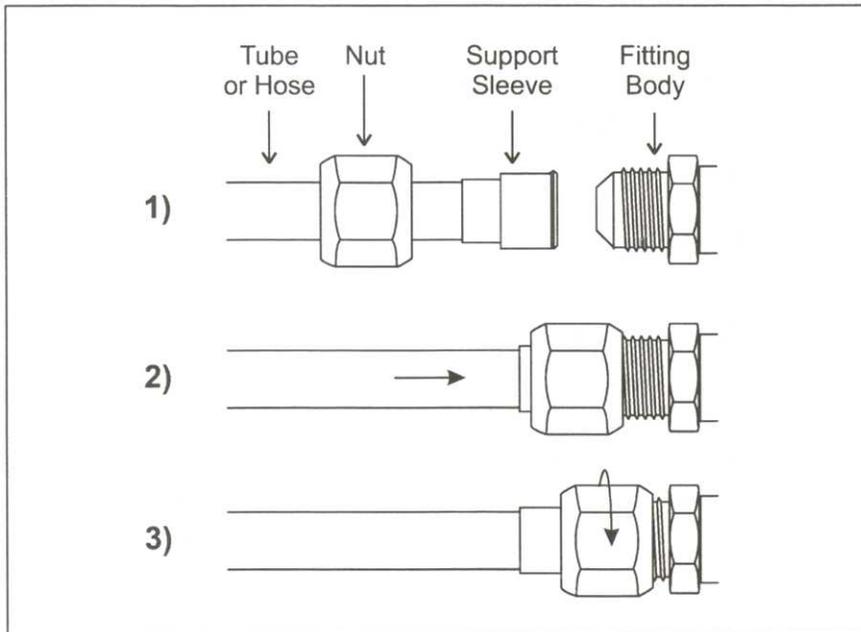


Figure 7-1 Fastening Flared Tube Fittings

Size	Thread Size	Torque (in-lb)	Torque (ft-lb)	Tube Connection (Flats)	Swivel Nut or Hose Connection (Flats)
-2	5/16-24	40 ± 5	3 + 1	-	-
-3	3/8-24	70 ± 5	6 ± 1	-	-
-4	7/16-20	140 ± 10	12 ± 1	2	2
-5	1/2-20	180 ± 15	15 ± 1	2	2
-6	9/16-18	250 ± 15	21 ± 1	1½	1¼
-8	3/4-16	550 ± 25	45 ± 2	1½	1
-10	7/8-14	700 ± 50	60 ± 5	1½	1
-12	1 1/16-12	1000 ± 50	85 ± 5	1¼	1
-14	1 5/16-12	1250 ± 50	105 ± 5	1	1
-16	1 5/16-12	1450 ± 50	150 ± 5	1	1
-20	1 5/8-12	2000 ± 100	170 ± 10	1	1
-24	1 7/8-12	2400 ± 150	200 ± 15	1	1
-32	2 ½-12	3200 ± 200	270 ± 20	1	1

Table 7-1 Flared Tube Fitting Torque Specifications

Re-tighten existing flared tube fittings only. New flared tube fittings must be swaged according to manufacturer's specifications using approved equipment.

Key Points & Notes



7.1.3.2 Compression Fittings

Compression fittings are commonly used on fuel lines and are rated to very high pressure. Each fitting consists of a tube, on which two ferrules are swaged and a nut is free to move, and a fitting body that includes male threads.

When fastening pre-swaged compression fittings:

1. Ensure that all parts are clean and undamaged.
2. Insert the tube with pre-swaged ferrules into fitting body until front ferrule seats. Do not apply Teflon tape or other thread compounds to the threads of fittings, ferrules or seat.
3. Tighten the nut by hand, then tighten the nut with a wrench 1/4 turn beyond the original position (an increase in resistance occurs at the original position).

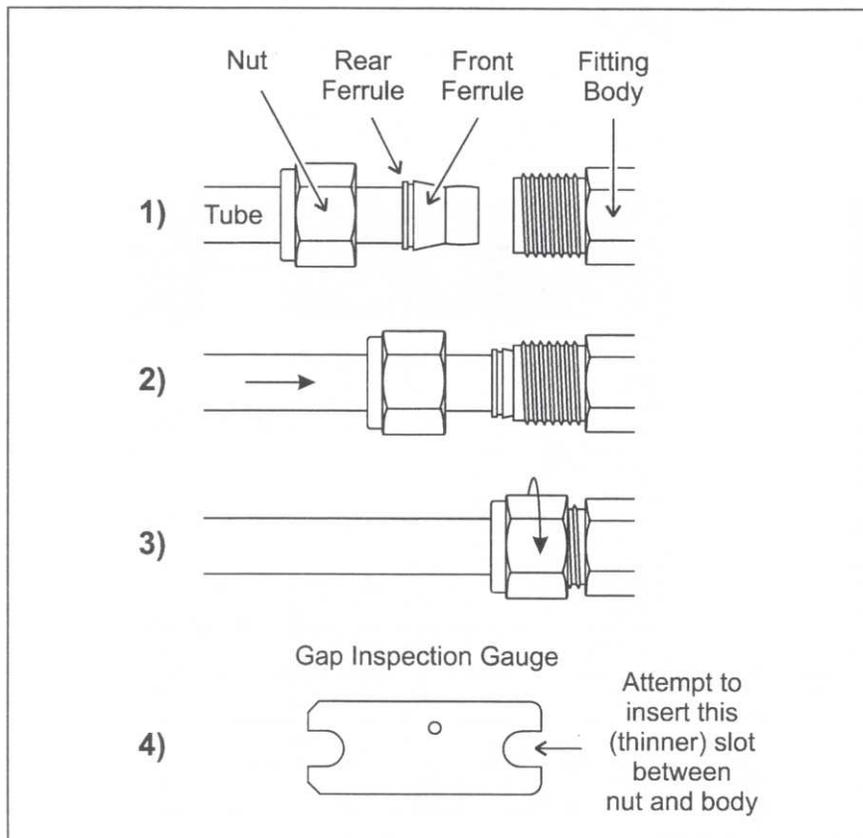


Figure 7-2 Fastening Compression Fittings

4. Attempt to insert *the thin end* (with rounded corners) of a gap inspection gauge (for the appropriate size of tube) between the nut and fitting body: if it fits, further tighten the nut and re-test; if it does not fit, the nut is sufficiently tightened. Six different gap inspection tools are required, for $\frac{1}{8}$ ", $\frac{1}{4}$ ", $\frac{3}{8}$ ", $\frac{1}{2}$ ", $\frac{3}{4}$ ", and 1" tubes.

Re-tighten existing compression fittings. New compression fittings must be swaged according to manufacturer's specifications.

Key Points & Notes



7.1.3.3 Pipe Thread Fittings

Pipe thread fittings are commonly used on all manner of fluid and gas connections. Each fitting consists of a tapered thread that forms an interference fit with a mating tapped hole. Teflon tape or sealant is added to the pipe threads to aid in seal formation.

When fastening pipe thread fittings:

1. Remove any old Teflon tape or sealant from the pipe threads.
2. Apply ample new Teflon tape to the pipe threads (typically two to three turns). Ensure that the leading 1.5 threads remain clear of tape to prevent orifice blockage.
3. Screw the two components together until tight: use only wrench flats provided when applying torque (never use sleeves or enclosures). Do not exceed the following tightening torques:

$\frac{3}{8}$ " NPT: 225 in-lb (25 Nm)

$\frac{1}{2}$ " NPT: 300 in-lb (34 Nm)

$\frac{3}{4}$ " NPT: 450 in-lb (50 Nm)

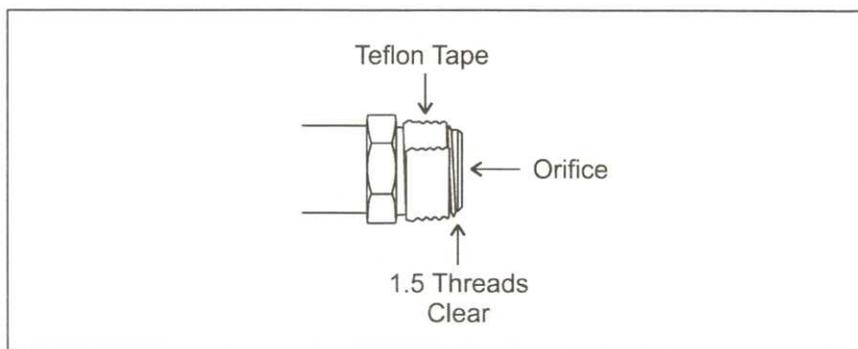


Figure 7-3 Pipe Thread Fitting

If an adequate seal cannot be achieved, replace the fitting or component as required.

7.1.3.4 Quick-Connect Fittings

Key Points & Notes

Quick-connect fittings are commonly used on fluid or gas lines that must be disconnected frequently or while under pressure. Each fitting consists of a stem and a body and the body is surrounded by a sleeve. The body, and sometimes the stem, contains a built-in check valve to minimize content spillage when disconnected.

When using quick-connect fittings:

- To couple, align stem with body and push stem into body until it clicks into place.
- To uncouple, pull body sleeve towards stem.

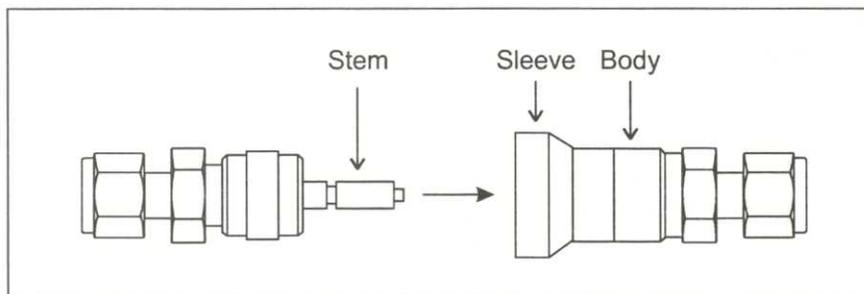


Figure 7-4 Quick-Connect Fitting

7.1.4 Valves

Fuel cell engines use a variety of valves for isolating and controlling gas and liquid flow. Some of the most common are described in the following sections.

7.1.4.1 Shutoff Valves

Shutoff valves are used on liquid and gas lines to interrupt or permit flow. Shutoff valves are also known as 2-way valves since they have two possible flow configurations: open and closed.

To use shutoff valves:

- The valve is open when the handle is parallel to the pipe on which it is mounted.
- The valve is closed when the handle is perpendicular to the pipe on which it is mounted.

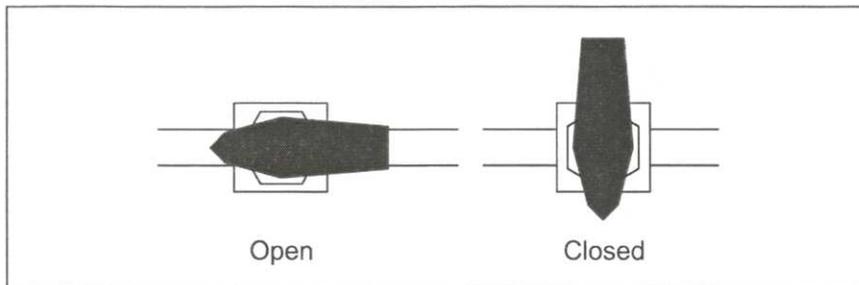


Figure 7-5 Shutoff Valve Use

7.1.4.2 Three-Way Valves

Three-way valves are used on fluid and gas lines to interrupt flow, or permit flow in either of two directions. Three-way valves therefore have two flow positions and one off position.

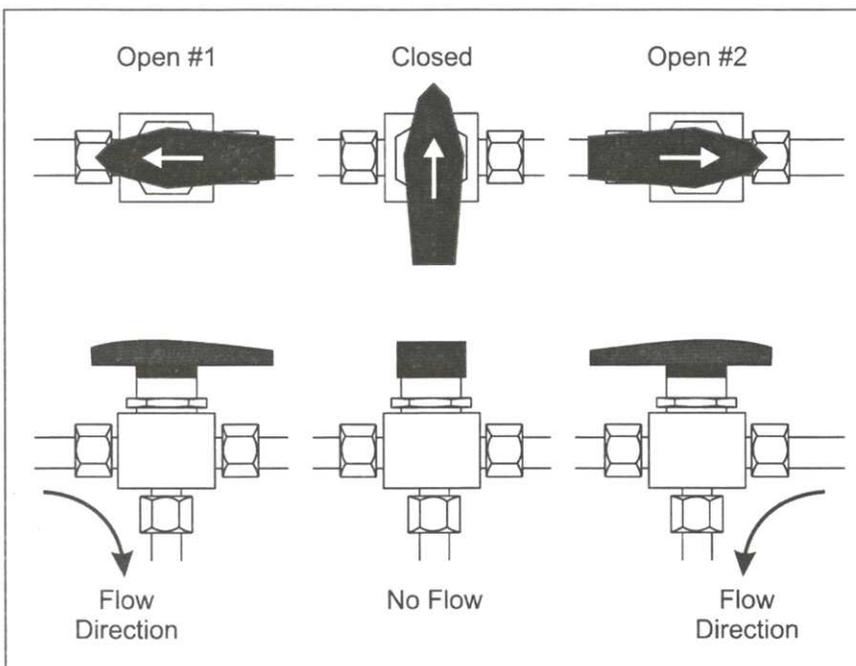


Figure 7-6 Three-Way Valve Use

To use three-way valves:

- The valve is open when the handle is parallel to the pipe on which it is mounted; the flow path passes between the direction the handle points and the outlet at the bottom of the valve
- The valve is closed when the handle is perpendicular to the pipe on which it is mounted.

Key Points & Notes

7.1.5 Materials

Key Points & Notes

A fuel cell bus uses special materials to prevent contamination of the fuel cells and to provide resistance to hydrogen embrittlement. These material restrictions apply to all process lines that pass fuel, air or coolant to or from the fuel cell stacks and apply equally to the system plumbing (lines, interface fittings or connections) and component part construction.

Use only the materials specified. Failure to do so may lead to component failure or damage to the fuel cells.



- For any *wet* or *dry* fluid or gas components:

Use 316 stainless steel, Teflon, EPDM, or Viton

- For any *dry* fluid or gas components, or *wet* components that are *not in direct contact* with process fluids that pass through the fuel cell stacks (such as the hydraulic fluid circuit):

Use 316 stainless steel, Teflon, EPDM, Viton, brass, copper, carbon steel, zinc, aluminum or Buna N. Stainless steel has better hydrogen embrittlement resistance than carbon steels.

- At all times:

No rare earth metals, alkali metals and alkaline earth metals. These metals react with hydrogen.

- All components must be kept free of contaminants. In particular, all surfaces and components must be kept free of oils, sulfur containing pipe dope, dirt, sand, rust, metal shavings and other particulates.

Key Points & Notes



7.1.6 Cleaning

A fuel cell bus requires special cleaning solutions and methods to prevent contamination of the fuel cells and to protect the hydrogen storage cylinders. Different cleaning procedures apply to each of the following four categories:

Fuel Cell Stacks And Membrane Humidifiers

Use only a dry or damp cloth when cleaning the fuel cell stack or membrane humidifier surfaces. **Never use solvents, steam, or soap or allow them to contact the components in any way. These solutions can be absorbed by the fuel cell stack or membrane humidifiers and can cause serious damage.**



Fuel Cell Engine Process Component Interior Surfaces

Use only manufacturer approved cleaning solution when cleaning the interior of any component (other than the fuel cell stacks) that passes fuel, air or coolant to or from the fuel cell stacks. **Never use soap or solvents (such as varsol, acetone, methyl-ethyl-ketone, paint thinner, lacquer thinner, gasoline, alcohol, etc.). These solutions may leave residues that could cause serious damage to the fuel cells.**



Fuel Cell Engine Exterior Surfaces

Key Points & Notes

Use standard cleaning procedures when cleaning fuel cell engine *exterior* surfaces provided that no soap or solvents contact the fuel cells or the interior of process components in any way. Use water and cleaning solution sparingly. For intensive cleaning, remove the stacks and seal manifold interfaces thoroughly to prevent contact. Do not use steam since this may penetrate electronic components or process streams.

Bus Exterior and Standard Bus Equipment (Including Hydrogen Storage Cylinders)

Use standard cleaning procedures when cleaning the exterior of the bus provided that no soap or solvents contact the fuel cells or the interior of process components in any way.

The soaps used in transit authority bus wash facilities are benign to the hydrogen storage cylinders. **Never expose the cylinders to unapproved soaps or any solvents. These solutions may corrode, weaken or seriously damage the cylinders.**



7.1.7 Fluids

A fuel cell bus uses specific fluids within its systems. Some of these fluids are different from those used on a conventional powered bus.

Humidification Water

The humidification system uses pure de-ionized (distilled) water. Regular water is not suitable as the ions in it would cause short-circuits within the fuel cells. De-ionized water must be stored in non-metal containers to prevent ion accumulation or passed through a de-ionizing filter prior to use. Do not re-use de-ionized water.

Use only pure de-ionized (distilled) water. Do not use tap water, drinking water or any other liquid.

*Stack Coolant*

The stack coolant system uses either de-ionized (distilled) water, or a custom mixture of de-ionized water with pure ethylene glycol. Regular water is not suitable as the ions in it would cause short-circuits within the fuel cells. Regular ethylene glycol is not suitable as it contains additives that can damage the fuel cell stacks. Pure propylene glycol is not suitable as it has insufficient cooling capacity. Used stack coolant may be re-used if kept clean.

Use only de-ionized (distilled) water with or without pure ethylene glycol solution as specified by the manufacturer. **Do not use tap water, drinking water, regular ethylene glycol, propylene glycol or any other liquid. Never add leak inhibitors or other additives.**

Bus Coolant

The bus cooling system uses a standard water/ethylene glycol solution since it never comes into direct contact with the fuel cell stacks. A propylene glycol solution is not suitable as it has insufficient cooling capacity. Used bus coolant may be re-used if kept clean.

Lubrication Oil

The lubrication system uses a specified synthetic oil of specific viscosity. This oil has been specially selected for its low vapor pressure property so that oil is less likely to enter the air stream that passes through the fuel cell stacks. Used lubrication oil may be re-used if kept clean.

Use only the specified lubrication oil. Never substitute other oil brands or viscosities.

Hydraulic Fluid

The hydraulic system uses a specified hydraulic fluid, typically commercial-grade automatic transmission fluid. Used hydraulic fluid may be re-used if kept clean.

Use only the specified hydraulic fluid. Do not substitute other fluid brands or specifications without prior permission from the bus manufacturer.

Transmission Fluid

The transmission fluid circuit uses a specified, commercial-grade automatic transmission fluid. Used transmission fluid may be re-used if kept clean.

Use only the specified transmission fluid. Do not substitute other fluid brands or specifications without prior permission from the transmission manufacturer.

HVAC Compressor Oil

The HVAC compressor uses a specified, commercial-grade compressor oil. This oil has been selected for its compatibility with the type of refrigerant used. Use of other oils may lead to air conditioning equipment damage. Used compressor oil may be re-used if kept clean.

Key Points & Notes



Use only the specified HVAC compressor oil. Do not substitute other fluid brands or specifications without prior permission from the air conditioner manufacturer.

Key Points & Notes

7.1.8 Hoisting and Jacking

Lift or jack a fuel cell bus using standard bus manufacturer procedures with an awareness of the following special considerations:

- A fuel cell bus typically weighs approximately 5000 lb (2300 kg) more than a diesel bus, and about 2200 lb (1000 kg) more than a CNG bus. Ensure that hoisting and jacking equipment is capable of safely supporting this weight.
- A fuel cell bus is taller than a diesel bus, especially with a roof canopy open. Ensure that sufficient space exists when hoisting or jacking the bus.
- Avoid lifting or supporting a fuel cell bus from the rear unless absolutely necessary since this may strain the fuel cell engine and/or the support chassis. **Never lift or support the bus from the rear unless all support struts are in place. Lifting or supporting the bus without the rear support struts could cause structural damage.**



7.1.9 Towing and Pulling

Towing and pulling instructions for a fuel cell bus vary according to whether the distance is less or greater than one mile (1.6 km). As an alternative to towing, the bus may be transported on a flatbed bus trailer.

Distances Greater Than One Mile

When transporting a fuel cell bus over distances greater than one mile (such as returning the bus to the transit facility after a road breakdown), tow or pull the bus using standard bus manufacturer procedures with the following restrictions:

- Disconnect the driveshaft or remove the rear axle shafts. This prevents transmission damage since it is not actively lubricated when the engine is off. It is not sufficient to place the shift selector in neutral and flat tow the bus.
- The bus may be towed from either the front or the rear. If towed from the rear, ensure that all rear support struts are in place. Towing the bus without the rear support struts in place could cause structural damage.

Distances Less Than One Mile

Key Points & Notes

When transporting a fuel cell bus over distances less than one mile (such as moving the bus within the transit facility), flat-tow or pull the bus from either the front or the rear without disconnecting the driveshaft or removing the rear axle shaft provided that:

- the towing distance does not exceed one mile (1.6 km)
- the towing/pulling speed does not exceed 5 mph (8 km/h)
- there has been no major failure within any portion of the power train
- there has been no loss of oil or fluid from the power train
- the shift selector is in neutral mode
- the towing/pulling occurs on structural components only

Do not flat tow or pull the bus even over short distances unless all above conditions are met. Doing so may cause serious damage.



7.1.10 Welding and Heating

Special safety precautions (in addition to those prescribed in standard bus welding procedures) must be applied when welding components or circuits on a fuel cell bus, or when heating components with oxygen/acetylene or propane equipment. Different welding and heating procedures apply to non-hydrogen bus chassis components and to hydrogen components and circuits.

Welding and heating are hazardous activities in the vicinity of hydrogen. Strictly follow these safety precautions.

*Non-Hydrogen Components or Circuits*

When welding or heating *non-hydrogen* bus chassis components or circuits, remove the component from the bus chassis if possible. If not:

1. Vent the fuel storage system (including all hydrogen storage cylinders) to 300 psig (21 barg).
2. Close all cylinder hand valves.
3. Disable the fire suppression system, if installed. (A welding arc near a fire sensor will cause it to trigger.)

4. Clamp the welding ground as close as possible to the weld area.
5. Protect stacks and fuel storage components from sparks and splatter.

Key Points & Notes

Hydrogen Components or Circuits

When welding or heating hydrogen components or circuits:

1. Isolate and vent the *hydrogen* circuit and remove component from bus
2. Weld the component away from the bus. Clean or passivate the component as required.
3. Allow component to cool to room temperature before re-installing.
4. Install the component into the bus.
5. Purge the hydrogen circuit if required.
6. When pressurized, leak test the circuit with special attention to all weld areas.

Never weld hydrogen components or circuits on the bus.



7.1.11 Parking and Storage

A fuel cell bus may be parked or stored at either an outdoor or indoor location provided all environmental and safety requirements are satisfied.

7. 1.11.1 Parking (0–1 Month)

Parking is defined as storing the bus for any period less than one month with the intention of continued operation. Parking of the bus requires attention to hydrogen safety and to freeze protection.

Hydrogen Safety

The parking location must accommodate potential hydrogen leaks. The on-board leak detection system typically inactive unless the engine is on. If the leak sensors have been unpowered for several days, they may take up to 24 hours of operation to stabilize. The fire suppression system, if installed, may be inactive when the battery knife switches are open (disconnected).

Indoor Parking

Key Points & Notes

When parking in a *hydrogen safe* facility (with specific leak detection, ventilation or electrical shut-off provisions), the fuel cylinders may remain pressurized. When parking in a *non-hydrogen safe* facility, the bus fuel cylinders must be vented to 10 psig (0.7 barg) prior to entrance. If parking the bus for several days, open (disconnect) the battery knife switches to prevent battery discharge.

Outdoor Parking

When parking outdoors, check the parking area for sources of ignition (such as operating electrical equipment) and overhead obstructions (such as wires or overpasses). If parking the bus for several days, open (disconnect) the battery knife switches to prevent battery discharge.

Freeze Protection

The parking location must prevent the fuel cell stacks from freezing at all times. All fuel cell stacks contain water in the air and hydrogen paths that is created during the power generation reaction and as a result of humidification.

In addition, some fuel cell stacks are cooled using pure de-ionized water, while others are cooled using a mixture of de-ionized water and ethylene glycol. If any of this water freezes, it can damage or destroy the fuel cell stacks. If the fuel cell stacks freeze in the absence of water, they may be harmed but not destroyed. Ice within other parts of the fuel cell engine can damage components.

Some fuel cell buses are equipped with freeze protection equipment that circulates warm water or heats specific areas in order to prevent freezing.

When parking the bus, ensure that the ambient temperature will not drop below 41 °F (5 °C). If the temperature may drop to this temperature, the options are:

- Operate the freeze protection equipment, if installed.
- Park the bus inside a heated facility. All heating equipment must conform to facility requirements (Section 10.2).
- Leave the engine running (only viable for short-term parking).
- Remove the stacks and store within a heated facility.

7.1.11.2 Short-Term Storage (1–4 Months)

Key Points & Notes

Short-term storage is defined as storing the bus for a period between one and four months with the intention to return the bus to operation. Short-term storage of the bus requires attention to hydrogen safety, freeze protection and to fuel cell stack ion protection.

Hydrogen Safety and Freeze Protection

Hydrogen safety and freeze protection for short-term storage is the same as for parking.

Fuel Cell Stack Ion Protection

Water in both the humidification system and the stack coolant system ionizes over time and can cause short-circuits within the fuel cells stacks. To minimize ionization, drain the humidification and coolant circuits.

When returning the bus to service, the humidification water and stack coolant circuits should be flushed with de-ionized water to remove residual ions from the fuel cell stacks. The on-board de-ionizing filters may become saturated with ions and need to be replaced. The control system may not permit the engine to start if the level of ionization is excessive.

7.1.11.3 Long-Term Storage (4+ Months)

Long-term storage is defined as storing the bus for a period or more than four months with no intention to operate the bus within the foreseeable future. Long-term storage of the bus requires attention to hydrogen safety, freeze protection and to fuel cell stack ion protection.

Hydrogen Safety and Freeze Protection

Hydrogen safety and freeze protection for long-term storage is the same as for parking.

Fuel Cell Stack Ion Protection

Long-term fuel cell stack ion protection requires fuel cell stack purges in addition to the short-term provisions. The purges blow compressed air through the fuel cell stacks to blow trapped water out of all circuits. The purges do not eliminate the need for fuel cell stack freeze protection.

7.1.12 Pre-Maintenance Preparation

Perform the following in preparation for fuel cell bus maintenance:

- Maintenance of the bus is normally done in a *hydrogen safe* facility (outfitted with hydrogen leak detection equipment and automated alarm response systems) that has been certified for full bus hydrogen pressure. To maintain the bus in a *non-hydrogen safe* indoor facility that does not have these safety provisions, vent the fuel storage system to 10 psig (0.7 barg).
- Record the fuel storage pressure.
- Apply lockout procedures.
- Wait five minutes after engine shut down before conducting any maintenance on the fuel cell engine components.
- Open (disconnect) the battery knife switches when servicing electrical components. This disconnects battery power from all circuits, and may disable the fire suppression system if installed.

Key Points & Notes

7.1.13 Post-Maintenance Checks

Perform the following power-off, power-on and engine-start checks after fuel cell bus maintenance:

Power-Off Checks

- Perform a leak-down test after any maintenance to the fuel delivery circuit or the fuel cell stacks.
- Perform a leak test and ground integrity on any hydrogen components or circuits that have been serviced.
- Ensure that the power cables are securely fastened to each stack and the inverter assembly.
- Ensure all electrical control cables have been connected.
- Ensure that all emergency shutdown switches are off.
- Ensure that all circuit breakers are closed.
- Ensure that the humidification, stack coolant, bus coolant, lubrication, hydraulic and transmission circuits have been filled and all vents are closed.
- Ensure that the bus chassis air system is pressurized to greater than 100 psig (7 barg).
- Ensure that all isolation valves are open on all circuits, including the cylinder shutoff valves.
- Ensure that the post-maintenance fuel storage pressure is not less than the pre-maintenance reading. If the current reading is lower, perform leak tests.

- Ensure that the amount of fuel pressure is adequate to start the bus (absolute minimum of 100 psig; 7 barg).
- Ensure that your lockout is removed.
- Check that there are no dangers around or under the bus.

Key Points & Notes

Power-On Checks

Close (connect) the battery knife switches:

- Check that all hydrogen leak indicators are powered.
- Check that all fire sensors are powered, if installed.
- Check that no alarms are active.
- Turn off the dump chopper pre-heat switch, if so equipped. When off, fuel cell power is not fed into the coolant by way of the dump chopper heater coils. This causes the fuel cell engine to warm more slowly which is advantageous in the event of a problem during startup. This switch is normally left on during normal operation.

Engine-Start Checks

Start the engine:

- If the engine fails to start, turn on the dump chopper pre-heat switch for two minutes to bleed residual voltage from the fuel cell stacks, if so equipped. Turn the switch off prior to the next start attempt.
- Have an assistant observe the rear of the bus and be prepared to shut off the engine if necessary.
- Check that the instrument panel, the message display centre, and other information systems are active and show no warnings, alarms or errors (other than a low fuel indication).

After two minutes of trouble-free operation:

- Check the humidification, stack coolant, bus coolant, lubrication, hydraulic and transmission fluid levels.

After five minutes of trouble-free operation:

- Turn on the dump chopper pre-heat switch, if so equipped.

7.2 Fuel System Operations

Key Points & Notes

7.2.1 Fueling

A fuel cell bus requires fueling when the hydrogen pressure in the cylinders drops to 500 psig (35 barg). At this fuel pressure, the bus provides a low fuel indication by way of dashboard lights, a message display centre or other means.

- At 500 psig (35 barg), there is fuel for about 25 miles (40 km)
- At 300 psig (21 barg), there is fuel for about 12 miles (20 km)
- At 100 psig (7 barg), fuel is absolutely essential
- At 50 psig (3.5 barg), the bus is unable to move

Fuel cell buses are fueled by way of a fueling receptacle, and are grounded during fueling by way of a grounding receptacle. These are typically located together at the rear of the bus within a special compartment. With some designs, the fueling compartment cannot be opened until the ground connection is made.

7.2.1.1 Fuel Specification

Hydrogen stored in high-pressure cylinders for fuel cell use must be very pure. In general, the fuel composition must be greater than 99.9% hydrogen, with no carbon monoxide or sulfides. Carbon monoxide and sulfide impurities can contaminate the catalyst within the fuel cells. Other impurities, although benign to the fuel cells, accumulate in the recirculating fuel delivery circuit and must be purged periodically, resulting in some hydrogen wastage.

7.2.1.2 Fueling Procedures

Hydrogen powered buses are normally fueled at a hydrogen fueling facility. When access to a fueling facility is not possible, a hydrogen tube trailer may bring fuel to the bus.

Fueling Facility Fueling Procedure

Perform pre-fueling checks. Verify that:

- the ambient temperature is above 40 °F (5 °C). If below this temperature, the fuel cell stacks must be protected from freezing. If the engine is warm and the fueling time is short, this is unlikely to be an issue. If the engine is not warm or the fueling time is long, external heat must



Fueling at BC Transit



Fueling at Chicago Transit

be provided in a manner that is compliant with fueling facility requirements.

Key Points & Notes

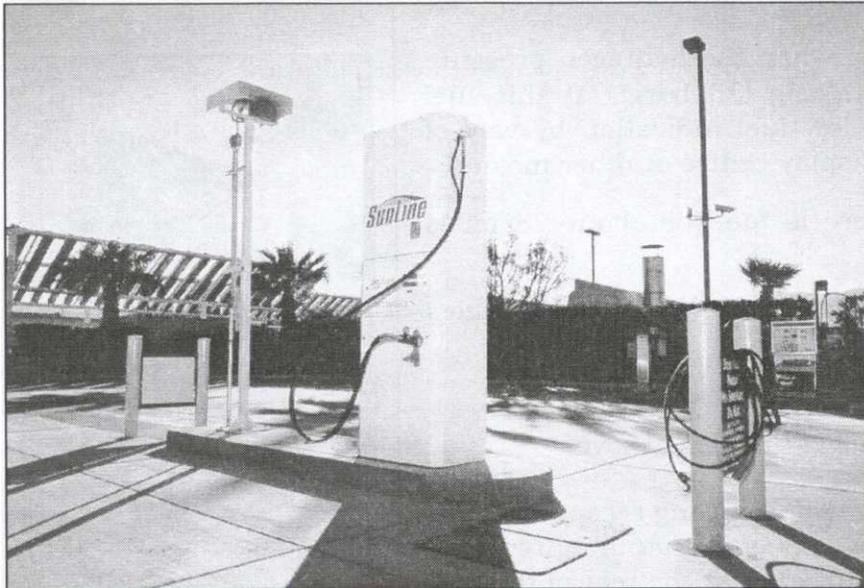


Figure 7-7 Hydrogen Fueling Station at SunLine Transit Agency

- all emergency fire equipment is in place
- no open flames, electric heat, sparks or smoking exist near the fueling site
- sufficient supply fuel pressure exists to fuel the bus the fueling supply hose is undamaged
- the fueling nozzle and internal O-ring (on hose) are clean and undamaged
- the fueling receptacle (on bus) is clean and undamaged

If any problems are found during the pre-fueling checks, do not continue with fueling.



Prepare the bus:

1. Turn the bus off, apply the parking brake, and chock the wheels.
2. Open (disconnect) the battery knife switches.
3. Record the fuel pressure.

Ground the bus:

4. Ground the bus to the fueling facility using the provided ground cable and receptacle. This is imperative to prevent static charge buildup.



MODULE 7: FUEL CELL BUS MAINTENANCE

Warning: Failure to provide an adequate ground may result in hydrogen auto-ignition during fueling.

Key Points & Notes

Make fueling connections:

Key Points & Notes

5. Remove the bus fueling receptacle cap. If it does not loosen by hand, a fault may have occurred and the receptacle may be pressurized; if this occurs, do not continue fueling.
6. Couple the fueling facility supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position. The nozzle and receptacle are designed to prevent air ingress into the supply hose and the bus.

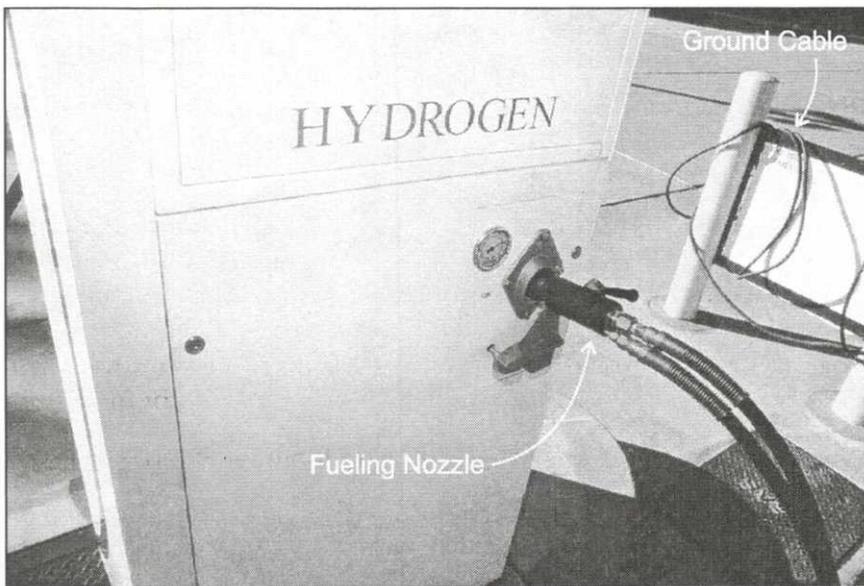


Figure 7-8 Hydrogen Fueling Equipment at SunLine Transit Agency

Fuel the bus:

7. Operate the fueling facility according to established procedures. The fueling station must never exceed the rated fueling pressure or temperature of the cylinders.

The fueling pressure of a cylinder is higher than the normal service pressure since the heat of compression raises the temperature of the fuel as it enters the cylinders. As the cylinders cool to ambient conditions, the pressure then drops accordingly. This pressure drop can be as much as several hundred psi and does not indicate a leak. Regardless of this pressure drop, cylinder manufacturers specify the maximum allowable pressure at any temperature. For example, a cylinder with a 3600 psig (250 barg) service pressure may never exceed 4040 psig (280 barg).

The maximum allowable cylinder temperature is a combination of the ambient temperature and the temperature



Automotive Fueling

rise during fueling. The temperature rise during fueling is governed by the fueling rate. The fueling station must therefore be calibrated to prevent cylinder overtemperature, or it must operate with reference to a temperature transducer located inside one of the bus fuel cylinders. A typical composite cylinder has a maximum allowable service temperature of 185°F (85°C) at any pressure.

Never exceed the cylinders' rated filling pressure or service temperature.

Key Points & Notes

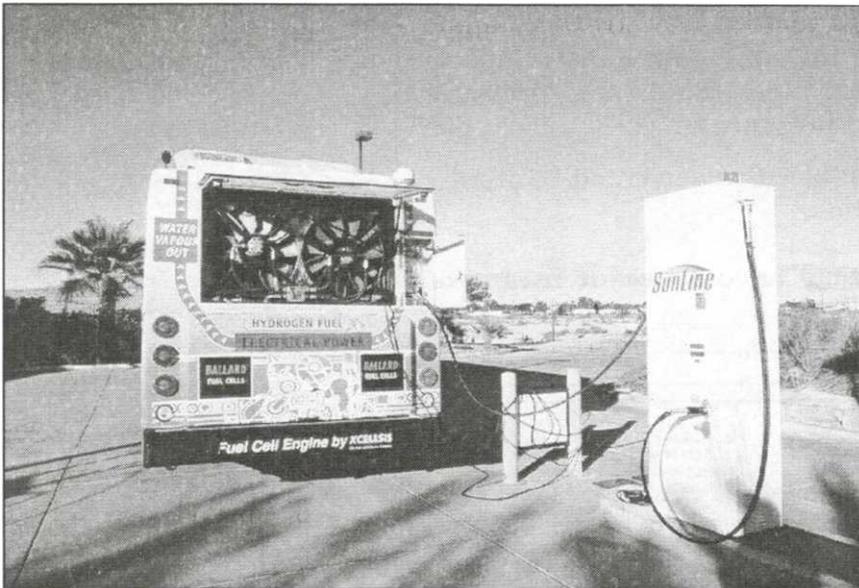


Figure 7-9 Fueling the XCELLSiS Phase 4 Bus at SunLine Transit Agency

After fueling:

8. Uncouple the fueling facility supply nozzle and re-cap, the fueling receptacle.
9. Remove the fueling facility ground connection from the bus.
10. Record the fuel pressure and complete a fueling log.
11. Close (connect) the battery knife switches and remove the wheel chocks.

Tube Trailer Fueling Procedure

A tube trailer may be used to fuel the bus when away from the fueling facility. Tube trailers are normally supplied at a maximum pressure of 2600 psig (180 barg) and are therefore not able to fully fuel the bus to the 3600 psig (250 barg) level. Typically, five tubes are required to fuel a bus to

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

2600 psig (180 barg). Tube trailer fueling must occur outdoors.

Key Points & Notes

A typical tube trailer is illustrated in Figure 7-10 and must include the following fueling equipment:

- A ground cable with a or suitable grounding clamp that can be attached to earth
- A ground cable capable of mating with the bus ground receptacle
- A fuel supply hose capable of mating with the bus fueling receptacle. The fuel supply hose must be constructed of synthetic material, stainless steel braid, and pressure tested to 1.5 times the rated pressure.
- A 3-way manual tube trailer bleed valve vented to atmosphere (to purge the supply hose)

Note: Different tube trailers may have different means of purging the supply hose.

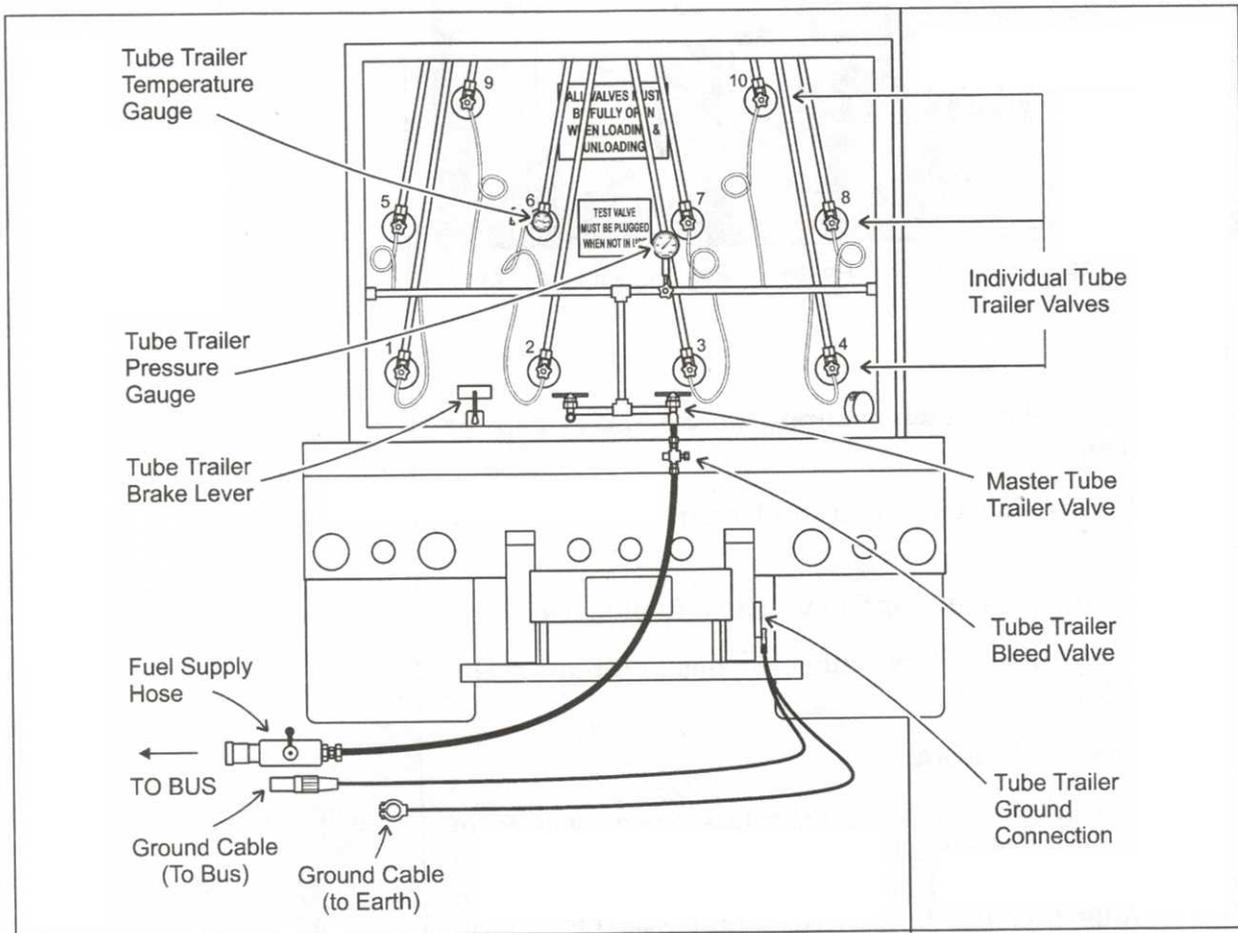


Figure 7-10 Typical Hydrogen Tube Trailer

Perform pre-fueling checks and prepare the bus as during facility fueling. Verify that:

- ambient conditions are suitable
- no ignition sources exist all emergency equipment is in place
- the fueling supply hose, nozzle and receptacle are undamaged
- the engine is off, the parking brake is on, and the wheels are chocked
- the battery knife switches are open
- the fuel pressure has been recorded

Warning: If any problems are found during the pre-fueling checks, do not continue with fueling.



Check the tube trailer pressure:

1. Ensure that the tube trailer's pressure gauge indicates at least 500 psi (35 bar) more than the bus fuel pressure.

Make ground connections:

2. Connect the tube trailer ground cable connector to earth.
3. Connect the bus ground cable to the bus grounding receptacle.

Purge the supply hose of air:

4. Open the master tube trailer valve.
5. Ensure that the fueling receptacle is not attached to the bus.
6. Set the tube trailer bleed valve so that the gas flows into the supply hose.
7. Open any individual tube trailer valve; this pressurizes the fuel supply hose.
8. Close the individual tube trailer tank valve.
9. Set the tube trailer bleed valve so that the gas vents to atmosphere.
10. Set the tube trailer bleed valve so that the gas flows into the supply hose.
11. Repeat for a total of three times.

Key Points & Notes

Make fueling connections:

Key Points & Notes

12. Remove the bus fueling receptacle cap. If it does not loosen by hand, a fault may have occurred and the receptacle may be pressurized; if this occurs, do not continue fueling.
13. Couple the fueling facility supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position. The nozzle and receptacle are designed to prevent air ingress into the supply hose and the bus.

Fuel the bus using only one tube trailer tank at a time:

14. Open any individual tube trailer valve so that gas flows into the bus. Fuel the bus using only one tube trailer tank at a time.
15. Continue to fuel the bus until the sound of rushing gas stops. The bus fuel pressure should be within 200 psi (14 bar) of the supply pressure as indicated on the tube trailer pressure gauge.
16. Close the individual tube trailer valve and open another tank's valve.
17. Repeat until the bus fuel pressure matches that in any of the individual tube trailer tubes, or the tube trailer is depleted.
18. Close the master tube trailer valve, and ensure that all other individual tube trailer valves are closed.

Never exceed the cylinders' rated filling pressure or service temperature.



Perform post-fueling activities as during facility fueling. Verify that:

- the fueling facility supply nozzle has been disconnected and the fuel receptacle cap has been installed
- the facility ground connector has been removed
- the fuel pressure has been recorded
- the knife switches are open

After completion:

19. Set the tube trailer bleed valve so that the gas trapped in the supply tube vents to atmosphere.

7.2.2 Venting

Key Points & Notes

Hydrogen resides under three different pressures within a fuel cell powered bus: high, motive and low. The high and motive-pressures are contained within the fuel storage system, and the low-pressure is contained within the fuel delivery circuit.

High-pressure hydrogen at up to the storage capacity of hydrogen cylinders resides in the cylinders and high-pressure circuit as far as the motive pressure regulator. This cylinder pressure reduces as hydrogen is consumed by the engine. The cylinders and high-pressure circuit are pressurized at all times, and can be vented manually through the vent valve.

Motive-pressure hydrogen at an intermediate pressure (typically 178 psig; 12 barg) exists during engine run between the motive pressure regulator and the pressure regulator of the fuel delivery circuit.

Low-pressure hydrogen at nominally 20 to 30 psig (1.4 to 2 barg) exists during engine run downstream of the pressure regulator and includes all components that circulate the hydrogen through the fuel cell stacks. The actual pressure is set to match the instantaneous air pressure entering the fuel cell stacks.

The motive and low-pressure circuits automatically vent upon bus shutdown, and remain open to atmosphere whenever the engine is off.

The terms depressurizing, venting and de-fueling all mean the release of gas from a vessel. The term *venting* is used here to mean the discharge of hydrogen from the fuel storage system. The term *de-fueling* is used to mean the capture of released hydrogen for future use; the reverse of fueling. Whenever venting is required, de-fueling is a superior option where facilities exist as it conserves hydrogen. Specific de-fueling procedures are determined by the de-fueling facility.

Venting of the fuel storage system (cylinders and high-pressure circuit) is not required when the bus is going into a *hydrogen safe* facility (with specific leak detection, ventilation or electrical shutoff provisions).

Venting of the fuel storage system to 10 psig (0.7 barg) is required when the bus is going into a *non-hydrogen safe* facility or prior to some maintenance procedures.

Venting to atmospheric pressure (0 psig/barg) is required prior to maintenance access of cylinders or high-pressure

circuit components. Venting of cylinders must be accompanied by nitrogen and hydrogen purges before returning to service.

Venting cylinders to 0 psig (0 barg) will potentially allow oxygen to enter the fuel cylinders!

7.2.2.1 Fuel Venting Equipment

Fuel cell buses include a roof-mounted vent valve to facilitate venting. In order to vent the fuel storage system, its high-pressure circuit and/or one or all of its cylinders, a facility venting tower or a portable venting tube must be connected to the vent valve. Typical venting equipment is shown in Figure 7-11. Direct opening of the vent valve is unacceptable since the hydrogen would be discharged in an undirected manner, thereby increasing potential damage to surrounding components and exposing personnel to an asphyxiation hazard.

Facility Venting Tower

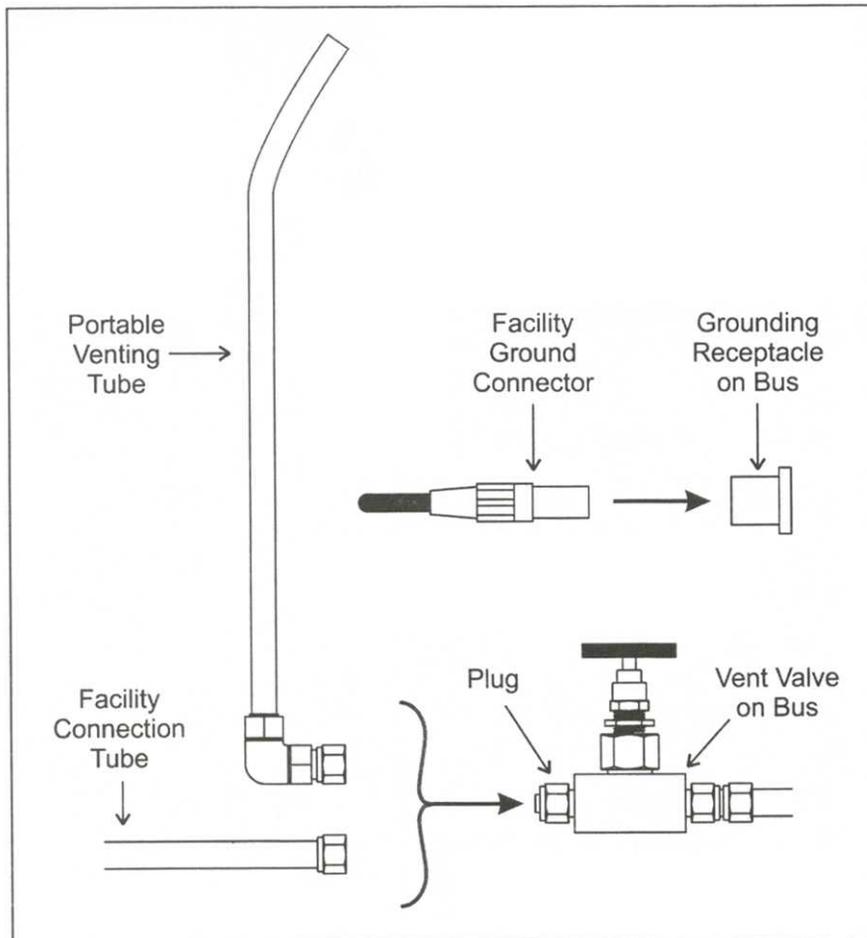
A facility venting tower is the preferred device for venting hydrogen from the high-pressure circuit or cylinders. The facility venting tower connects to the vent valve (by way of a tube) and directs the hydrogen to a remote location where it is released into the atmosphere. A facility ground connection connects to the bus and prevents static charge buildup.

Portable Venting Tube

A portable venting tube is designed for venting or purging the high-pressure circuit and cylinders whenever a facility venting tower cannot be used. The portable venting tube connects to the vent valve and releases hydrogen above the level of the canopies. The tube and vent valve are both metal, so the portable venting tube is grounded to the high-pressure circuit once attached. It may not always be possible to attach the bus to a ground reference point when venting in the field. For this reason it is always preferable to vent at a facility with a proper ground connection.

Key Points & Notes





Key Points & Notes

Figure 7-11 Typical Venting Equipment

7.2.2.2 Facility Venting

Venting usually occurs at a designated facility, often in conjunction with the bus fueling equipment.

When venting, heed the following warnings:

- Heed all rooftop warnings and cautions (Section 7. 1. 1).
- Wear eye and hearing protection at all times when venting. Gas venting can be very noisy.
- Keep all sources of ignition away. Do not smoke.
- Do not vent during an electrical storm.
- Each cylinder has an internal excess flow valve that closes if venting with an excessive flow rate. This can give the false impression that the cylinder has depressurized whereas it remains at a potentially high pressure. Accessing a cylinder in this condition is extremely dangerous; furthermore, the valve may re-open after several minutes expelling the remaining cylinder contents.



To ensure complete venting, never open the vent valve more than one turn. After venting, close the vent valve, wait five minutes, and re-check the high-pressure gauge before accessing any high-pressure component. This waiting period permits any closed excess flow valves to reset.

Key Points & Notes

Prepare to vent:

1. Park the bus in the designated venting area only and turn off the engine. Apply the parking brake and chock the wheels.
2. Insert the facility ground connector into the bus grounding receptacle.
3. Open and latch the canopy.
4. Ensure that vent valve is closed.
5. Slowly unfasten the plug from the vent valve.
6. Fasten the facility venting tower connection tube or the venting tube to the vent valve.
7. Ensure that the cylinder hand valves are *open* on any cylinder that needs to be vented. *Close* the cylinder valves on any cylinder that should *not* be vented. When venting the fuel storage system, hydrogen flows from the high-pressure circuit and from any cylinders with open hand valves.
8. Open the cylinder solenoid valves. These valves are normally open during operation and closed whenever the engine is off. Consequently, the solenoid valves must be opened using some specific sequence of switches on the side console and/or engine compartment that has been programmed into the control system. Listen for the clicking sound of the cylinder solenoid valves opening. Since the solenoid valves must remain open throughout venting, the battery knife switches must remain closed (connected).

Vent fuel:

9. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

An excessive venting flow rate causes the cylinders' internal excess flow valve to close.



10. Have an assistant monitor the fuel pressure and allow the system to vent to the specified pressure. If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.
11. Once venting is complete, close the vent valve.
12. Wait five minutes and re-read the fuel pressure. If the pressure has increased, re-open the vent valve to resume venting. If the pressure remains the same, proceed as below

Key Points & Notes

Complete:

13. Close the cylinder solenoid valves using a specific sequence of switches defined by the bus manufacturer.
14. Unfasten the facility venting tower connection tube or the venting tube from the vent valve.
15. Re-fasten the cap on the vent valve.
16. Unlatch and close the canopy.
17. Remove the facility ground connector from the grounding receptacle.

7.2.2.3 Emergency Venting

Venting normally occurs at the facility fueling station. If the fuel *must* be vented away from the fueling station, locate the bus away from sources of ignition and overhead obstructions, such as:

- open flames
- operating electrical equipment
- overhead power lines
- electrical storms
- overhead roofs, canopies or bridges

Venting with a portable venting tube is the same as for facility venting procedure except for the absence of a ground connection.

7.2.3 Purging

Key Points & Notes

Purges flush residual gases from the fuel storage system and are used *after* cylinder maintenance, or any time the cylinder pressure has vented to atmospheric (0 psig). Purges are not required *before* servicing the cylinders or high-pressure circuit. Once vented to atmospheric pressure, the residual gas volume within the fuel storage system is too small to pose a combustible gas hazard.

A nitrogen purge eliminates air from the cylinders prior to re-exposure to hydrogen, thereby preventing the formation of a potentially combustible gas. When returning the cylinders to service, a hydrogen purge flushes out the nitrogen from the nitrogen purge, and leaves only pure hydrogen in the cylinders.

Purges are not normally performed after servicing the other high-pressure circuit components. Any residual air within the high-pressure circuit after service is automatically purged during engine operation. Purges are not required when servicing components of the motive circuit or the fuel delivery circuit. These circuits vent and are exposed to air whenever the engine is shut down, and are automatically purged during operation.

Nitrogen Purge

Nitrogen purges require a source of regulated nitrogen that is introduced through the fueling receptacle and vented through the vent valve. The vent valve must be connected to the facility venting tower connection tube or a portable venting tube.

Typical nitrogen purge equipment is illustrated in Figure 7-12 and must include:

- Multiple standard T bottles of nitrogen (99.99% minimum purity)
- To nitrogen purge one cylinder, one bottle is normally sufficient. Six bottles are required to purge eight cylinders. **Note: For convenience and speed, the bottles should be connected to a common manifold.**
- A nitrogen supply hose capable of mating with the bus fueling receptacle. The fuel supply hose must be constructed of synthetic material, stainless steel braid, and pressure tested to 1.5 times the rated pressure.



Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

- a venting pressure regulator (4,000-psig (275-barg) inlet; 300-psig (21-barg) outlet) with inlet and outlet pressure gauges

Key Point & Notes

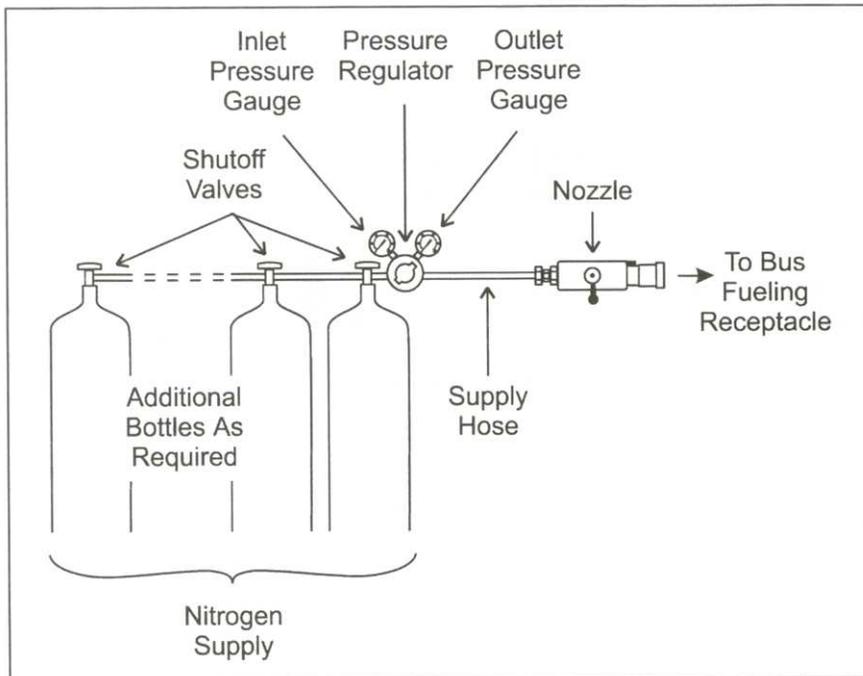


Figure 7-12 Typical Nitrogen Purge Equipment

Prepare to nitrogen purge just like during venting. Verify that:

- the engine is off, the parking brake is applied, and the wheels chocked.
- the facility ground connector is properly fitted into the bus grounding receptacle.
- the bus vent valve is attached to the facility venting tower or portable venting tube, and the valve is closed.
- the fuel storage system and associated cylinders have been vented to atmospheric pressure.
- the cylinder hand valves are open on those cylinders that need to be purged, and closed on those cylinders that can remain pressurized.
- the cylinder solenoid valves are open.

Attach supply hose:

1. Remove the cap from the bus fueling receptacle, and couple the supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position.

Purge:

Heed all venting warnings when purging.

2. Open the shutoff valve on any of the nitrogen bottles.
3. Pressurize the fuel circuit to 100 psig (7 barg). Adjust the pressure regulator on the nitrogen supply as required.
4. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

An excessive venting flow rate causes the cylinders' internal excess flow valve to close.

5. Have an assistant monitor the fuel pressure and allow the system to vent to 10 psig (0.7 barg). If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.
6. Repeat purge for a total of three times, replacing nitrogen bottles as required.
7. Wait five minutes and re-read the fuel pressure. If the pressure has increased, repeat the purge procedure. If the pressure remains the same, proceed as below.
8. Proceed with a hydrogen purge if required.

Remove supply hose:

9. Uncouple the supply hose nozzle and re-cap, the fueling receptacle.

Complete the nitrogen purge just like during venting. Verify that:

- the solenoid valves are closed.
- the facility venting tower connection tube or venting tube has been removed from the vent valve, and the vent valve cap has been installed.
- the facility ground connector has been removed
- the canopies are closed.

Key Points & Notes



Hydrogen Purge

Key Points & Notes

Hydrogen purges require a source of regulated hydrogen that is vented through the vent valve. When purging the high-pressure circuit, plus at most a few cylinders, the hydrogen stored in the remaining cylinders may be used as a hydrogen source, provided those cylinders contain a minimum of 100 psig (7 barg) hydrogen.

If insufficient hydrogen volume exists in the remaining cylinders, a fueling facility or a tube trailer is required to provide hydrogen by way of the fueling receptacle. The vent valve must be connected to the facility venting tower connection tube or a portable venting tube.

During the hydrogen purge, it is essential to differentiate between those cylinders that *supply* the hydrogen and those that *receive* it. One supply cylinder with at least 100 psig of hydrogen is enough to purge the high-pressure circuit several times. Multiple supply cylinders with at least 100 psig of hydrogen are required to purge other cylinders.

Hydrogen purges only occur after cylinder service, and only following a nitrogen purge. With respect to this, verify that:

- the fuel storage system and associated *receiving* cylinders have been purged with nitrogen and vented to 10 psig (0.7 barg).
- the hand valves are *open* on the *receiving* cylinders (cylinders that need to be hydrogen purged) and *closed* on the *supply* cylinders (cylinders that remain pressurized with hydrogen).

In addition, prepare for the hydrogen purge just like during venting or a nitrogen purge. Verify that:

- the engine is off, the parking brake is applied, and the wheels chocked.
- the facility ground connector is properly fitted into the bus grounding receptacle.
- the bus vent valve is attached to the facility venting tower or portable venting tube, and the valve is closed.
- the cylinder hand valves are open on those cylinders that need to be purged, and closed on those cylinders that can remain pressurized.
- the cylinder solenoid valves are open.

Purge:

Key Points & Notes

1. Open the hand valve on one or more of the *supply* cylinders that contain at least 100 psig (7 barg) hydrogen.
- Have an assistant monitor the fuel pressure. Allow the circuit to pressurize to 100 psig and close all *supply* cylinder hand valves. If the pressure does not reach 100 psig, open the hand valves on additional *supply* cylinders. If all supply cylinder hand valves are open and the pressure still does not reach 100 psig, fuel the bus until the fuel pressure indicates 100 psig. Pressure greater than 100 psig is not required, but does no harm.
3. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

An excessive venting flow rate causes the cylinders' internal excess flow valve to close.



4. Have an assistant monitor the fuel pressure and allow the system to vent to 10 psig (0.7 barg). If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.
5. Repeat purge for a total of three times, adding additional hydrogen as required.
6. Wait five minutes and re-read the fuel pressure. If the pressure has increased, repeat the purge procedure. If the pressure remains the same, proceed as below.

Complete the hydrogen purge just like during venting or a nitrogen purge. Verify that:

- the solenoid valves are closed.
- the facility venting tower connection tube or venting tube has been removed from the vent valve, and the vent valve cap has been installed.
- the fueling facility supply nozzle has been disconnected and the fuel receptacle cap has been installed if fuel was added externally.
- the facility ground connector has been removed.
- the canopies are closed.

7.3 Routine Maintenance

Fuel cell bus routine maintenance can be divided into the following categories:

- **Fuel cell engine procedures** that are unique to fuel cell buses
- **Fuel system procedures** that are common to those found on CNG or hydrogen powered internal combustion engine buses
- **Conventional procedures** that are typical of those normally required on any bus, although different in detail when applied to a fuel cell bus
- **Standard coach procedures** that are identical to those performed on any bus, irrespective of the type of engine

Of these four service categories, the first three are described below whereas the fourth is not as it has no bearing on fuel cell engines or hydrogen fuel systems.

The following maintenance schedules and service information is based on the Phase 3 and 4 fuel cell buses designed and built by XCELLSiS Fuel Cell Engines, Inc. This information represents the most complete description of fuel cell bus maintenance currently available, although it cannot cover all hardware configurations and variations.

Fuel cell technology is evolving rapidly, and no two current bus designs are identical. With this in mind, the maintenance information is intended to be representative of the type of service required, why it is required, and how it is done in principal, without providing hardware-specific, step-by-step instructions.

Always refer to manufacturer's instructions when servicing a fuel cell bus.

Routine maintenance is performed at Daily, Weekly, 3750 Mile (6000 km), 7500 Mile (12,000 km), 15,000 Mile (24,000 km), and 30,000 Mile (48,000 km) service intervals, or at some variation of these intervals. Representative service schedules are presented in the following tables. Procedure descriptions are presented in Sections 7.4 to 7.6.

Key Points & Notes



Fuel Cell Buses Under Test



Daily Inspection and Service

Key Points & Notes

Fuel Cell Engine Procedures
Check ground fault monitor resistance and replace water or de-ionizing filter if required
Check stack vent fans
Inspect water traps
Inspect air system oil detector
Inspect hydrogen diffuser
Fuel System Procedures
Inspect burst disk vent cap
Conventional Procedures
Check leak indicators and sensors, and calibrate system if required
Check for fluid leaks or puddles
Check humidification water level
Check lubrication oil level
Check transmission fluid presence
Inspect air intake, air exhaust and canopies

Weekly Inspection and Service

Fuel Cell Engine Procedures
Perform leak-down test
Check cell voltage monitor
Fuel System Procedures
Perform fuel delivery circuit leak test
Conventional Procedures
Inspect fire suppression sensors
Clean stack vent fan filters
Inspect stack air inlet filters and replace if required
Inspect sintered air vents and clean as required
Inspect filter minder and replace air intake filter if indicated
Inspect lubrication oil sump magnetic plug
Drain turbocharger oil trap
Check transmission fluid level
Check hydraulic fluid level
Check stack coolant level
Check bus coolant level
Inspect hoses and tubes

3750 Mile (6000 km) Inspection and Service

Key Points & Notes

Fuel Cell Engine Procedures
Perform fuel cell external and transfer leak test
Perform glycol system integrity test
Check power cable connections
Fuel System Procedures
Perform high-and motive-pressure circuit leak test
Inspect high, motive and fuel delivery circuit components
Inspect roof vent caps
Compare fuel pressure transducer readings
Replace hydrogen particulate filter
Conventional Procedures
Inspect fire suppression hoses, nozzles and retardant tanks
Inspect belts
Inspect radiator
Inspect HVAC compressor oil
Inspect transmission

7500 Mile (12,000 km) Inspection and Service

Fuel Cell Engine Procedures
Check dump chopper resistance
Fuel System Procedures
Check the motive pressure regulator solenoid valve
Conventional Procedures
Take a lubrication oil sample
Take a transmission fluid sample
Take a hydraulic fluid sample

Hydrogen Fuel Cell Engines	MODULE 7: FUEL CELL BUS MAINTENANCE
-----------------------------------	--

15, 000 Mile (24, 000 km) Inspection and Service

Key Points & Notes

Fuel Cell Engine Procedures
None
Fuel System Procedures
Perform cylinder installation and external inspections
Perform ground integrity test
Conventional Procedures
Inspect and/or replace bus chassis air intake filter
Inspect and/or clean humidification water strainers
Replace lubrication system filter and oil
Replace hydraulic system filter and fluid
Replace transmission filters and fluid

30, 000 Mile (48, 000) Inspection and Service

Fuel Cell Engine Procedures
None
Fuel System Procedures
Perform cylinder internal inspection
Replace pressure regulator diaphragm, seal and seat replacement
Perform fire suppression system tests
Conventional Procedures
Inspect power train and stack vibration mounts

7.4 Fuel Cell Engine Procedures

Key Points & Notes

Fuel cell engine procedures pertain to routine service that is unique to fuel cell powered buses.

7.4.1 Ground Fault Monitor Check and Conditional De-Ionizing Filter Replacement

The ground fault monitor is an integral part of the inverter. The ground fault monitor measures the approximate electrical resistance between the fuel cell stack power connections and the bus chassis. A high resistance indicates that there is little or no power leakage onto the chassis (as it should be), and a low resistance indicates that a leakage current exists. A leakage current (or "ground fault") occurs wherever a short-circuit occurs. If the resistance is too low, the ground fault monitor generates a warning or alarm.

A ground fault can occur as the result of an electrical component failure, but most occurrences result from an increase in conductivity of the humidification water or stack coolant. As the ions found in normal water conduct electricity, both these circuits use de-ionized water.

The de-ionized water ionizes over time through contact with metal. Both the humidification water and stack coolant circuits have de-ionizing filters to remove the accumulating ions, but these filters degrade with time, especially at elevated temperatures. The ground fault monitor, therefore, becomes a useful indicator of filter condition as well as guarding against dangerous short circuits.

A ground fault monitor check consists of reading the resistance as measured by the ground fault monitor. Typically, this resistance can be read directly from the bus' diagnostics interface. Ground fault readings should be taken with the bus running at the end of the service day. This ensures that all water has passed through the de-ionizing filters and as many accumulated ions have been removed as possible. Premature testing results in a low measured resistance value:

- If the resistance is >200 k Ω no action is required
- If the resistance is <200 k Ω assess the results:
 - a) If the decrease in resistance is sudden, an electrical short may exist. Trace as required.
 - b) If the decrease in resistance has been gradual (over a period of days), water ionization may be increasing.

Replace the water sometime before the resistance drops to 120 k Ω . The resistance should increase during the subsequent engine run and remain above 200 k Ω for up to six weeks. If the water has been replaced within the last four weeks, replace the de-ionizing filters at the next convenient service interval. If the resistance drops below 40 k Ω , the filters must be replaced immediately.

Key Points & Notes

De-ionizing filter media consist of a mixture of resins that take the form of small beads of plastic material. These beads are used to fill large filters directly, or are arranged into cartridges for use in small filters. Filter canisters and cartridges are designed for easy replacement; this usually involves draining all or part of the corresponding water or coolant circuit, disconnecting fittings and undoing brackets. Large canisters can be emptied and refilled with new resin.

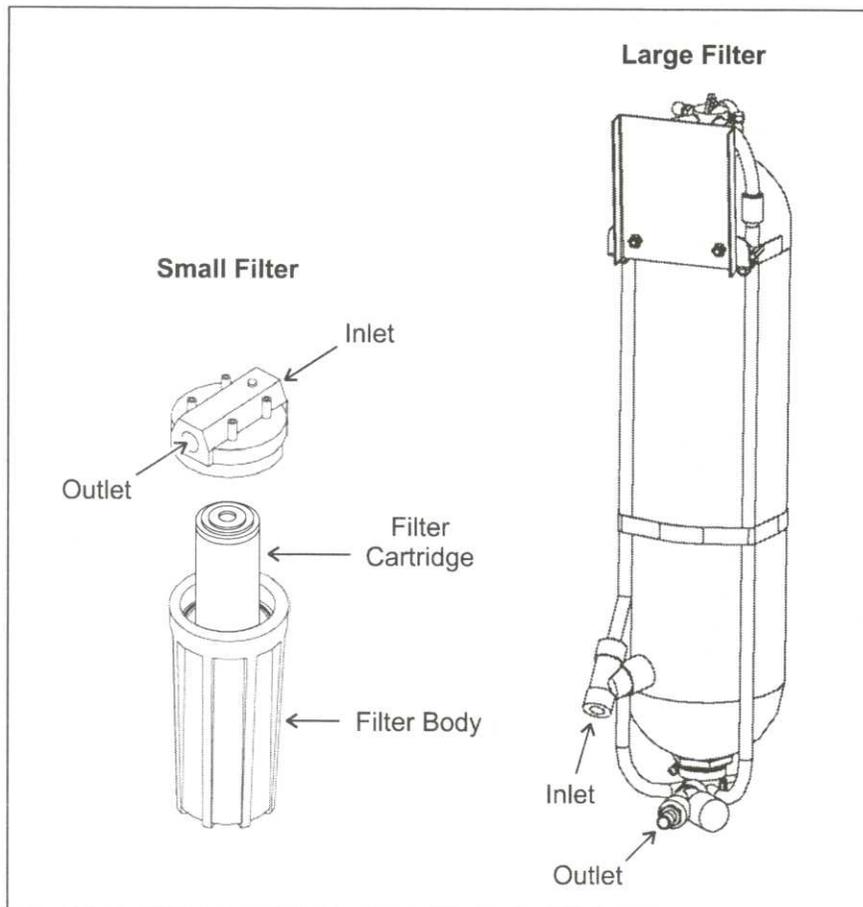


Figure 7-13 Typical De-ionizing Filters

7.4.2 Water Trap Inspections

Water traps allow the separation of liquid water from a gas stream while under pressure. In a fuel cell engine, water

traps are used when venting a wet gas stream, or when draining a water stream with entrained gas. Typical circuits include the hydrogen purge line, the hydrogen/water separator drain or the humidifier drain.

Water traps consist of a chamber through which the water/gas mixture passes and in which the water can condense and collect. A float at the bottom of the chamber opens and closes according to water level.

Water trap inspections consist of a visual confirmation that the water traps are half-filled with water, the float is not stuck open, and the float moves freely when jostled. If the water is not present or the float is stuck open, the gas discharges through the water outlet port. In the case of a hydrogen line, this causes hydrogen discharge and a flammable gas leak hazard. If the float does not move freely, the water may not drain as required. If the float does not function properly, the water trap must be replaced.

Key Points & Notes

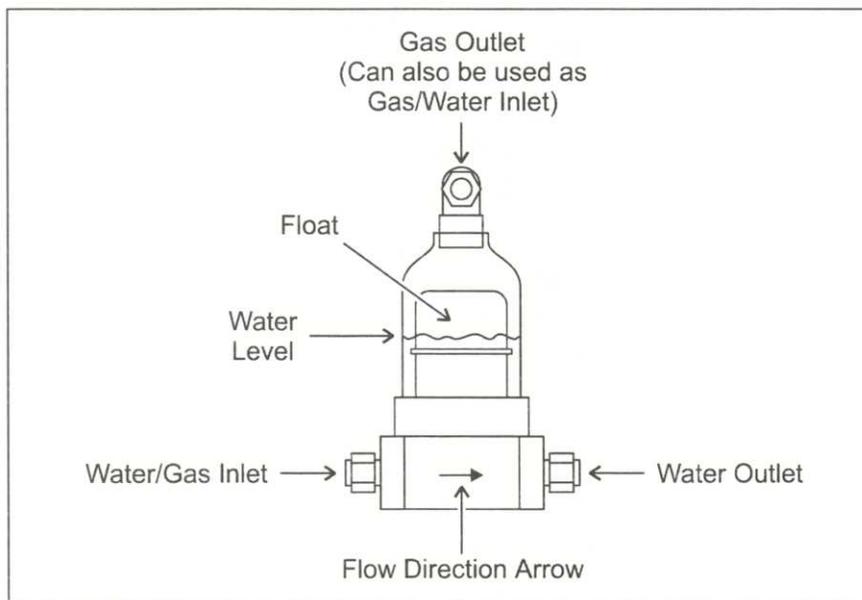


Figure 7-14 Typical Water Trap

7.4.3 Air System Oil Detector Inspection

The oil detector is installed within the air system to detect the presence of oil in the air stream. Oil presence can seriously damage the fuel cells and can potentially enter the air stream where it interacts with the air compressor or turbocharger.

The oil detector inspection is a visual check for oil presence. The oil detector contains crystals that are pale pink, but turn vibrant red when they have been exposed to oil. When

oil exposure is indicated, inspect the air inlet filters for oil presence, and report to the bus manufacturer; do not operate the bus until repairs are completed. The oil detector must be replaced once exposed to oil.

Key Points & Notes

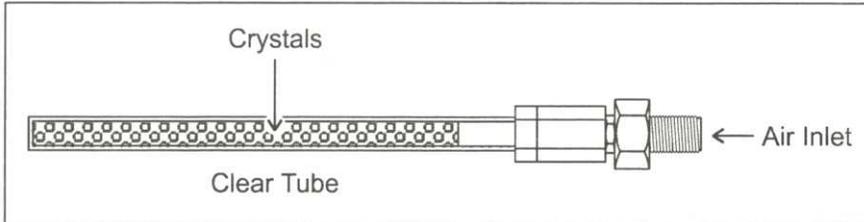


Figure 7-15 Oil Detector

7.4.4 Hydrogen Diffuser Inspection

The hydrogen diffuser disperses hydrogen purged from the fuel delivery circuit into a forced air stream. This ensures that the hydrogen concentration is lowered to well below the LFL, thereby preventing potential fire and explosions.

The hydrogen diffuser consists of a fan that passes air through a series of flow channels. An embedded tube releases hydrogen into the flow channels through a series of holes. A bus coolant tube accompanies the hydrogen tube and prevents water in the vent stream from freezing and blocking the vent holes.

The hydrogen diffuser inspection consists of a visual confirmation that the fan is operating and that the inlet and outlet are free of obstructions. The hydrogen diffuser only operates when the engine is on.

7.4.5 Stack Vent Fans Check

The stack vent fans provide positive pressure to the fuel cell stack enclosures to prevent any potential hydrogen accumulation in the event of fuel cell stack leakage.

Stack vent fan checks consist of tactile confirmation that each fan is sucking air into the corresponding fuel cell stack enclosure and an audible check for any evidence of bearing failure. Replace faulty fans. The stack vent fans only operate when the engine is on.

7.4.6 Cell Voltage Monitor Check

The cell voltage monitor measures the voltage of each fuel cell, and transmits these voltages to the control system, in addition to low-voltage warnings and alarms.

Fuel cell stack voltages are monitored by a series of pins, each in contact with the graphite plates on either side of each individual fuel cell. These pins transmit the voltages to the cell voltage monitor, which converts the cell voltage data into digital form and generates analog warning and alarm signals. The resulting cell voltage values pass to the control system where they can be viewed directly using the bus' diagnostics interface.

Key Points & Notes

A cell voltage monitor check consists of a visual assessment of all individual cell voltages for irregular high-low patterns or unusual cell voltages. These patterns are illustrated in Figure 7-16 based on the cell voltage monitor display from the XCELLSiS Phase 4 bus:

- High-low patterns are representative of one or two disconnected cell voltage monitor wires. If these are observed, note the fuel cell stack letter designator and cell number and service the cell voltage monitor the next time that stack is disassembled.
- Individual cell voltages are normally between 0.78 and 0.85 V at idle. Note any cell voltages below 0.5 V and monitor the cell daily for further degradation. A low cell voltage warning occurs at 0.4 V; alarms occur at 0.0 V and -0.2 V.
- If any cell voltage registers off-scale (above 1 V or less than -1 V without generating an alarm), note the fuel cell stack letter designator and cell number and service the cell voltage monitor the next time that stack is disassembled.

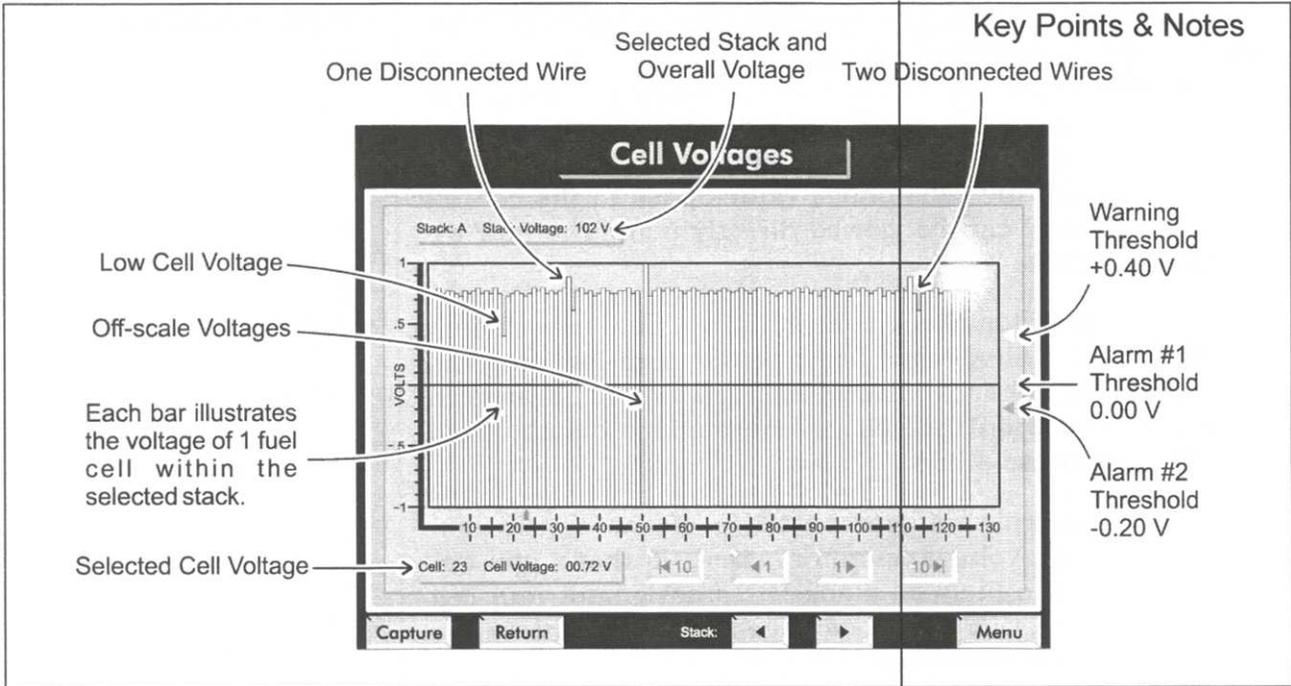


Figure 7-16 Cell Voltage Monitor Check

7.4.7 Fuel Cell Engine Leak Tests

Fuel cell stacks are designed so that the internal air, hydrogen and coolant streams never mix or leak. This is also true of membrane humidifiers, which are constructed in a similar fashion to stacks, but not of contact humidifiers (which mix the water and gas directly). In reality, some small amount of leakage always occurs. If a leak becomes excessive, replace the stack or membrane humidifier.

Leaks can be *external* (leaking to atmosphere) or *internal* (leaking from one flow path to another). External leaks result from seal malfunctions, plate cracks or other damage. Internal leaks result from membrane holes or other damage.

External and internal leaks reduce the power generating capacity of the fuel cell engine, and they permit hydrogen to mix with air, resulting in a potentially flammable mixture. The amount of mixing that can occur during an internal leak is limited by the pressure balance between the fuel and air streams; during steady state conditions, the air stream is approximately 2 psi (14 kPa) above the fuel pressure.

To combat leaks, each stack enclosure is actively ventilated and leak tests are performed routinely to quantify leakage rates. These leak tests are by far the most important set of fuel cell engine maintenance procedures and, along with the cell voltage monitor, the primary indicators of fuel cell stack

and humidifier condition. The leak tests are important in identifying potential fire hazards, as well as maintaining the power output and efficiency of the engine.

Leak tests fall into three categories: leak-down test, external leak test and transfer leak tests.

Leak-Down Test

The leak-down test indicates the presence of leaks within any part of the fuel delivery circuit. This test uses pressure-drop principles to determine whether a leak exists in the fuel path of any of the fuel cell stacks, any of the components within the re-circulating fuel circuit (including humidifiers), or any associated plumbing.

The leak-down test measures leaks that flow both to the atmosphere and to other internal flow paths (oxidant or coolant) within the stacks. Since it operates on so many components at once, it is not good at isolating and quantifying leaks within individual stacks. However, it is quick and easy to perform and is a useful indicator of whether more detailed tests are required.

The amount of leakage flow that corresponds to a given pressure drop depends on the internal volume of all components within the test circuit. Consequently, the leak-down test thresholds cannot be stated as a general value and must be calibrated for the engine design.

External Leak Test (and Variations)

The external leak test quantifies the *total* amount of leakage from *all* flow paths (fuel, oxidant and coolant) to *atmosphere*. This test measures the leakage flow directly using an upstream mass flow meter or rotameter. Variations of this test use similar techniques to measure the leakage flow from an *individual* flow path to *atmosphere* and *the other internal flow paths*, or to measure the leakage flow from an *individual* flow path to *atmosphere only*.

Cumulatively, the external leak test and its variations can be applied equally to groups of stacks (typically arranged within a single enclosure or module) or individual stacks. The test thresholds must reflect the total internal volume of the test circuit. When applied to groups of stacks, external leak tests serve to indicate whether individual stack tests are required. When applied to an individual stack, the tests serve to isolate specific leaks.

Adjoining stack groups can be tested while installed on the bus, whereas individual stacks must be removed prior to

Key Points & Notes

testing. Similarly, these tests can also be applied to membrane humidifiers (in groups or individually). These leak tests do not apply to contact humidifiers, which do not require leak tests.

Key Points & Notes

Transfer Leak Tests

The transfer leak tests quantify the amount of leakage from *one flow path* into *another flow path*. These leak tests measure the leakage flow directly using downstream, volumetric displacement techniques. The transfer leak tests can be applied to each combination of flow paths (fuel-to-oxidant, oxidant-to-fuel, fuel-to-coolant, etc.) but in practice are usually limited to fewer combinations.

Like the external leak test and its variations, the transfer leak test can be applied equally to groups of stacks or individual stacks using appropriate test thresholds. When applied to groups of stacks, the transfer leak tests serve to indicate whether further individual stack tests are required. When applied to an individual stack, the tests serve to isolate specific leaks. Adjoining stack groups can be tested while installed on the bus, whereas individual stacks must be removed prior to testing.

Also like the external leak test and its variations, the transfer leak tests can also be applied to membrane humidifiers, and do not apply to contact humidifiers.

Leak Test Sequence

The purpose of the stack (and humidifier) leak tests is to identify and isolate leaks so that the defective component can be replaced. When taken as a whole, the range of all possible leak test combinations is quite large and very time-consuming to conduct in their entirety.

To reduce the amount of work, specific leak tests are done in a logical sequence that successively isolate the leak while bypassing tests that are of no immediate consequence. For example, if a group of stacks fails a fuel path external test, but passes the oxidant and coolant external tests, there is no need to conduct oxidant or coolant path transfer tests. The fuel path transfer tests alone are needed to locate the leak.

The logical leak test sequence is encapsulated in a flowchart such as the one shown in Figure 7-17. Although this flowchart looks complicated, it actually simplifies the process of isolating leaks.

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

The leak-down test provides the initial leak assessment, and is performed at the weekly service interval. If the fuel cell engine passes this test, no further tests are required. If the fuel cell engine fails the leak-down test, a leak exists somewhere within the fuel delivery circuit. If no leaks can be found within the components of the fuel circuit or any associated plumbing (using a leak detection solution), the leak must exist within a fuel cell stack or membrane humidifier.

Fuel cell stacks are typically arranged in modules that include several stacks and associated humidifiers. These modules are tested at the 3750 mile service interval (regardless of the leak-down test results) for external leaks from all flow paths combined, and internal/external leaks from each individual flow path. If the stack module passes these four tests, no further tests are required.

If the stack module fails the external leak test from all flow paths, the leak exists within one or more individual stacks or membrane humidifiers. If the stack module fails any of the internal/external leak tests from individual flow paths, corresponding transfer tests must be performed on the entire module to isolate the leakage path. As an additional diagnostic tool, the external leakage (to atmosphere only) from the fuel path is also conducted prior to transfer tests on that circuit.

Once external and transfer tests have been completed on the overall stack module, the corresponding external and/or transfer tests are required on individual stacks or membrane humidifiers in order to isolate the faulty component.

Transfer tests that indicate leakage to or from the coolant path may originate within a stack or membrane humidifier, although leakage between gas paths can only originate within a stack due to the construction arrangement of the humidifiers. These tests necessitate the removal of the stacks and membrane humidifiers from the stack module. Individual stacks or humidifiers that fail any of these tests must be replaced.

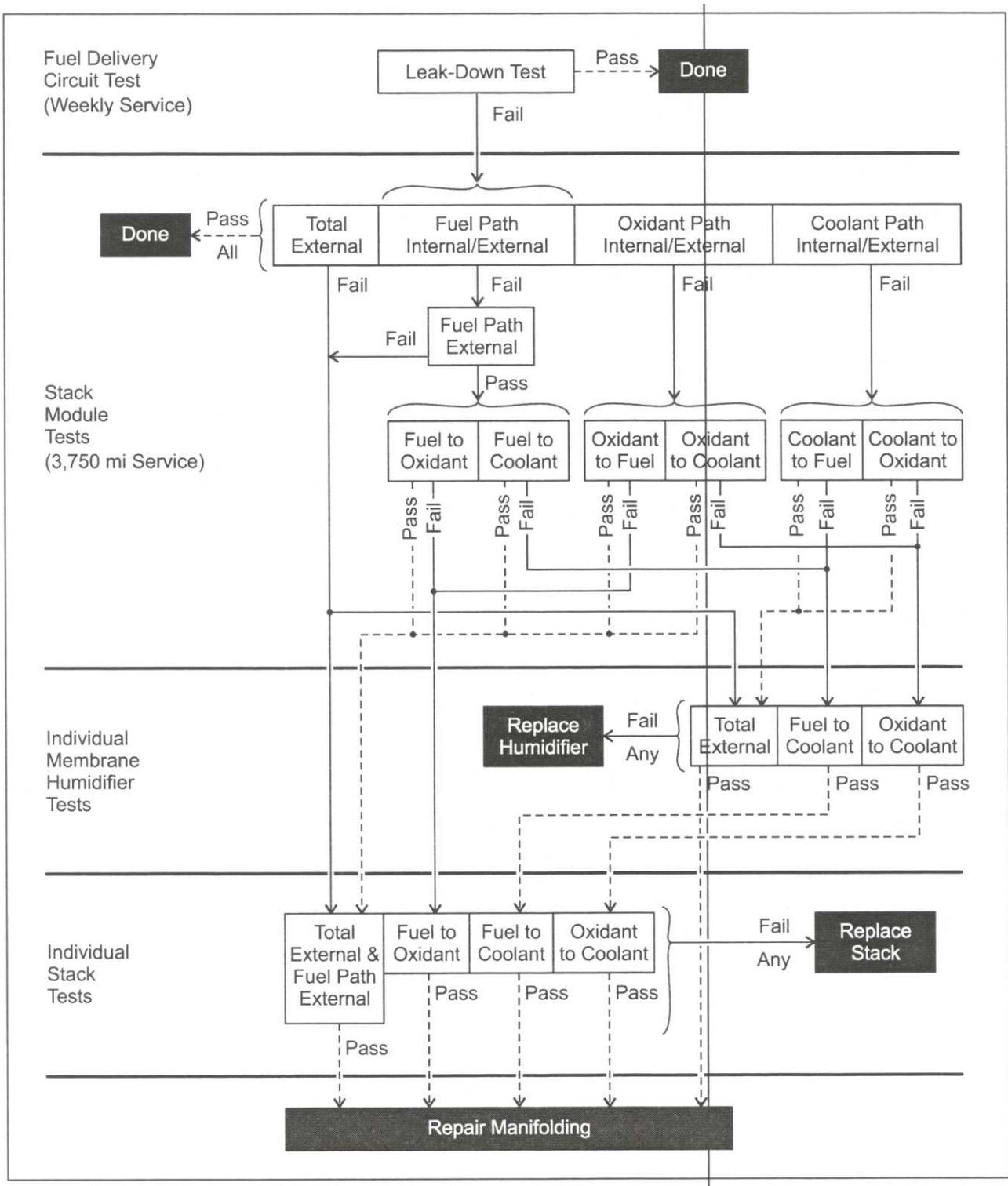
If individual stack or membrane humidifier leak cannot be found despite leak indications at the module level, the leak exists in some portion of the manifolding that interconnects the components within the module. These leaks can be traced using leak detection solution, and repaired as required.

Key Points & Notes

Fuel cell stacks and membrane humidifiers can only be serviced by the original manufacturer. In preparation for shipping, fill humidifiers with de-ionized water, and the inlet and outlet ports on both humidifiers and stacks must be capped. Crate components securely to prevent damage during shipment. Ensure that the shipment will not be subject to freezing

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE



Key Points & Notes

Figure 7-17 Typical Leak Test Sequence Flowchart

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

Leak Test Logs

Key Points & Notes

Leak test logs identify the test and summarize the resulting leak data. These records are important for assessing component behavior over time. Typical test logs are shown in Figures 7-18 and 7-19.

Bus/Module Leak Test Log				
IDENTIFICATION				
Bus				
Hourmeter Reading		Technician		
Hubodometer Reading		Date		

LEAK-DOWN TEST	Test Pres. (psig)	Acceptance Threshold (psig)	Pressure After 1 Minute (psig)	
External	7.0	>xxx		

STACK MODULE LEAK TESTS	Test Pres. (psig)	Acceptance Threshold (cc/min)	Module 1 (Roadside) (cc/min)	Module 2 (Curbside) (cc/min)
Total External	30.0	<xxx		
Fuel Path External	30.0	<xxx		
Fuel Path Internal/External	7.25	<xxx		
Fuel to Oxidant	7.25	<xxx		
Fuel to Coolant	7.25	<xxx		
Oxidant Path Internal/External	7.25	<xxx		
Oxidant to Fuel	7.25	<xxx		
Oxidant to Coolant	7.25	<xxx		
Coolant Path Internal/External	7.25	<xxx		
Coolant to Fuel	7.25	<xxx		
Coolant to Oxidant	7.25	<xxx		
			Disassembled: <input type="checkbox"/> yes <input type="checkbox"/> no	Disassembled: <input type="checkbox"/> yes <input type="checkbox"/> no

Figure 7-18 Typical Stack Module Leak Test Log

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

Key Points & Notes

Stack/Humidifier Leak Test Log						
IDENTIFICATION						
Bus						
Hourmeter Reading		Technician				
Hubodometer Reading		Date				

Stack Identifier / Serial Number:						
STACK LEAK TESTS	Test Pres. (psig)	Acceptance Threshold (cc/min)	(cc/min)	(cc/min)	(cc/min)	(cc/min)
Total External	30.0	< xxx				
	7.25	< xxx				
Fuel Path External	30.0	< xxx				
Fuel to Oxidant	7.25	< xxx				
Fuel to Coolant	7.25	< xxx				
Oxidant to Coolant	7.25	< xxx				
Replaced:			<input type="checkbox"/> yes <input type="checkbox"/> no			

Humidifier Identifier / Serial Number:				
HUMIDIFIER LEAK TESTS	Test Pres. (psig)	Acceptance Threshold (cc/min)	(cc/min)	(cc/min)
Total External	30.0	< xxx		
Fuel to Water	7.25	< xxx		
Oxidant to Water	7.25	< xxx		
Replaced:			<input type="checkbox"/> yes <input type="checkbox"/> no	<input type="checkbox"/> yes <input type="checkbox"/> no

Figure 7-19 Typical Stack/Humidifier Leak Test Log

Leak Test Box

Key Points & Notes

Leak tests require a source of regulated nitrogen to pressurize the flow paths under test. For some tests, the supply's flow rate must be measured. For other tests, measured and unmeasured nitrogen streams are required. For convenience, this flow distribution and control equipment is combined into a leak test box. A typical leak test box, linked to a nitrogen supply, is shown in Figure 7-20. The components shown have the following functions:

- The nitrogen supply consists of a standard T bottle of nitrogen with a minimum purity of 99.99%. The integral shutoff valve isolates the bottle contents.
- The nitrogen supply pressure regulator (4000-psig (275-barg) inlet; 100-120 psig (7-8 barg) outlet) with inlet and outlet pressure gauges provides first-stage regulation of the nitrogen pressure. The pressure regulator must be a *venting* type so that it can be bled to atmospheric conditions while the outlet flow path is blocked.
- The nitrogen supply tube mates with and passes nitrogen to the leak test box.
- The stack pressure regulator and gauge on the leak test box set the test pressure. An electronic pressure display could be used instead of the pressure gauge.
- The rotameter valve on the leak test box engages or bypasses the rotameters, depending on its position.
- The rotameter selection valves on the leak test box engage or disengage individual rotameters, depending on their positions.
- The rotameters on the leak test box each has a different flow range and measure the nitrogen flow. An electronic mass flow meter could be used instead of the rotameters.
- The metered supply tube mates with and passes the nitrogen from the rotameter flow path to the equipment under test.
- The unmeasured supply tube mates with and passes nitrogen directly from the outlet of the stack pressure regulator to the equipment under test.

Key Points & Notes

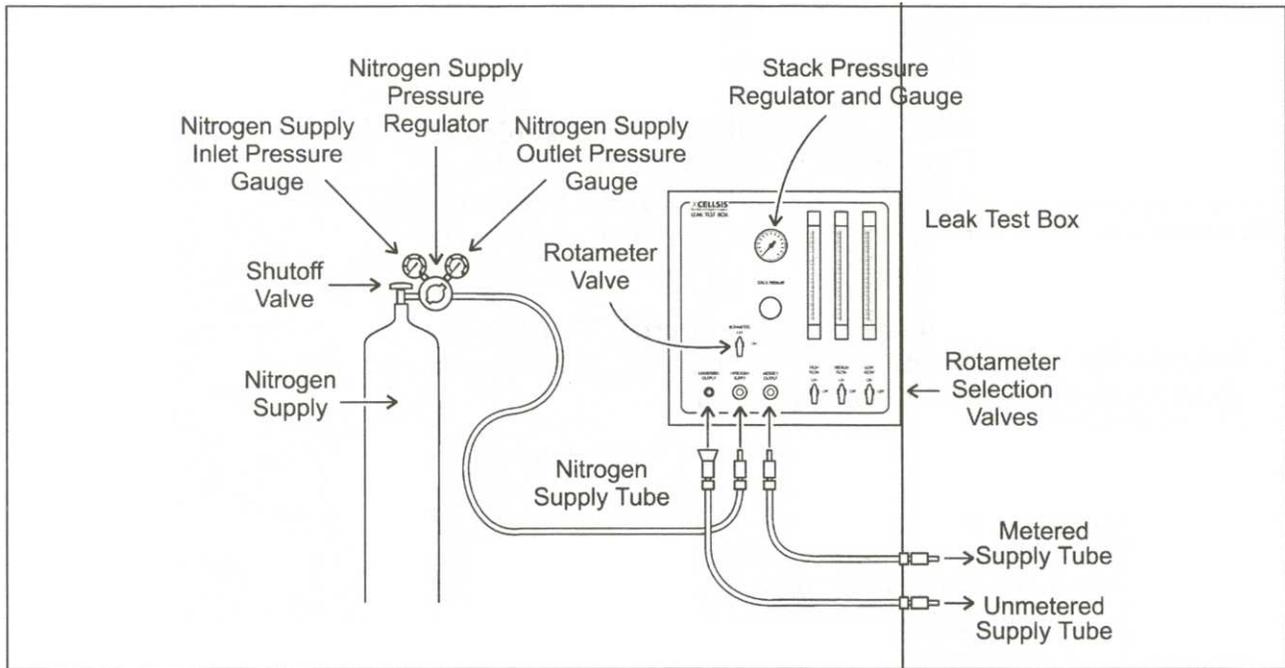


Figure 7-20 Typical Leak Test Box

Downstream of the metered and unmetered supply tubes, other special equipment is needed depending on the specific test. That equipment is described in the following sections.

When the leak test box uses rotameters instead of an electronic mass flow meter to measure the nitrogen flow, calibration curves are required to convert the rotameters readings to flow units of cc/min. These curves are derived through experiment using standard calibration procedures. Published calibration curves are valid only for the specific rotameter, pressure and gas composition indicated. A sample calibration curve is shown in Figure 7-21. When referring to a calibration curve:

- Locate the rotameter reading on the vertical axis of the graph.
- Draw a line horizontally from the rotameter reading until it intersects the calibration curve for the given test pressure.
- Draw a line vertically downwards from the intersection to the horizontal axis of the graph.
- Read the flow rate in cc/min off the horizontal axis.

Rotameters and mass flow meters must be calibrated regularly to maintain test accuracy.

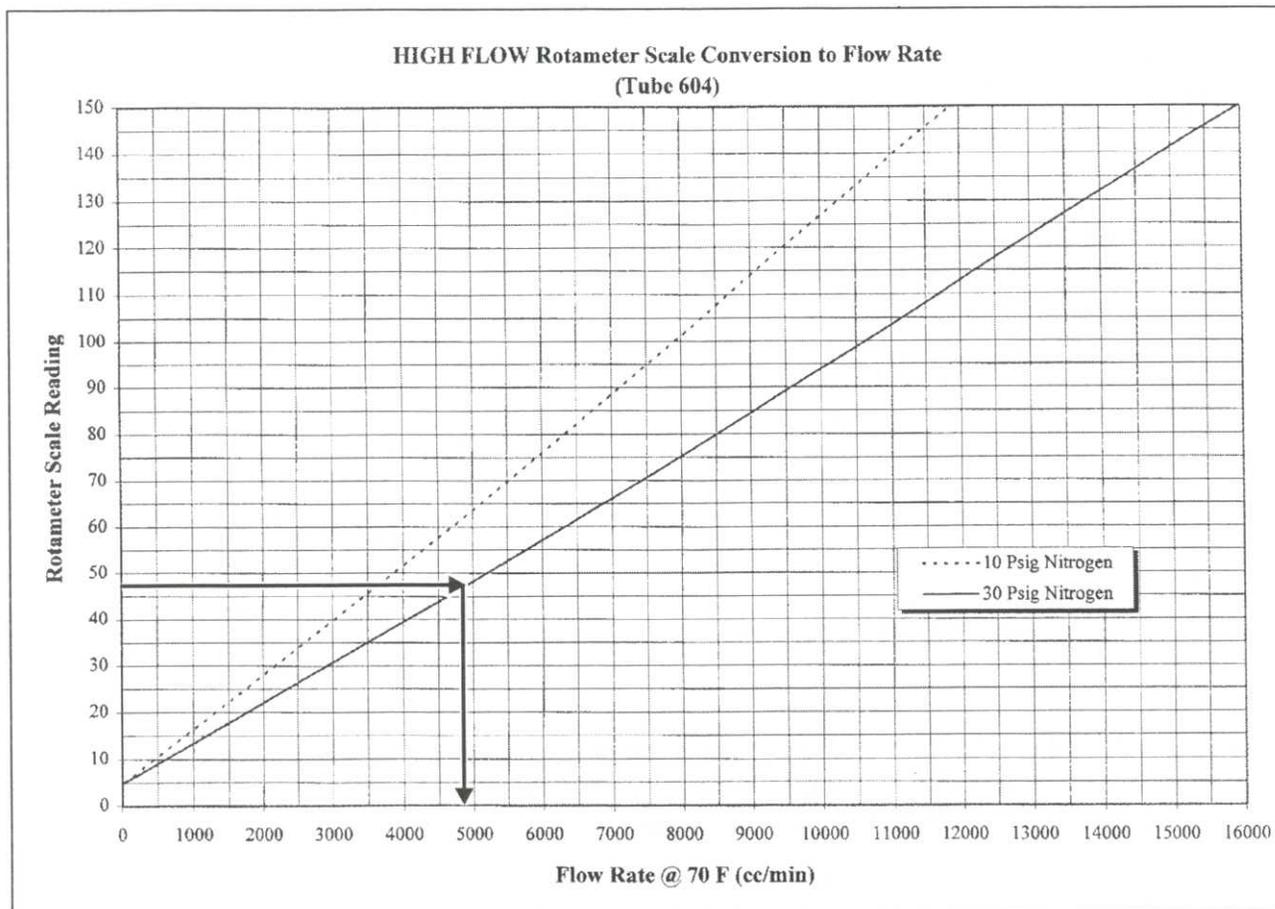


Figure 7-21 Typical Rotameter Calibration Curve

7.4.7.1 Leak-Down Test

The leak-down test indicates the presence of leaks within any part of the fuel delivery circuit by pressurizing the circuit and measuring the pressure drop over time.

The fuel delivery circuit is normally vented to atmosphere by way of the purge line whenever the engine is off. In order to pressurize this circuit, isolate it by closing the purge valve. You can then apply pressure through a pressurization port incorporated into the circuit.

Typical leak-down test equipment is illustrated in Figure 7-22 and must include the following:

- a nitrogen supply, leak test box, and metered supply tube as described above
- an extension tube with digital manometer
- two stack module blanking plates
- a stopwatch

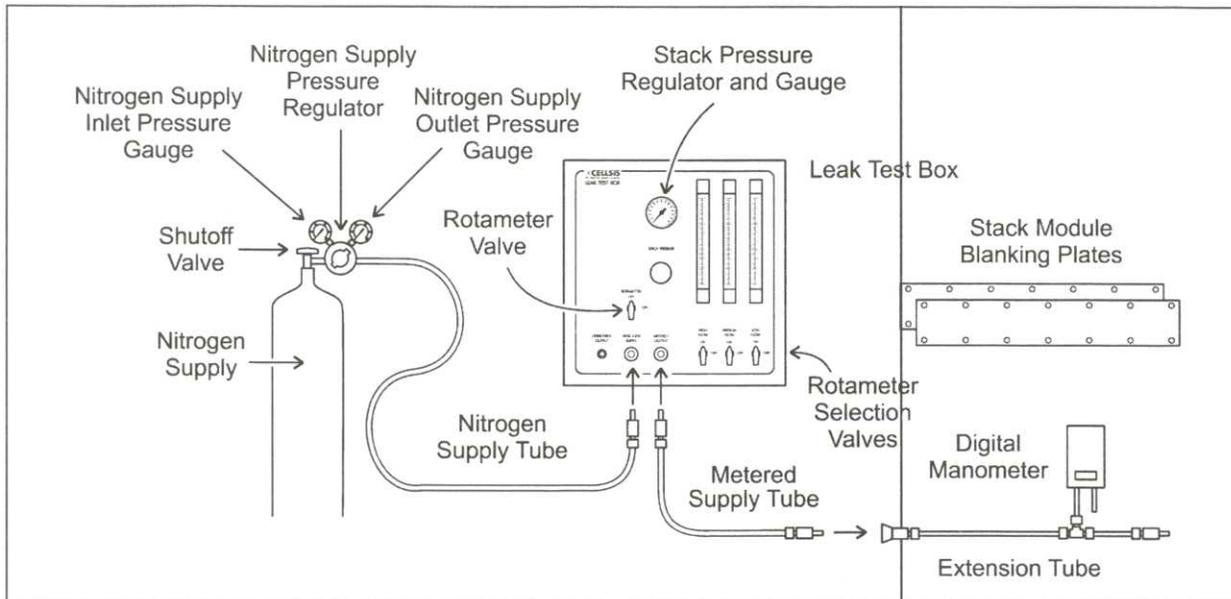


Figure 7-22 Typical Leak-Down Test Equipment

Prepare to test:

1. Ensure the fuel cell engine is warm and off. If the engine is not warm, misleading results may occur since some sealing surfaces may not have fully sealed.
2. Remove the cap from the bus' pressurization port and connect the test equipment as illustrated in Figure 7-23.

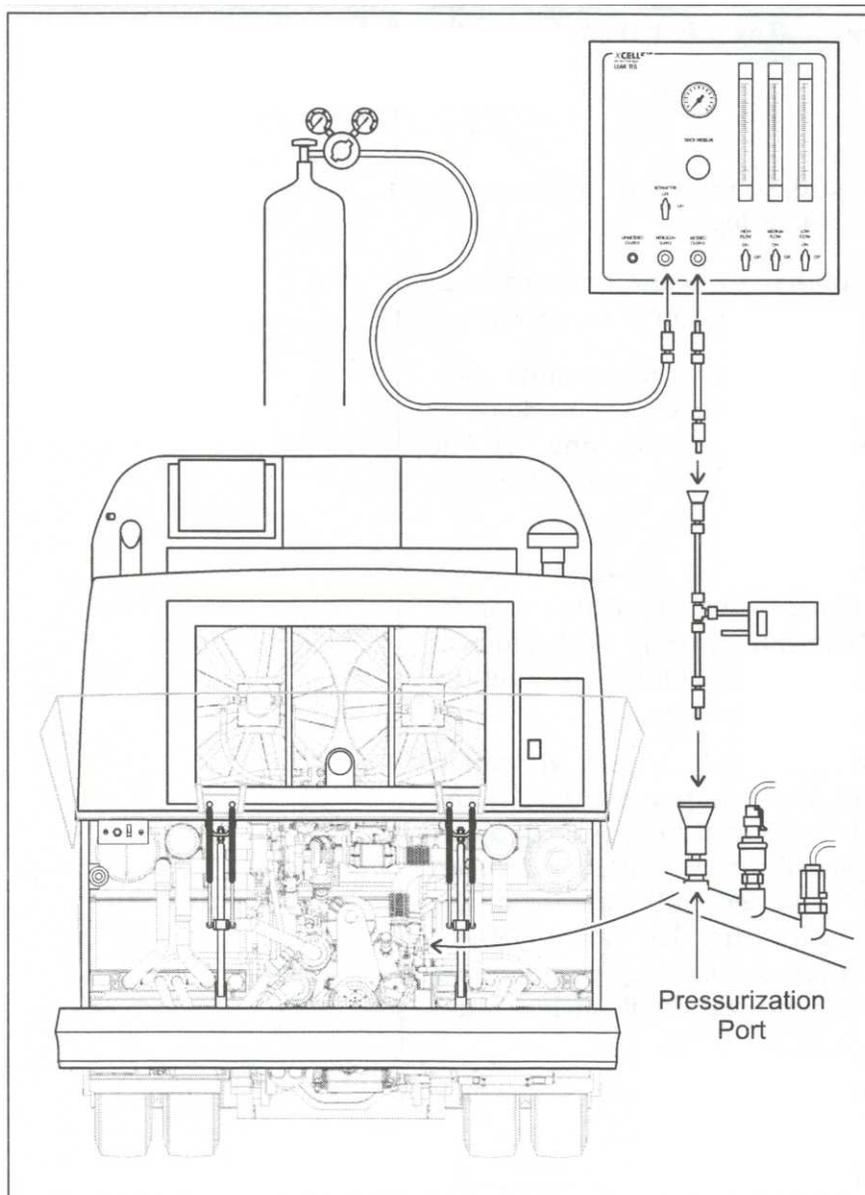
Prepare the test equipment:

3. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.
4. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates 7.0 psig (0.5 barg).

Pressurize the circuit:

5. Close the bus purge solenoid valve. This valve is normally open whenever the engine is off. Consequently, the valve must be closed using some specific sequence of switches on the side console and/or engine compartment that has been programmed into the control system. Listen for the clicking sound of the solenoid valve closing.

Key Points & Notes

**Figure 7-23** Leak-Down Test

6. Pressurize the fuel circuit by turning the rotameter valve off. This allows nitrogen to flow into the fuel delivery circuit.
7. Use a leak detection solution to confirm that no leaks exist on the leak test equipment.
8. Adjust the stack pressure regulator as required until the digital manometer indicates *7.0 psig (0.5 barg)*.

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**



9. Turn the rotameter valve on and re-read the digital manometer accurately.

Key Points & Notes

Assess the results:

10. Allow one minute to pass and re-read the manometer. Record the results on the leak test log:

- a) If the pressure remains higher than the amount indicated on the test log, no further action is required.
- b) If the pressure drops to less than the amount indicated on the test log, there is an excessive leak or leaks in the fuel delivery circuit, plumbing, or the stack modules. To eliminate any leaks within the fuel delivery circuit:
 - Depressurize the test equipment, drain the stack modules, disconnect the stack module connections, and attach a blanking plate to both sides of the exposed connections. This isolates the fuel delivery circuit from the stack modules.
 - Repeat the leak test and apply a leak detection agent on every fitting and component within the fuel delivery circuit. Use a hand-held leak detector to probe the hydrogen diffuser: leaked hydrogen within the hydrogen diffuser indicates that the purge solenoid valve is leaking. Tighten any leaking fittings and/or replace leaking components and repeat the test as required until all leaks are eliminated.
 - Remove the blanking plates, re-attach the stack modules, and repeat the test.

11. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

12. Depressurize the test equipment and close the nitrogen supply shutoff valve.

13. Open the purge solenoid valve using the specific sequence of switches defined by the bus manufacturer.

14. Disassemble the test equipment.

7.4.7.2 External Leak Test (and Variations)

Key Points & Notes

The *external leak test* quantifies the *total* amount of leakage from *all* flow paths (fuel, oxidant and coolant) to *atmosphere*. Variations of this test include the *individual internal/external leak test*, which measures the leakage flow from an *individual* flow path to *atmosphere and the other internal flow paths*, and the *individual external leak test* which measures the leakage flow from an *individual* flow path to *atmosphere only*. These tests can be applied to stack modules, individual stacks, or individual membrane humidifiers.

In each test, pressurized nitrogen is supplied to one or more terminated flow paths and the amount of nitrogen flow is measured directly. Since the flow paths are terminated, all nitrogen flow is the direct result of leakage. These tests are *upstream* tests, since the leakage is measured in terms of the dry nitrogen flowing through the leak test box upstream of the equipment under test.

Typical external leak test equipment is illustrated in Figure 7-24 and must include the following:

- a nitrogen supply, leak test box, and metered and un-metered supply tubes as described above
- two stack module leak test adapters (with non-venting quick-connection fittings)
- six stack/humidifier leak test adapters (with non-venting quick-connection fittings)
- four open (venting) stems (for quick-connection fittings)
- two linkage tubes (to mate with quick-connection fittings)
- two discharge tubes with 2-way valve (to mate with quick-connection fittings)

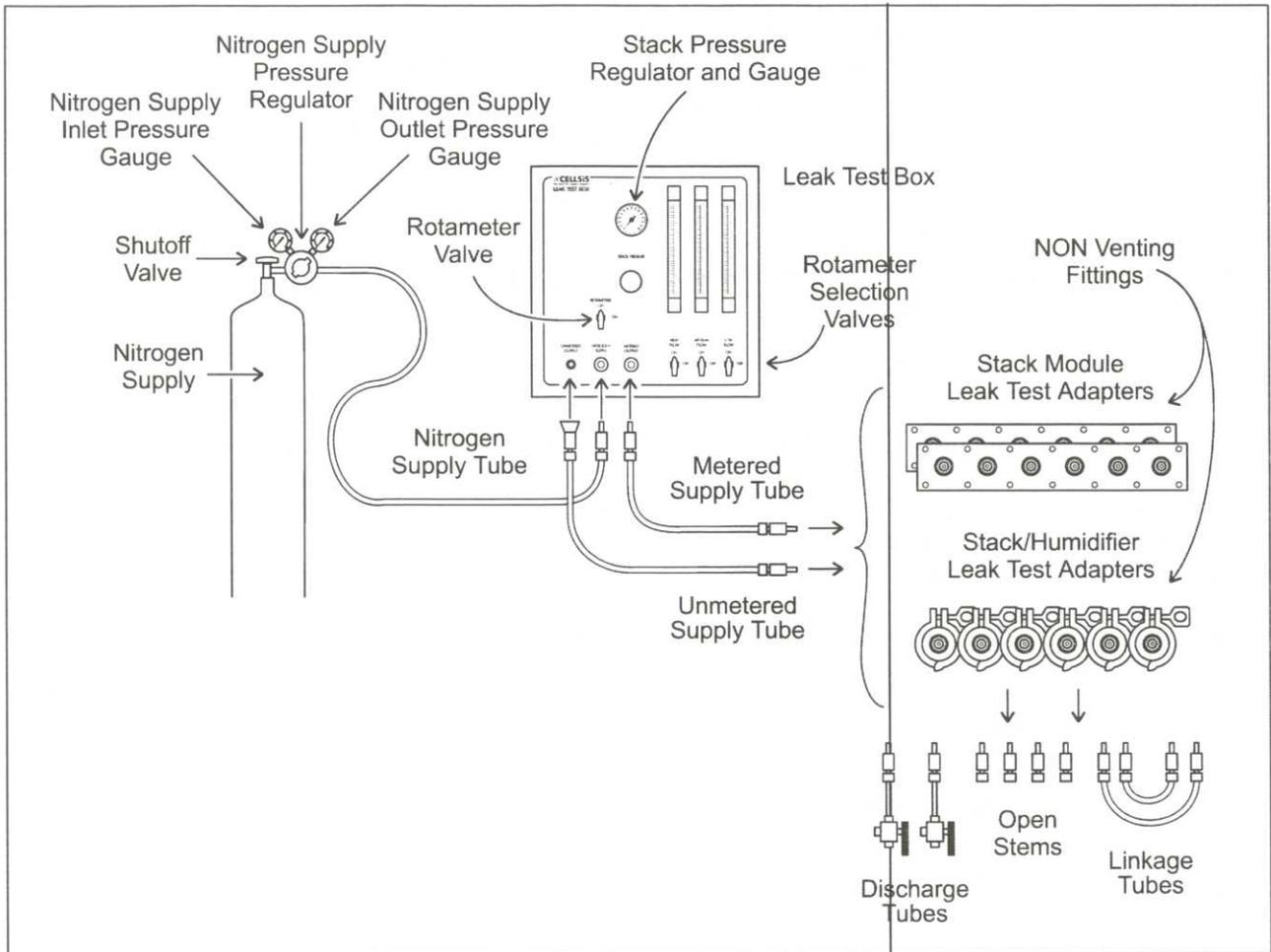


Figure 7-24 Typical External Leak Test Equipment

Key Points & Notes

Total External Leak Test

In the total external leak test, all flow paths are linked together, terminated and pressurized. Since all internal circuits are pressurized together, all leakage flow must pass into the atmosphere.

Prepare to test:

1. Ensure the fuel cell engine is off.
2. When performing stack module tests, drain the modules, disconnect the module connections, and attach the stack module leak test adapter. When performing stack or humidifier tests, remove the component and attach the stack/humidifier leak test adapters.
3. Connect the test equipment as illustrated in Figure 7-25.

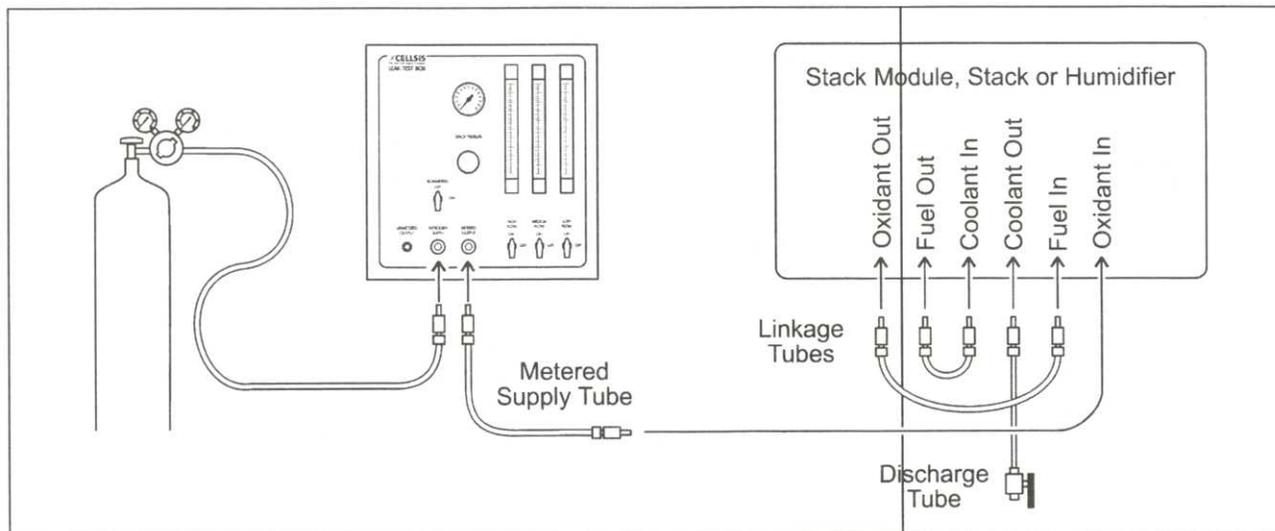


Figure 7-25 Typical Individual Internal/External Leak Test Equipment

Prepare the test equipment:

4. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.
5. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates *30.0 psig (2.07 barg)*. As this pressure acts on all internal flow paths, a differential pressure across the internal membranes cannot develop.

Pressurize the circuit:

6. Turn the high flow rotameter selection valve on. This allows nitrogen to flow into the equipment under test. Allow the rotameter to stabilize.
7. Use a leak detection solution to confirm that no leaks exist on the leak test equipment. **Do not allow leak detection solution to contact the fuel cells or humidifier plates.**
8. Read the flow rate ^{low} indicated on the rotameter; if the flow rate is too small to read accurately on the rotameter, use the rotameter selection valves to select the medium flow or low flow rotameters as required.



Complete:

9. Turn all three rotameter selection valves off.

Key Points & Notes

10. Slowly open the 2-way valve on the discharge tube to depressurize the equipment under test.

Key Points & Notes

Assess:

11. Convert the rotameter flow readings to units of cc/min using the published rotameter calibration curves. Record the results on the leak test log:

Units of “ml” and “cc” are equivalent.

- a) If the flow rate is less than the amount indicated on the test log, no further action is required.
- b) If the flow rate is greater than the amount indicated on the test log, there is an excessive leak within the component under tested.

12. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

13. Depressurize the test equipment and close the nitrogen supply shutoff valve.

14. Disassemble the test equipment.

Individual Internal/External Leak Test

In the individual internal/external leak test, one flow path (fuel, oxidant or coolant) is terminated and pressurized. Leakage gas can therefore pass from the pressurized circuit into one of the other flow paths or to the atmosphere.

This test is performed in an identical manner to the external leak with the following differences:

- Connect the test equipment as in Figure 7-26. The figure illustrates the test setup for the fuel path; if testing a different flow path the setup is similar: plumb the metered supply tube to the flow path outlet and the discharge tube to the flow path inlet. Add open stems to all other ports.
- Pressurize the flow path to 7.25 psig (0.5 barg), not 30.0 psig (2.07 barg).

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**



Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

Key Points & Notes

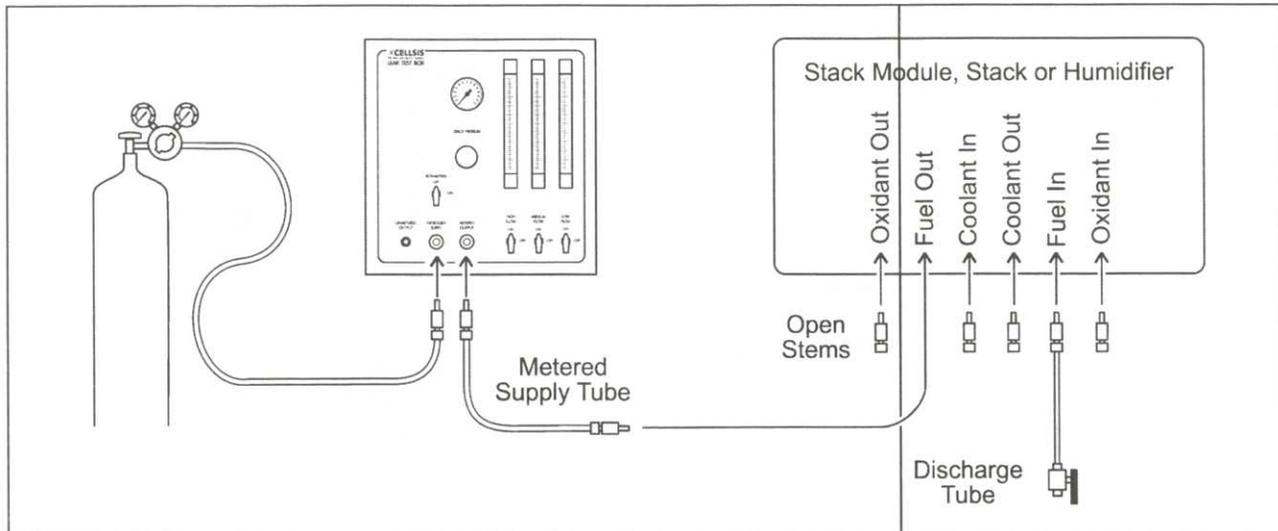


Figure 7-26 Fuel Internal/External Leak Test

Individual External Leak Test

In the individual external leak test, one flow path (fuel, oxidant or coolant) is terminated and pressurized while the other two flow paths are linked together, terminated and pressurized using a separate, unmetereed gas stream. Leakage gas can therefore pass from the pressurized circuit only to the atmosphere since no differential pressure exists between the tested and untested flow paths.

This test is performed in an identical manner to the external leak with the following differences:

- Connect the test equipment as in Figure 7-27. The figure illustrates the test setup for the fuel path; if testing a different flow path the setup is similar: plumb the metered supply tube to the flow path outlet and the discharge tube to the flow path inlet. Plumb the unmetereed supply tube to the outlet of either of the other two flow paths, link the two flow paths using a linkage tube, and terminate the remaining port with a discharge tube.
- Pressurize the flow path to 30.0 psig (2.07 barg), not 7.25 psig (0.5 barg). Since this pressure acts on all internal flow paths, a differential pressure across the internal membranes cannot develop.
- When venting, open both discharge valves in tandem to avoid a differential pressure within the equipment under test.

Key Points & Notes

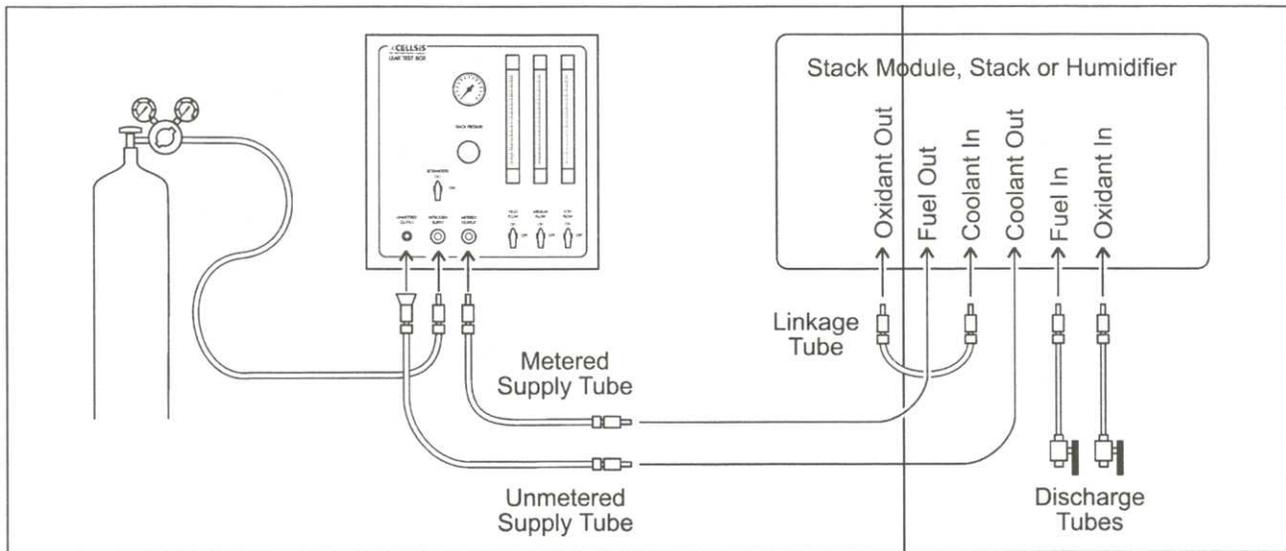


Figure 7-27 Fuel External Leak Test

7.4.7.3 Transfer Leak Tests

The transfer leak tests quantify the amount of leakage from *one flow path* (fuel, oxidant or coolant) into *another flow path*. These tests can be applied to stack modules, individual stacks, or individual membrane humidifiers. Six possible transfer leak test combinations exist:

- Fuel to oxidant
- Fuel to coolant
- Oxidant to fuel
- Oxidant to coolant
- Coolant to fuel
- Coolant to oxidant

At first glance, transfer tests that comprise complementary pairs (fuel to oxidant and oxidant to fuel) should produce the same results and therefore seem redundant. Although this is usually true, the process of pressurizing one path as opposed to the other can sometimes affect the internal seals in different ways, leading to different results. For this reason both tests are often performed.

In each transfer test, pressurized nitrogen is supplied to a single terminated flow path and is allowed to leak to another flow path and the ambient environment. The specific leakage coming out of the other flow path is then measured using volumetric displacement techniques. The remaining flow

path plays no part in the test and is vented to atmosphere so that pressure cannot build up within it.

Key Points & Notes

Transfer tests are *downstream* tests, since the leakage is measured in terms of the nitrogen flowing out of a flow path, downstream of the equipment under test. The nitrogen flow measurement equipment on the leak test box is not used.

Downstream test measurements are complicated by the fact that stacks and humidifiers are fundamentally wet so that some water always passes out of a flow path in conjunction with the leakage gas. The resulting wet gas stream cannot be measured using rotameters or electronic mass flow meters and the water content must be excluded from the leakage calculation.

For this reason, leakage measurements are made using a water-filled graduated cylinder assembly. This assembly consists of a pair of nested, graduated cylinders, with the inner cylinder inverted. At the start of the test, both cylinders are completely full of water. As the wet gas is introduced into the inner cylinder, the water combines with the water already there, and the gas accumulates at the top of the cylinder, causing it to rise. The leakage gas can therefore be obtained directly by measuring the quantity of gas that accumulates within the inner cylinder over a period of time.

Typical transfer leak test equipment is illustrated in Figure 7-28 and must include the following:

- a nitrogen supply, leak test box, and metered supply tubes as described above
- two stack module leak test adapters (with non-venting quick-connection fittings)
- six stack/humidifier leak test adapters (with non-venting quick-connection fittings)
- two open (venting) stems (for quick-connection fittings)
- one discharge tube with 2-way valve (to mate with quick-connection fittings)
- one vent tube with 3-way vent valve (to mate with quick-connection fittings)
- graduated cylinder assembly (water-filled)
- stopwatch

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

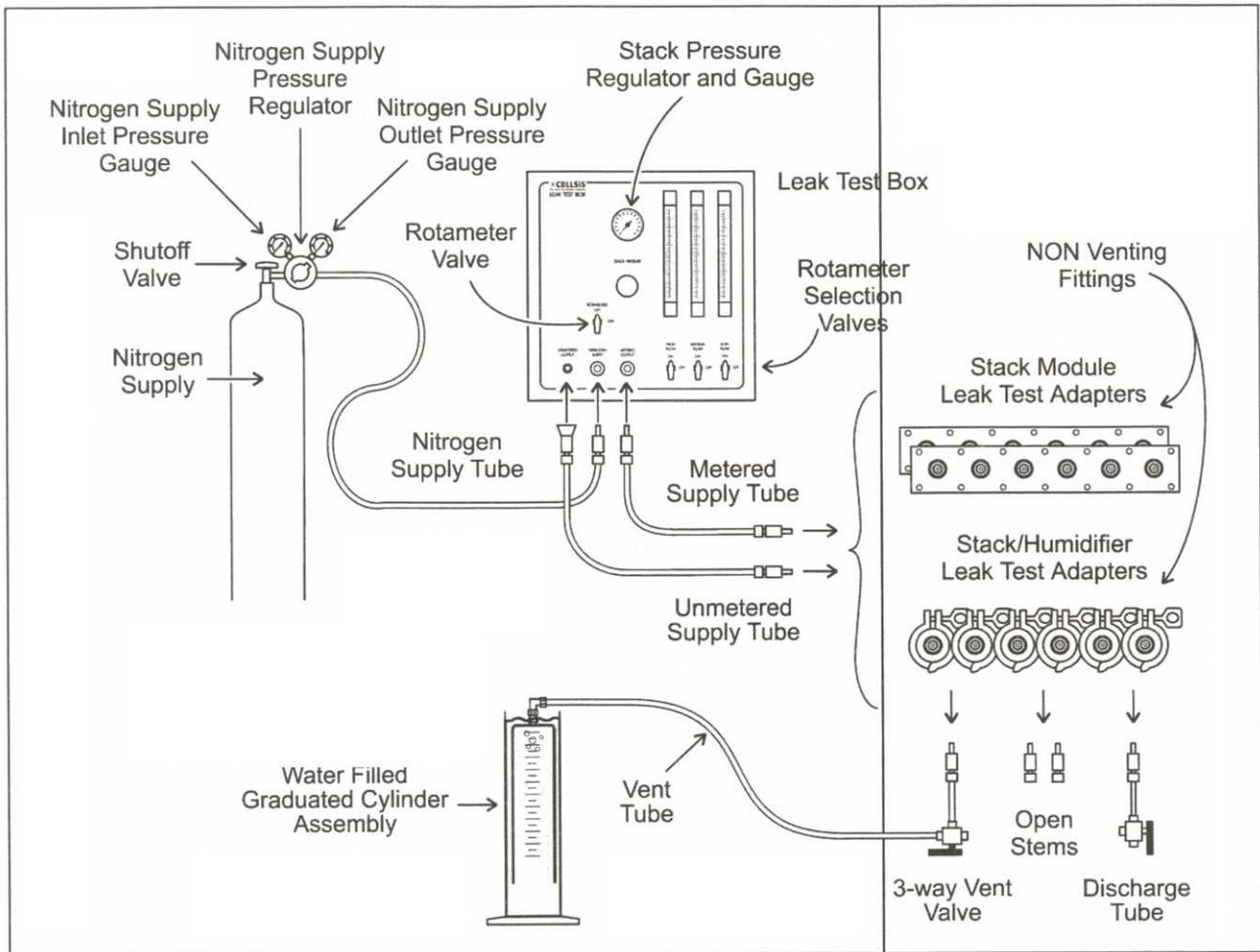


Figure 7-28 Typical Transfer Leak Test Equipment

Key Points & Notes

Prepare to test:

1. Ensure the fuel cell engine is off.
2. When performing stack module tests, drain the modules, disconnect the module connections, and attach the stack module leak test adapter. When performing stack or humidifier tests, remove the component and attach the stack/ humidifier leak test adapters.
3. Connect the test equipment as in Figure 7-29. The figure illustrates the test setup for the fuel to oxidant test; if testing a different combination of flow paths the setup is similar: plumb the metered supply tube to the source flow path outlet and the discharge tube to the source flow path inlet. Attach the vent tube and water-filled graduated cylinder assembly to the measured flow path inlet and leave the outlet closed (by virtue of the non-venting

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

quick-connection fitting). Add open stems to the remaining two ports.

Key Points & Notes

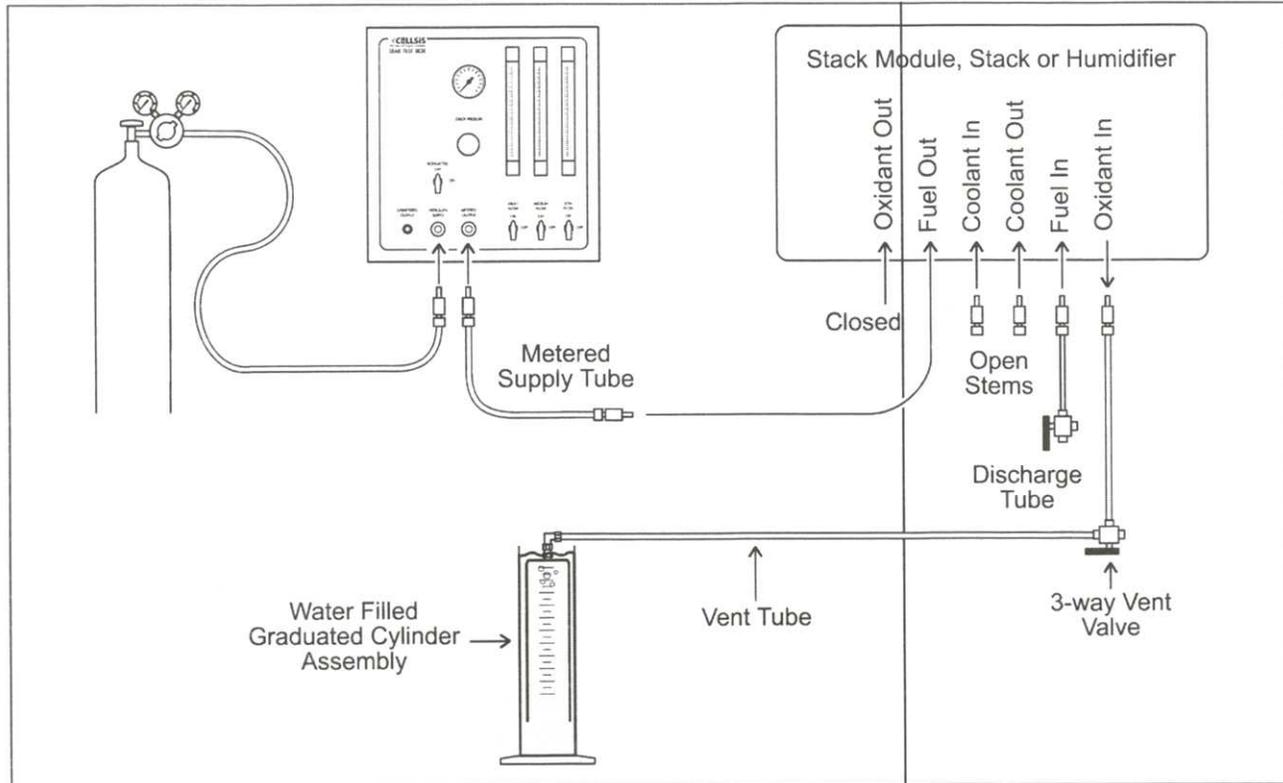


Figure 7-29 Fuel to Oxidant Transfer Leak Test

Prepare the test equipment:

4. Detach the vent tube from the leak test adapter and turn the vent valve so that any air trapped in the inner graduated cylinder expels to atmosphere. Re-attach the vent tube.
5. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.
6. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates *7.25 psig (0.5 barg)*.

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**



Pressurize the circuit:

7. Turn the rotameter valve off. This allows nitrogen to flow into the equipment under test.

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

8. Use a leak detection solution to confirm that no leaks exist on the leak test equipment. **Never allow leak detection solution to contact the fuel cells or humidifier plates.**
9. Set the vent valve position so that any leakage gas expels to atmosphere.
10. Once a steady state stream of gas is established, simultaneously turn the vent valve so that the leakage gas passes into the graduated cylinder assembly and begin timing.
11. Continue collecting gas until two minutes has passed, then simultaneously turn the vent valve so that the leakage gas expels to the atmosphere and stop timing.
12. Read the displaced volume in the *inner* graduated cylinder and calculate the flow rate as follows:

Key Points & Notes



$$\text{Flow rate [cc / min]} = \left(\frac{\text{Volume [ml]}}{\text{Time [min]}} \right)$$

Complete:

13. Turn the rotameter valve on. This interrupts the nitrogen flow.
14. Slowly open the 2-way valve on the discharge tube to depressurize the equipment under test.

Assess:

15. Record the results on the leak test log:
 - a) If the flow rate is less than the amount indicated on the test log, no further action is required.
 - b) If the flow rate is greater than the amount indicated on the test log, there is an excessive leak within the flow path tested.
16. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

17. Depressurize the test equipment and close the nitrogen supply shutoff valve.
18. Disassemble the test equipment.

7.4.8 Power Cable Connection Checks

Key Points & Notes

Power cables link the fuel cell stacks to the inverter, and the inverter to the drive motor and dump choppers. If any of these power cables are not attached during operation of the fuel cell stacks, a very large charge can result with no discharge path presenting a serious shock hazard.

The power cable connection checks consist of checking by hand that each of the power cable connections are tightly connected. Some connectors have a molded arrow on their ends that indicate the location of its locking pin. All cables tighten clockwise.

When tightening cables, ensure that they do not spring back to their original position. Take care to avoid inadvertently loosening connections in this way.



7.4.9 Glycol System Integrity Test

The glycol system integrity test ensures that no leakage exists between the air and coolant circuits. The air and stack coolant streams come into close contact within the humidifiers and the stacks. The air and bus coolant streams come into close contact within the intercooler, aftercooler, and condenser. Any glycol leak into the air stream could cause serious fuel cell damage as glycol can poison the fuel cell catalyst.

The glycol system integrity test is similar to a conventional radiator leakage test and consists of pressurizing each coolant path in turn and measuring any pressure drop over time. Test equipment typically consists of a standard radiator system pressure tester, an external digital manometer, and a stopwatch. The digital manometer is more accurate than the pressure gauge that normally accompanies the pressure tester.

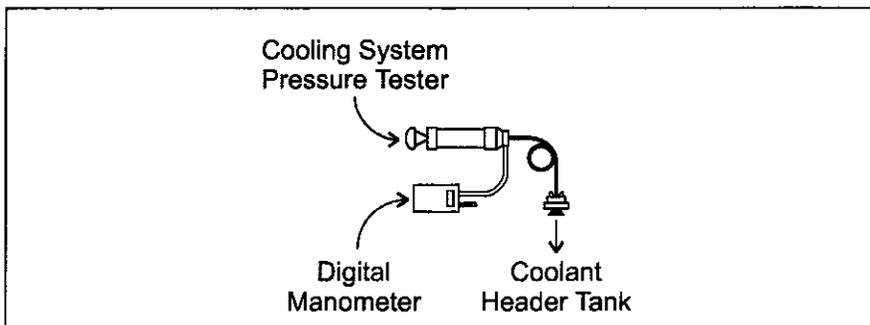


Figure 7-30 Typical Glycol Integrity Test Equipment

To perform the glycol system integrity test, the stack and bus coolant circuits must be fully charged and the engine must be off. The system pressure tester is applied, in turn, to the stack and bus coolant header tank fill ports. Ensure that the tester makes a fully sealed connection with the fill port. Each circuit is pressurized using the tester pump until the manometer indicates 16 psig (1.1 barg). After 20 minutes, the manometer pressure must be re-assessed:

Key Points & Notes

- If the pressure remains greater than 15.5 psig (1.07 barg), no action is required.
- If the pressure drops to less than 15.5 psig (1.07 barg), inspect all fittings and components associated with that coolant circuit (including the pressure tester connection) for leaks: Tighten any leaking fittings and repeat the test. If no leak can be found but the pressure loss persists, contact the bus manufacturer. Do not operate the bus until authorized to do so by the bus manufacturer.

Test results are normally recorded on a test log that indicates the date, the hourmeter and odometer readings and the measured pressure drop.

7.4.10 Dump Chopper Resistance Check

A dump chopper is essentially a resistor in contact with a coolant stream. This resistor converts electrical power into heat either during startup (to hasten warmup) or during situations where excess power must be “dumped”. The dump chopper is typically installed in the stack coolant circuit, but some buses include a second dump chopper in the bus or HVAC coolant circuits.

The dump chopper resistor is part of an assembly that may contain other fluid flow control equipment. The resistor itself consists of a series of individual resistive elements that are wired together in parallel. Each element has the same resistance so that the power absorption is shared equally. If an element burns out (becomes an open circuit), the net parallel resistance of the remaining elements increases.

The dump chopper resistance check uses an ohmmeter to confirm that the overall resistance is within specifications. The resistance is measured directly across the entire resistor by removing the power cables from each dump chopper assembly with the engine off. Moisture within the electrical portion of the dump chopper can affect resistance values slightly.

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

Resistance specifications are unique to each bus design. The low end of the acceptable resistance range represents the expected value if all elements are functional; lower resistances indicate that the resistor is completely short-circuited. The high end of the acceptable resistance range represents the expected value if at most two elements have burned out; higher resistance indicate that an unacceptable number of elements are no longer functional. If measurements are within the specified range, no further action is required. If the measurements are outside the specified range, individual resistor elements must be replaced as required

Key Points & Notes

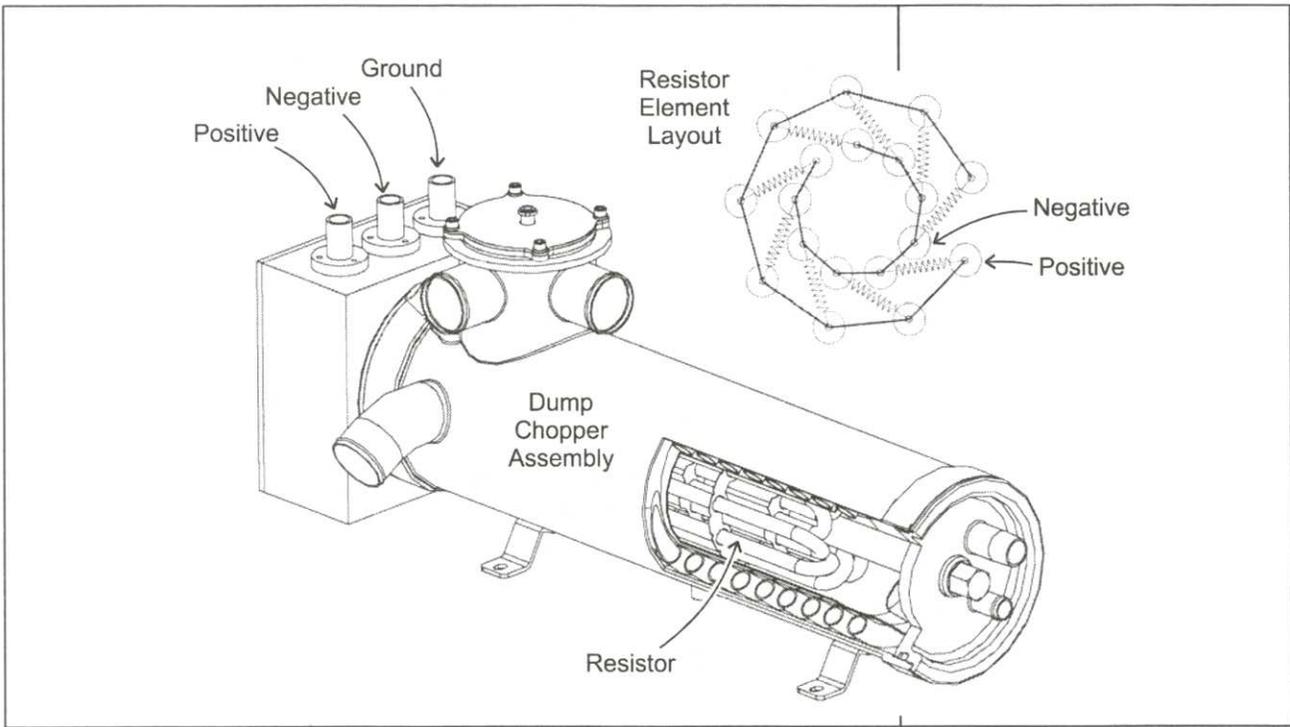


Figure 7-31 Dump Chopper

7.5 Fuel System Procedures

Key Points & Notes

Fuel system procedures pertain to routine service that is common to that found on CNG or hydrogen powered internal combustion engine buses.

7.5.1 Fuel Circuit Leak Tests

Fuel circuit leak tests ensure that fuel is not leaking from any part of the system. These tests augment the use of the on-board leak detection system to mitigate potential fire hazards.

Hydrogen is present in three circuits of different pressures:

- high-pressure circuit at high pressure up to 3600 psig (250 barg)
- motive-pressure circuit at intermediate pressure of 178 psig (12 barg)
- fuel delivery circuit at the low-pressure of up to 30 psig (2 barg)

Leak tests are conducted using a hand-held leak detector and leak detection solution as described in Section 6.1.1.

Never tighten any fitting while it is under pressure; doing so could cause the fitting to shatter with serious personal injury. Never loosen a fitting while under pressure; doing so may cause the fitting or component to be propelled with extreme force.



High-Pressure Circuit Leak Test

The high-pressure circuit is always pressurized so that it can be tested for leaks while the engine is off. However, to obtain meaningful results, the leak test must be performed when the circuit contains at least half of its service pressure i.e. 1800 psig (125 barg). Inspect fittings and components for damage when performing the leak test.

To test for leaks, apply a leak detection solution to every fitting, connection and component, including:

- semi-spherical ends of cylinders, including end bosses
- pressure relief devices and valves
- shutoff, vent and other hand valves
- solenoid, check and excess flow valves
- hydrogen particulate filter
- fueling receptacle

- pressure and temperature transducers, switches and gauges

If a leak is detected, vent the high-pressure circuit to 10 psig (0.7 barg) (and cylinder, if applicable), tighten leaking fittings, and repeat the test. **Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.**

Replace any component or fitting that continues to leak despite tightening. **Do not *loosen* any fitting on the high-pressure circuit or any cylinder without first venting the high-pressure circuit to atmospheric pressure. Vent individual cylinders prior to loosening any fitting or component associated with that cylinder. Do not loosen or adjust cylinder solenoid valves in any way.**

Cylinders that have been vented to atmospheric pressure and exposed to air require nitrogen and hydrogen purges before fueling.

After repairing a leak, pressurize the component and repeat the leak test.

Motive-pressure Circuit Leak Test

The motive-pressure circuit is only pressurized during engine operation, so the engine must be on to test for leaks. Inspect fittings and components for damage when performing the leak test.

To test for leaks, apply a leak detection solution to every fitting, connection and component, including:

- motive pressure regulators or regulator assemblies
- fuel shutoff and other hand valves
- solenoid valves
- pressure transducers, switches and gauges

If a leak is detected, shut down the engine to vent the motive-pressure circuit, tighten the leaking fittings, and repeat the test. **Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.**

Replace any components or fittings that continue to leak despite tightening. **Do not *loosen* any fittings on the motive-pressure circuit without first shutting down the engine to vent the fuel.**

Key Points & Notes



Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

The motive-pressure circuit is connected to the high-pressure circuit at the motive pressure regulator. Therefore, the regulator (or its assembly) is always exposed to high-pressure fuel. **Do not service the motive pressure regulator without first venting the high-pressure circuit.**

Fuel Delivery Circuit Leak Test

The fuel delivery circuit is only pressurized during engine operation so the engine must be on to test for leaks. Inspect fittings and components for damage when performing the leak test.

To test for leaks, use a hand-held leak detector to probe every fitting, connection and component, including:

- pressure regulator
- ejector
- contact humidifiers
- hydrogen/water separator
- filters
- water traps
- burst disk
- solenoid valves
- check valves
- stack module interface hoses
- pressure, temperature and level transducers, switches and gauges

If a leak is evident using the hand-held leak detector, apply a leak detection solution to localize it.

If a leak is detected, shut down the engine to vent the fuel delivery circuit, tighten the leaking fittings, and repeat the test. Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.

Replace any components or fittings that continue to leak despite tightening. Do not *loosen* any fittings on the fuel delivery circuit without first shutting down the engine to vent the fuel.

If a leak appears to originate within the fuel cell stacks, perform the fuel cell engine leak tests (Section 7.4.7).

Key Points & Notes



7.5.2 Fuel System Inspections

Key Points & Notes

Fuel system inspections ensure the overall integrity and safety of the fuel system. Specific checks include vent cap inspections, component inspections, and fuel pressure transducer comparisons.

7.5.2.1 Vent Cap Inspections

Vent caps seal the end of gas pressure relief lines to prevent debris and water from getting in and clogging the line. Besides clogging the line, water can expand through freezing and damage the line or components.

Vent lines serve all three fuel circuits. The vent lines are linked to:

- each cylinder pressure relief device (two per cylinder)
- the motive-pressure circuit pressure relief valve
- the fuel delivery circuit burst disk

All hydrogen vents are at roof level. During a hydrogen release, the vent pressure is sufficient to blow the cap off the vent line.

The vent cap inspections consist of a visual confirmation that each vent cap is firmly installed, undamaged and unobstructed.

The vent caps associated with the pressure relief devices (PRD) and the motive-pressure relief valve should be completely sealed with silicone.

The burst disk vent cap should be screwed into place: do not attach the burst disk vent cap with silicone. A seal of silicone would result in pressure build-up within the line, and the consequent false trigger of the nearby pressure switch, resulting in alarm shutdown.

Hydrogen Fuel Cell Engines

MODULE 7: FUEL CELL BUS MAINTENANCE

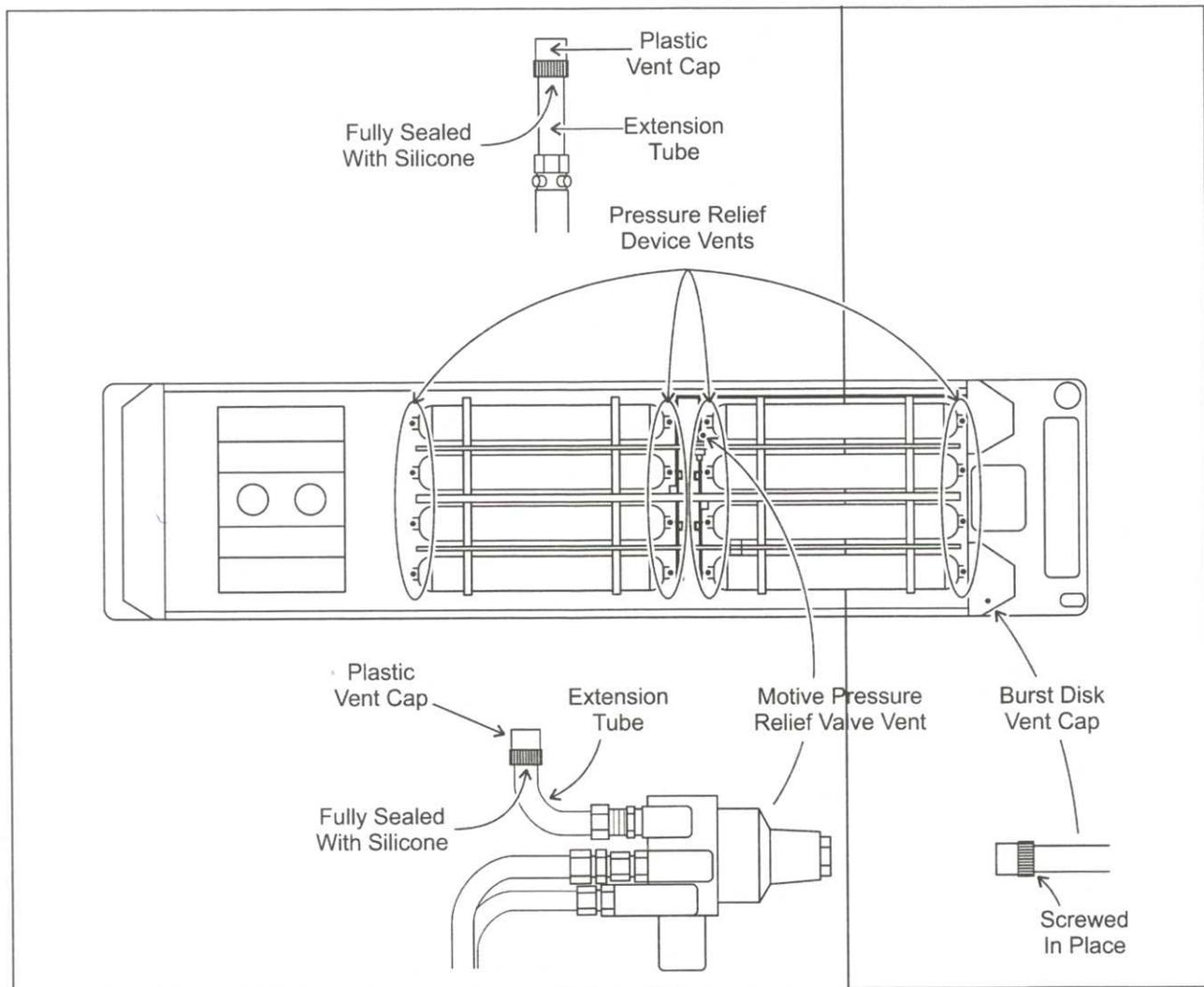


Figure 7-32 Typical Vent Cap Locations

Some vent caps include an extension tube to align the discharge point with holes in the canopy or to otherwise prevent obstruction. Alter these extension tubes if required to maintain alignment. For vent lines that protrude through holes in the canopy, confirm that each cap is located within the canopy hole, that it is protected by the hole, and that it does not stick out beyond the canopy surface.

If a vent cap is damaged or missing, check for water or dirt in the vent line and clean as required. Replace the cap as soon as possible. **Damaged, missing or incorrectly sealed vent caps can lead to pressure relief component failure.**

Key Points & Notes



7.5.2.2 Component Inspections

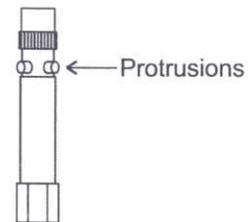
Key Points & Notes

Component inspections apply to all components in the high-pressure, motive-pressure and fuel delivery circuits. Refer to Section 7.5.2 for a component inspection list.

Component inspections consist of a visual confirmation that no component shows signs of deformities or other damage. Check that all electrical connections to solenoid valves, transducers and pressure switches are tight and uncorroded. Wherever possible, check the security of electrical connections by hand.

Check specifically that pressure relief devices are not exuding their eutectic compound. To check, run your finger over each of the two protrusions; they should be flat or slightly concave. If not, the eutectic compound is starting to protrude and the PRD must be replaced. Confirm that all hand valve handles are tight.

Fuel cylinder inspections form a special class of component inspections and are described in detail in Section 7.5.6.



7.5.2.3 Fuel Pressure Indicator Readings Comparison

The fuel pressure within the cylinders and high-pressure circuit is normally measured using multiple pressure transducers or gauges. The pressure value is normally displayed at various locations on the bus, such as on a message display center, through the diagnostics interface, within the fueling box, or by other means. If any one of these indicators is faulty, you may get the false impression that the high-pressure circuit is depressurized (thereby permitting access) while it is not.

The fuel pressure indicator readings comparison consists of a visual confirmation that all indicators display approximately the same pressure, typically within 250 psi (17 bar). If the values do not coincide, the faulty indicator must be traced and replaced.

7.5.3 Hydrogen Particulate Filter Replacement

The hydrogen particulate filter collects any debris that may enter the high-pressure circuit during fueling. This filter impedes hydrogen flow as it clogs and therefore must be replaced periodically.

As with all high-pressure circuit maintenance, the circuit must be vented to atmospheric pressure prior to access although it is not necessary to vent any of the cylinders. To disassemble, unscrew the filter enclosure from the filter

base. Inspect the retaining spring for damage and replace as required. Replace the filter element and ensure that it is oriented correctly prior to installation. Check the filter for leaks once the circuit is pressurized.

The used filter element and any accumulated material may provide useful diagnostic information when troubleshooting fuel storage system problems. Return this material to the bus manufacturer on their request.

Key Points & Notes

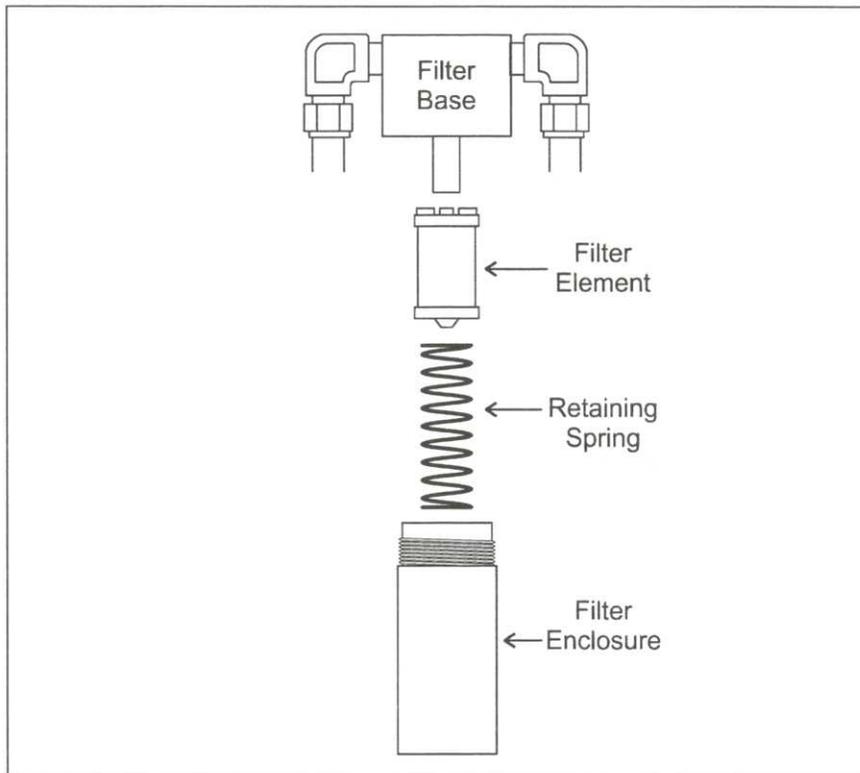


Figure 7-33 Typical Hydrogen Filter

7.5.4 Motive Pressure Regulator Solenoid Valve Check

The motive pressure regulator reduces the high pressure of the cylinders to an intermediate pressure during operation. This regulator is outfitted with a solenoid valve that isolates the fuel cell engine from the fuel storage system whenever the engine is off.

Upstream of the solenoid valve, pressure is retained when the engine is off. Downstream, pressure is vented when the engine is off. If the solenoid valve leaked while the engine is off, hydrogen would continue to vent through the inactive hydrogen diffuser, resulting in a potentially flammable mixture.

The motive pressure solenoid valve check is a confirmation that all operating and non-operating pressures are correct. Incorrect values indicate solenoid valve leakage.

Key Points & Notes

View the high and motive pressures while the engine is on:

- The motive-pressure display should indicate 170 – 186 psig (11.5 – 12.5 barg.)
- The high-pressure display should indicate the current fuel pressure within the hydrogen cylinders (varies between 300 psig (21 barg) when effectively empty, up to 3600 psig (250 barg) when fully fueled.)

Shutdown the engine and view the high and motive pressures:

- If the motive pressure drops to 0 psig/barg and the high pressure is less than the fuel pressure, the solenoid valve is not leaking and no further action is required.
- If the motive pressure does not drop to 0 psig or the high pressure is less than the fuel pressure (or is dropping), the solenoid is leaking and the pressure regulation assembly needs to be replaced. Confirm the leak using a portable hydrogen leak detector directed at the hydrogen diffuser.

7.5.5 Ground Integrity Check

The flow of hydrogen can result in static electricity buildup. This static can generate sparks and provide ignition to a flammable gas mixture. To eliminate this potential hazard, all *metal* hydrogen-containing equipment on the bus is thoroughly grounded.

Ground integrity is essential to hydrogen safety.



The ground integrity check consists of verifying by ohmmeter that all portions of the high-pressure, motive-pressure and fuel delivery circuits are grounded. Refer to Section 7.5.1 for a component list. This check proceeds by touching the first probe of the ohmmeter to a known ground point (such as the fueling grounding receptacle), and touching the second probe to the metal body of every component and length of tubing within the immediate vicinity. The meter should show continuity for each item.

Any reading other than continuity indicates a lack of grounding integrity. Once the ground integrity of a given component has been established, it can act as the new ground reference: in this way, the entire fuel system can in-

spected, incrementally moving farther away from the original ground reference at each step.

Concurrent with the continuity measurements, visually inspect all components and ground connections for corrosion, and check each ground connection by hand for tightness. Repair ground connections as required.

7.5.6 Fuel Cylinder Inspections

The fuel cylinders hold the majority of all the hydrogen on the bus, and are subject to the highest fuel pressures. To assure the safety of the cylinders, inspections of their installation and their external and internal surfaces are required.

7.5.6.1 Fuel Cylinder Installation Inspections

Fuel cylinder installation inspections consist of a visual confirmation that each cylinder is affixed to the bus roof in an appropriate manner. A typical fuel cylinder installation is shown in Figure 7-34.

To inspect the cylinder installation, check that:

- the surface of the installed cylinder is clear of all objects by at least $\frac{3}{4}$ " (20 mm)
- the lines to the cylinder show no evidence of damage due to bus flexure or cylinder expansion
- water and other fluids can drain freely from the cylinder's position
- the label is clearly visible

To inspect the cylinder mounting bracket installation, check that:

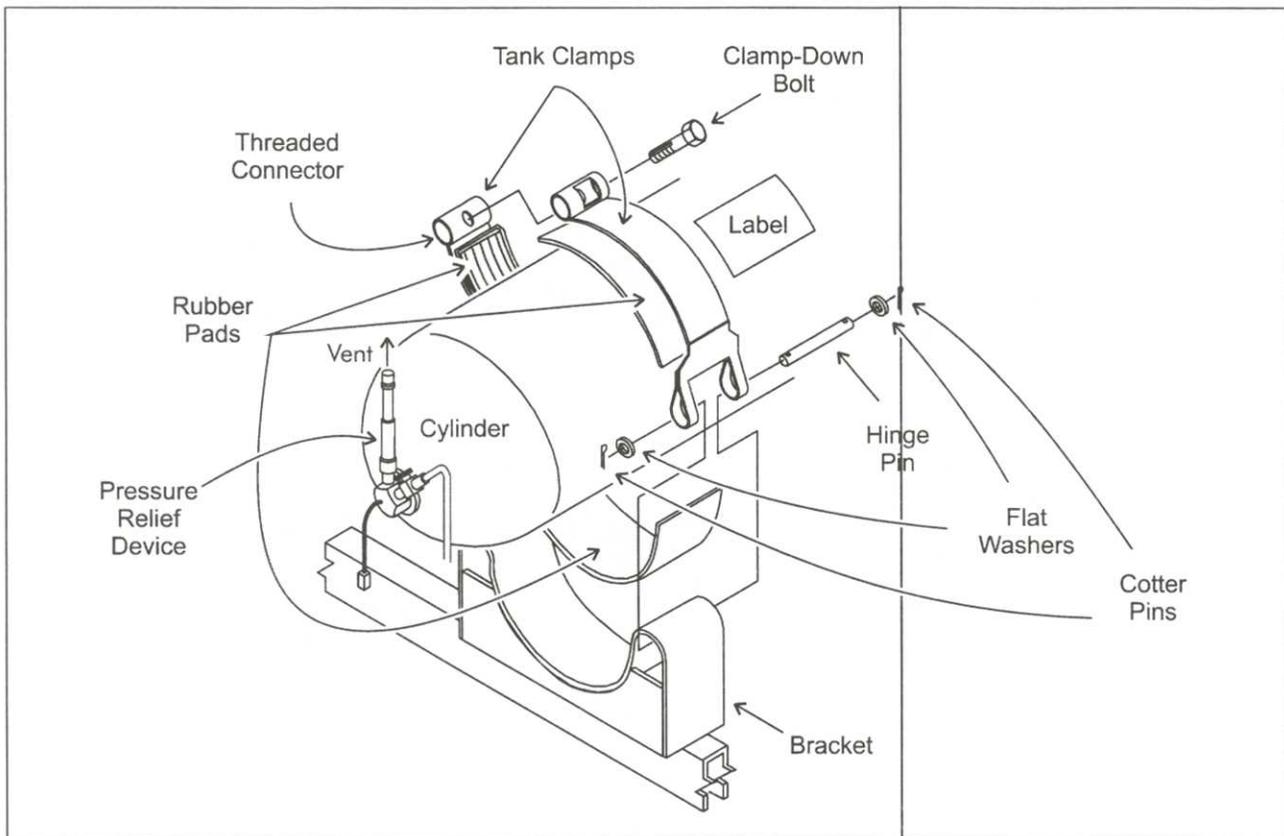
- the cylinder mounting system allows the cylinder to expand and contract as the internal pressure fluctuates without causing the cylinder to be abraded
- the interface between the cylinder and the bracket is lined with a rubber pad to allow limited movement of the cylinder
- the rubber pads are in place and in good condition
- the cylinder is firmly restrained
- the cylinder and brackets are firmly attached to the bus and do not permit rocking or other looseness
- the bolts that secure the brackets to the bus are present and tight

Key Points & Notes

<i>Refer to the scope at the start of this manual for other courses offered by the College of the Desert pertaining to high-pressure gas training and cylinder safety and certification training.</i>

Key Points & Notes

- where brackets are bolted to sheet metal panels, washers with minimum 3" (76 mm) outside diameter are used
- the brackets are in good condition
- a ½ " SAE washer is used in conjunction with bracket bolts
- the clamp-down bolts that secure the cylinder to the mounting bracket are properly torqued to manufacturer's specifications
- the metal strips do not touch the cylinder at any point
- the hardware, bolt and bus attachments do not exhibit severe corrosion or cracking


Figure 7-34 Typical Cylinder Installation

To inspect the cylinder pressure relief device installation, check that:

- all pressure relief devices are installed and are of a type approved by the bus manufacturer
- the pressure relief device vents pass without obstruction through holes in the roof canopies so as to vent external to the bus, are free of debris, and are capped (see Section 7.5.2.1)

7.5.6.2 Fuel Cylinder External Inspections

Key Points & Notes

Fuel cylinder external inspections consist of an assessment of any external damage on *all* cylinders.

Inspection Documentation

Cylinder external inspection records provide a permanent chronicle of cylinder history. Inspection results are normally recorded on a test log that indicates the date, the hourmeter and odometer readings, cylinder serial numbers, and observed damage levels for all components in each inspection category. Damage descriptions, repairs and other relevant comments must also be added to the inspection documentation.

Tools

Assemble the following tools in preparation for the external cylinder inspections:

- mirrors to provide visual access to obscured portions of the cylinders
- depth gauge to measure cut depth
- caliper or ruler to measure cut length

Preparation

In preparation for the external cylinder inspections:

1. Check the cylinder's inspection and service record, and/or speak to the bus drivers and maintenance personnel for information on known conditions or incidents that may have caused damage to the cylinder. Incidents that may lead to the cylinder being condemned include but are not limited to:
 - dropping or impacts of the cylinder
 - exposure of cylinder to excessive heat, fire or harsh chemicals
 - accidents
2. Open canopies or remove shields to access all cylinder surfaces.
3. Clean the outside surface of the cylinders using clean water or water mixed with a mild soap solution consistent with bus exterior cleaning procedures. Do not remove or add coatings of any type. Contact the cylinder manufacturer if surface re-finishing is required.

4. Ensure cylinders are well illuminated for damage observations.

Key Points & Notes

Never expose hydrogen storage cylinders to unapproved soaps or solvents (such as varsol, acetone, methyl-ethyl-ketone, paint thinner, lacquer thinner, gasoline, alcohol, ammonia, etc.). These solutions may corrode, weaken or seriously damage the cylinders. Contact the manufacturer if in doubt.



Damage Observations

Cylinder damage is categorized as either level 0, 1, 2, or 3 depending on severity. Refer to the Table 7-2 and Figure 7-35 when performing the external cylinder inspection.

Composite cylinders do not dent like all-metal cylinders. **Impacts may cause more severe damage within the wall of the cylinder than at the surface, as the surface tends to return to its original shape after impact.**



Damage Level	Observations and Limiting Parameters
Cut, Scratch, Abrasion and Scuff Damage	
Level 1	Shallow cuts, scratches, abrasions or scuffs are noticeable in the laminate. The depth and length of these defects are too small to be measured. A very limited amount of carbon fibre or epoxy has been worn away.
Level 2	Definite cuts, scratches, abrasions or scuffs are noticeable in the laminate: Defects over 1" (25 mm) long are less than 0.06" (1.5 mm) deep Defects under 1" (25 mm) long are less than 0.08" (2 mm) deep
Level 3	Definite cuts, scratches, abrasions or scuffs are noticeable in the laminate: Defects over 1" (25 mm) long are more than 0.06" (1.5 mm) deep Defects under 1" (25 mm) long are more than 0.08" (2 mm) deep

Observations and Limiting Parameters	
Impact Damage	
Level 1	Highly localized imprinting as caused by impact of a small stone. Damage is limited in both length and depth. Small random hairline cracks in the resin surface parallel to the reinforcing fibers, but not localized in one area of the cylinder. These cracks are common on glossy laminate surfaces and are not a sign of impact damage.
Level 2	Light impact damage indicated by scuffs, surface discoloration, concentration of micro-cracks and/or a few broken fibers. A coin tap test does not indicate damage.
Level 3	Heavy impact damage indicated by obvious scuffs, surface discoloration, concentration of micro-cracks and/or numerous broken fibers. A coin tap test indicates damage. Obvious damage to cylinder ports; the end boss or valve is skewed and/or leaking.
Chemical Surface Damage	
Level 1	Minor discoloration and/or etching of the cylinder surface caused by a mild non-corrosive contaminant. The contaminant is easily removed by cleaning.
Level 2	The cylinder surface has been exposed to a corrosive chemical. Discoloration is not easily removed by cleaning, but there are no soft spots, blistering, swelling, etching, unraveling of fibers, or removal of resin.
Level 3	Heavy chemical attack has occurred. The cylinder surface shows any of the following: <ul style="list-style-type: none"> • soft spots • blistering • swelling • etching • unravelling of fibers • resin removal
Fire and Excessive Heat Damage	
Level 3	The cylinder has been exposed to excessive heat or fire. The cylinder surface shows any of the following: <ul style="list-style-type: none"> • darkening • charring • bubbling of epoxy
Weather Damage	
Level 1	Discoloration or chalking of the epoxy on the cylinder surface external after prolonged exposure to sunlight, but no evidence of loose fibers.
Gas Leaks	
Level 3	Cylinder does not hold gas at full pressure when outlets are definitely undamaged and properly sealed as verified by applying a leak detection solution.

Table 7-2 Cylinder Damage Levels

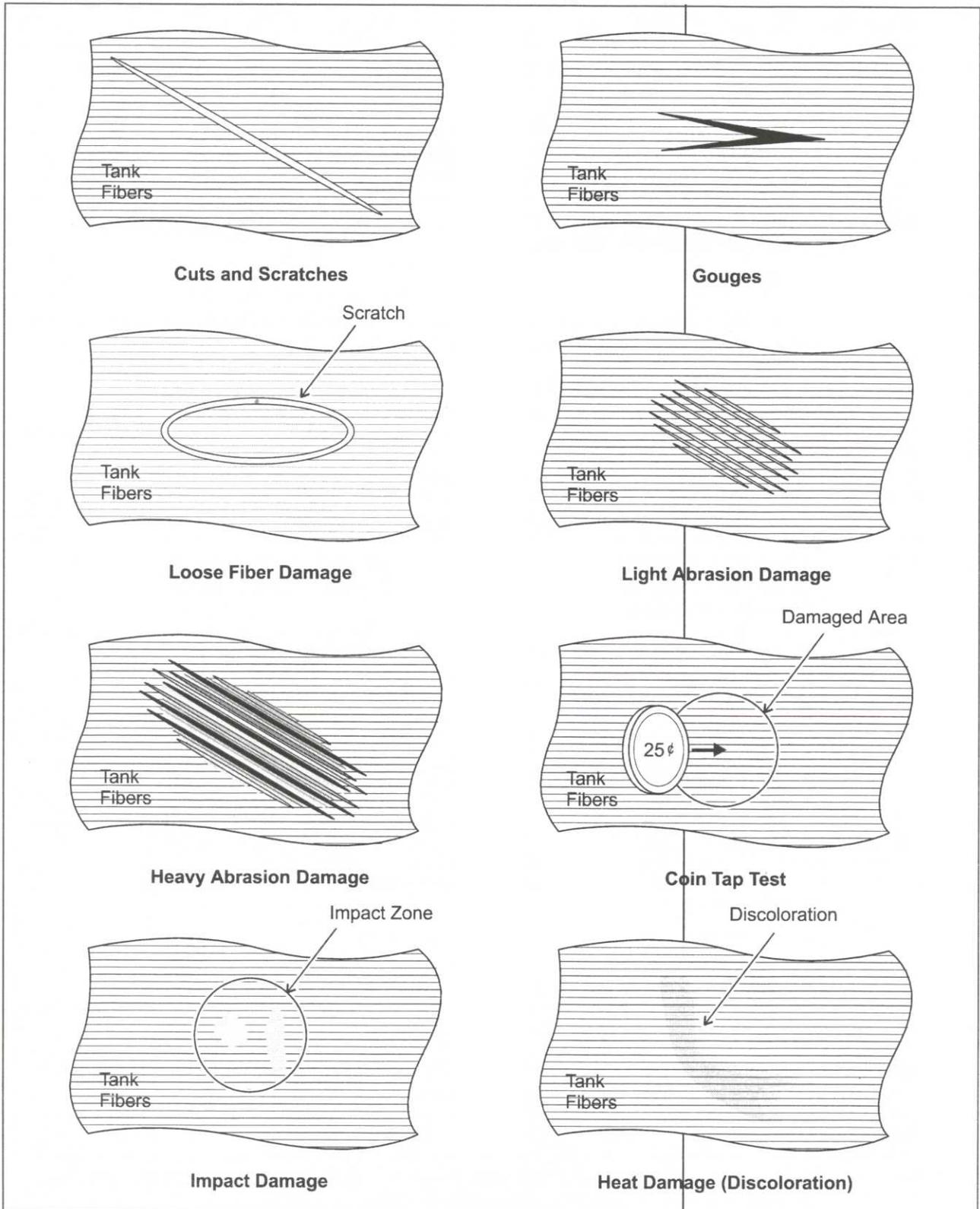


Figure 7-35 Composite Cylinder Damage

Key Points & Notes

Procedure

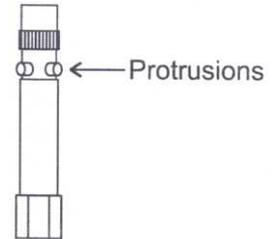
Key Points & Notes

For each cylinder, check and inspect the following:

1. Check cylinder data:
 - Check that the cylinder's pressure rating is equal to the pressure it is being used for
 - Check the cylinder service life: cylinders that have reached their service life must be replaced.
 - Check that the cylinder serial number is clearly legible on the cylinder label. If the serial number is not legible, contact the manufacturer for a replacement label. Record each serial number.
2. Inspect exterior surface of cylinder laminate for cuts, loose fibers, abrasion, wear or dents and assess cylinder damage level according to Table 7-2 and Figure 7-35. Pay particular attention to cylinder areas in contact with the cylinder clamps.
3. Inspect the exposed aluminum end boss (at both ends of the cylinder):
 - Check for signs of corrosion and assess damage level according to Table 7-2 and Figure 7-35.
 - Using a leak detection solution, check the O-ring seal between the end boss and the cylinder shell for leakage.
4. Inspect the mounting bracket (at both ends of the cylinder):
 - Confirm that the rubber extrudes beyond the top and bottom metal portions of the clamp and is well seated. Use a mirror as required to inspect the bottom clamp.
 - Remove top clamp of the mounting bracket and inspect cylinder laminate for wear, and assess cylinder damage level according to Table 7-2 and Figure 7-35.
 - With top clamp of the mounting bracket removed, inspect the rubber pad for deterioration.
5. Perform a coin tap test:
 - Grasp a quarter between your fingers, tap on the cylinder surface, and listen to the sound it makes.
 - Compare zones of potential damage to undamaged areas. Cylinder and dome areas have naturally different sounds.

Key Points & Notes

- If differences in sound are evident within like areas, the cylinder is damaged (Level 2) and must be repaired by the manufacturer. If uncertain, contact the manufacturer.
6. Inspect the pressure relief devices (at both ends of the cylinder):
- Using a leak detection agent, inspect pressure relief devices for leaks.
 - Check that the pressure relief devices are not exuding their eutectic compound: run your finger over each of the two protrusions; they should be flat or slightly concave. If not, the eutectic compound is starting to protrude and the pressure relief device must be replaced.



Disposition

Assess cylinder damage with reference to Table 7-3.

Damage Level	Description	Action
External Cylinder Damage Levels		
Level 0	Cylinder is not damaged	No action is required. The cylinder may return to service.
Level 1	Cylinder is slightly damaged	Leave the cylinder in service, but isolate the source of damage to prevent further damage. Contact the manufacturer for repair procedures and use approval.
Level 2	Cylinder is damaged, but can be repaired	Remove cylinder from service and contact the manufacturer for inspection/repair.
Level 3	Cylinder is damaged and cannot be repaired	Remove the cylinder for service, condemn and return to the manufacturer for recycling.

Table 7-3 Cylinder Disposition

7.5.6.3 Fuel Cylinder Internal Inspection

Fuel cylinder internal inspections consist of an assessment of any internal damage on *one* cylinder.

Tools

A boroscope is required for internal cylinder inspections.

Procedure

Key Points & Notes

For *one* cylinder:

1. Vent the cylinder to atmospheric conditions and close its shutoff valve.
2. Confirm that the cylinder has vented by measuring the resistance of the cylinder solenoid valve coil and comparing it to manufacturer's specifications. A short circuit (0 Ω) indicates that the solenoid valve has failed and that high-pressure gas may be trapped within the cylinder despite venting or other procedures.

An increase in resistance indicates that some form of corrosion or material buildup has occurred within the coil or connecting wires. If the resistance increase is sufficient, the solenoid may not draw enough current to actuate the valve and high-pressure gas may be trapped within the cylinder despite venting or other procedures.

Report any resistance variations to the bus manufacturer. If you are in any way uncertain that the cylinder has fully depressurized, open the manual lockdown assembly on the cylinder end boss according to manufacturer's instructions.

Do not access the cylinder unless you are positive it has fully vented.



3. Remove the end boss (with pressure relief device attached) and O-ring from the *non*-solenoid valve end of the cylinder.
4. Using the boroscope, inspect interior surface of the cylinder liner for corrosion pitting, moisture or damage. Record the cylinder tag identifier, serial number and observation results.

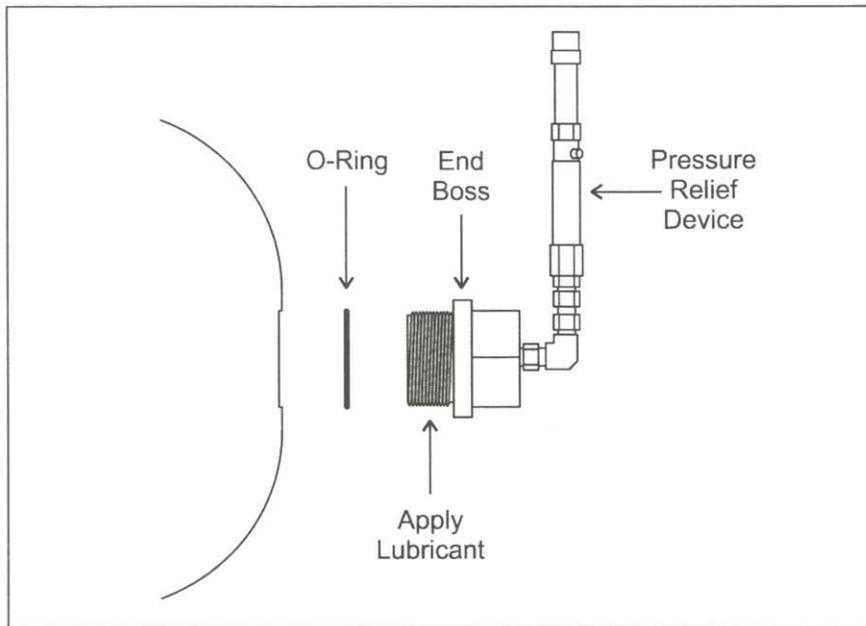


Figure 7-36 Cylinder Internal Inspection

Report any damage to the manufacturer before proceeding.

5. Replace the O-ring, apply the manufacturer approved thread lubricant to the end boss threads, and torque the end boss into the cylinder according to manufacturer's specifications. Ensure that at least seven threads have engaged. Confirm that the pressure relief device points straight up, and adjust as required.
6. Open the shutoff valve, nitrogen purge, and hydrogen purge the cylinder. Once pressurized, perform a leak test in the vicinity of cylinder end boss.

7.5.7 Pressure Regulator Diaphragm, Seal and Seat Replacement

The pressure regulator reduces the hydrogen gas pressure for use in the fuel cell engine. The regulator diaphragm, seals and seats must be replaced periodically as a preventative measure to prevent leaks that could otherwise occur due to hydrogen embrittlement.

The pressure regulator service uses a manufacturer supplied kit and instructions. Perform a leak check and a ground integrity check on the regulator after installation.



Key Points & Notes

7.6 Conventional Procedures

Key Points & Notes

Conventional procedures pertain to routine service that is typical of any bus, although different in detail on a fuel cell bus.

7.6.1 General Inspections

General inspections provide a quick check for obvious bus damage or failures.

7.6.1.1 Air Intake and Exhaust Inspection

The air intake draws process air from the ambient environment. The air exhaust discharges depleted air back to the environment. Both the intake and exhaust are at roof level.

The air intake and exhaust inspection consists of a visual confirmation that neither component is obstructed or damaged. Clear or replace as required.

7.6.1.2 Canopy Inspections

The canopies cover and protect the fuel cylinders and other roof components.

The canopy inspection consists of a visual confirmation that no canopy displays obvious damage. If canopy damage exists, check for cylinder and cylinder installation damage; repair as required.

7.6.1.3 Fluid Leak Checks

The bus uses a variety of fluids in the coolant, lubrication, hydraulic, transmission and HVAC circuits.

The fluid leak checks consist of a visual confirmation that no fluid leaks or puddles are evident. Check for leaks and puddles:

- beneath the bus
- in the engine compartment
- in the cooling compartment
- in the radiator compartment
- on or around the power train
- in the holding tank area

As the fuel cell engine produces water, some water naturally accumulates beneath the holding tank drain valves as well

as under water trap drain ports. This water can be ignored, unless substantial enough to indicate leaking components.

Identify the type of fluid by its color and viscosity, and assess the severity of any leak. Repair as required.

7.6.2 Leak Detection System Checks and Conditional Calibration

The leak detection system guards against hydrogen leaks and must be checked for functionality and calibrated for accuracy. If any part of the system is not functioning or is uncalibrated, the system may fail to detect gas leaks, resulting in a potential fire hazard. The bus may not be operated without a fully functional leak detection system.

Key components of the leak detection system include leak indicators (or some other form of system controller) and leak sensors.

7.6.2.1 Leak Indicator Checks

Some leak detection systems include leak indicators that display gas concentration, alarm or fault information associated with each leak sensor. Typically, the leak detection system indicators are only active when the engine is on.

The leak indicator checks consist of a visual confirmation that each indicator is powered, does not display any error codes, and indicates no hydrogen presence. Specific messages and error codes depend on the leak detection system manufacturer, but in general the codes differentiate between warning or alarm triggers (at 5, 15 and 25% LFL) and different types of faults. All faults or errors must be remedied according to manufacturer's instructions.

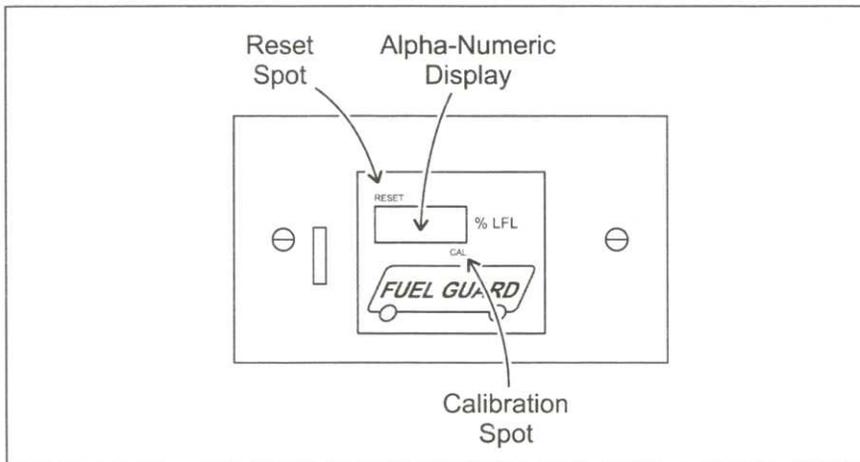


Figure 7-37 Typical Leak Indicator

During normal operation, the indicators display the hydrogen concentration value in %LFL at the corresponding sensor location. Leak sensors tend to drift over time and as a result the leak indicators may display a hydrogen concentration where none exists. However, all leak indications must be taken seriously and be either confirmed or disproved using a hand-held leak detector in the vicinity of the sensor. All legitimate leaks must be traced and repaired. False readings below 4% LFL may be ignored. If a false reading above 4% LFL occurs, calibrate the system (Section 7.5.5.3).

Key Points & Notes

7.6.2.2 Sensor Inspections

The leak sensors detect hydrogen presence and are located at key locations throughout the bus. These sensors must be undamaged for the leak detection system to operate properly. Typically, the leak sensors are only active when the engine is on.

Each leak sensor consists of the sensor base, a sintered flame arrestor, a foam splash guard, vibration isolators and an electrical connector. The sensor base contains the sensor electronics into which gas passes through the sintered flame arrestor. The foam splash guard prevents water and dirt from plugging the flame arrestor. The vibration isolators reduce shocks to the sensor. The electrical connector passes power and signals to and from the sensor.

The sensor inspections consist of a visual confirmation that no sensor components are missing, and that all components are undamaged and free of cracks, distortion, dirt or obstruction. Replace components as required. The splash guard may be cleaned with soapy water if not excessively dirty. If replacing the splash guard, trim the new unit as required using the shape of the original splash guard as a guide.

Replace the sensor if the flame arrestor is impeded in any way. **Do not attempt to clean the sensor with steam, solvents or other cleaning solutions.**



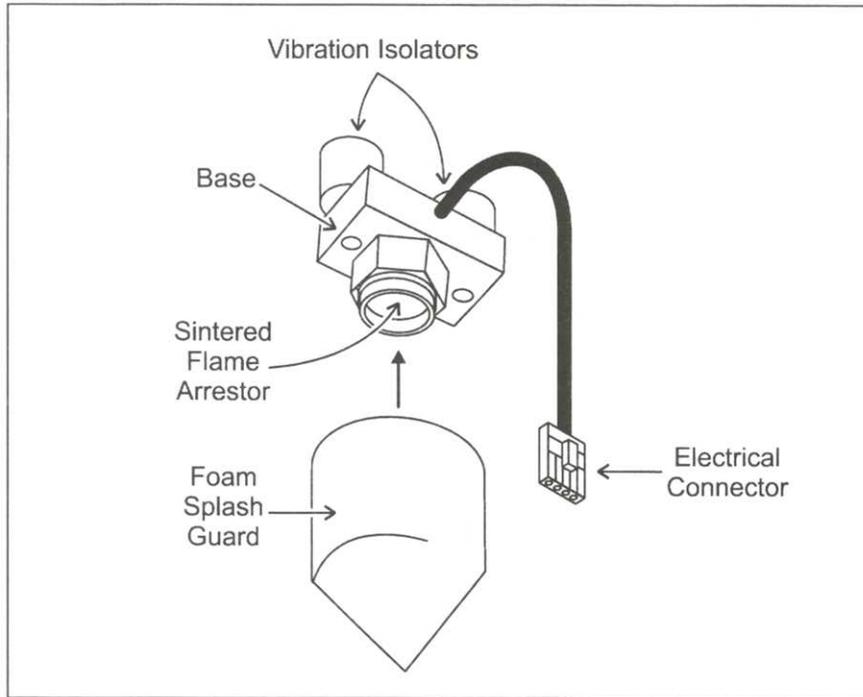


Figure 7-38 Typical Leak Sensor

7.6.2.3 System Calibration

Key Points & Notes

The leak detection system must be calibrated periodically to correct for sensor drift and aging. On systems that include leak indicator displays, the system is commonly calibrated whenever any indicator displays greater than >4% LFL with no gas present.

System calibration consists of exposing each sensor to laboratory gases with 0 and 50% LFL hydrogen and programming the leak detection system controller at each of the two concentrations. In effect, these two reference gas concentrations establish the “zero” point (system offset) and the “span” (system scaling factor) for the interpretive algorithms. After calibration, the leak detection system interprets detected gas concentrations relative to these two calibration reference points.

Typical leak detection system test equipment is illustrated in Figure 7-39 and must include the following:

- “Zero Air” (pure air) calibration gas
- “Span Gas” (2% hydrogen (50% LFL)) calibration gas
- Calibration gas regulator and sensor connector assembly
- System specific programming tool. Some systems use a magnetic calibrator for this purpose; the calibrator has “zero” and “span” ends that are placed near appropriate

spots on the corresponding leak indicator during calibration.

Key Points & Notes

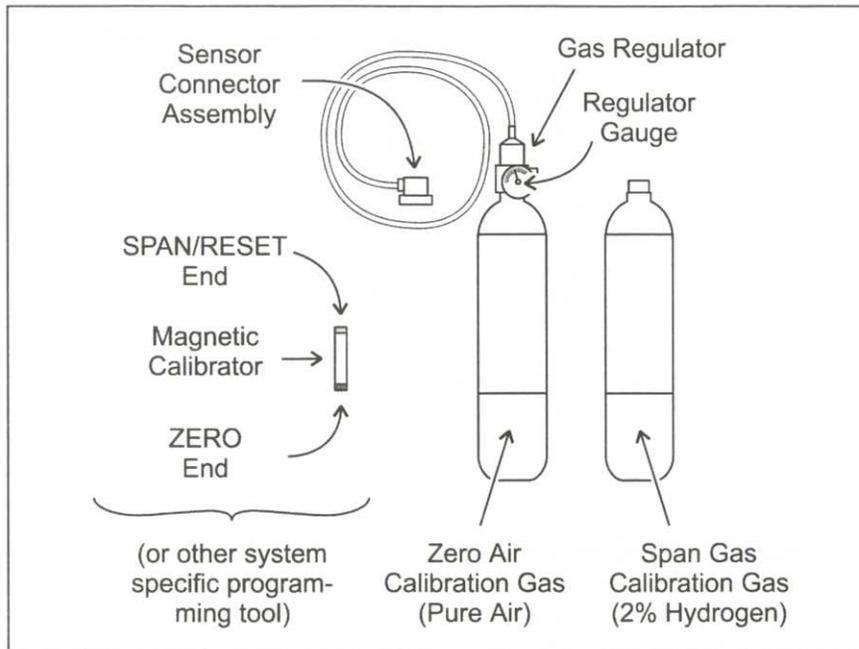


Figure 7-39 Typical Leak Detection System Calibration Equipment

Leak detection system calibration usually requires two people. One person applies the calibration gases to the sensors while the other person programs the system. Test results are normally recorded on a calibration record that indicates the date, the hourmeter and odometer readings, and sensor serial numbers.

Specific calibration (and particularly programming) procedures depend on the leak detection system manufacturer but generally involves the following steps. Systems usually display calibration related messages, fault or error codes by way of the leak indicators or other means.

Prepare to calibrate:

1. Ensure that the leak detection system is powered and is free of faults or errors. All errors must be cleared before calibration can proceed.
2. Ensure that no combustible gas is present.

Apply Zero Air:

3. Assemble the zero air test equipment, and open the regulator valve for a couple of seconds so that the sensor connector assembly is flushed out with the test gas.

4. For each leak sensor:

Key Points & Notes

- a) Remove the foam splash guard, and inspect the sensor and ensure that the sintered flame arrestor is intact, undamaged and clean.
- b) Place the end of the sensor connector assembly onto the flame arrestor, and open the regulator valve to apply Zero Air to the sensor.
- c) Program the leak detection system using the system specific programming tool. If applicable, view the leak indicator codes to confirm that the calibration was successful.
- d) Close the regulator valve and remove the sensor connector assembly from the sensor.

Apply Span Gas:

4. Repeat steps 3 and 4 using the span gas test equipment.

Complete:

5. Wait while system stores the new calibration values into memory.
6. Confirm that each sensor now indicates 0% LFL. Repeat calibration as required; if a sensor cannot be successfully calibrated, it must be replaced.
7. Disassemble test equipment.

7.6.3 Fluid Level Checks, Samples and Assessments

The fuel cell bus uses the following fluids:

- humidification water
- stack coolant
- bus coolant
- lubrication oil
- hydraulic fluid
- transmission fluid
- HVAC compressor oil

These fluids must be present in adequate quantities and be free of contamination for proper engine operation. Like a conventional powered bus, fluid levels may be reduced through leakage or lost during maintenance procedures, and contaminants may be introduced from external or internal

sources. Unlike a conventional powered bus, the fuel cell bus produces water, does not burn oil, and does not generate combustion related contaminants.

Standard fluid procedures include level checks, sample collections, and condition assessments as described in the following sections.

7.6.3.1 Humidification Water

Level Check

The humidification water level check is normally done with reference to a header tank sightglass. The engine may be on or off and the water may be hot or cold for the level check. Water for the humidification circuit is drawn from the product water stream produced by the fuel cells; thus, any water shortfall indicates that the bus is not recovering sufficient water from the air exhaust stream.

Humidification water may be added directly through a fill port. Use only clean de-ionized (distilled) water. Record the amount of water added.

The humidification water circuit is pressurized during operation but depressurizes upon engine shutdown. **Always turn off the engine before opening the fill port.**



7.6.3.2 Stack Coolant

Level Check

The stack coolant level check is normally done with reference to a header tank sightglass. The engine may be on or off and the coolant may be hot or cold for the level check.

Stack coolant may be added directly through a fill port. Use only clean de-ionized water with or without pure ethylene glycol as specified by the manufacturer. Record the amount of coolant added.

The stack coolant circuit is pressurized during operation and remains pressurized for some period of time after engine shutdown. **Always turn off the engine and relieve the circuit pressure before opening the fill port.**



7.6.3.3 Bus Coolant

Level Check

The bus coolant level check is normally done with reference to a header tank sightglass. The engine may be on or off and the coolant may be hot or cold for the level check.

Key Points & Notes

Bus coolant may be added directly through a fill port. Use a standard water/ethylene glycol mixture. Record the amount of coolant added.

The bus coolant circuit is pressurized during operation and remains pressurized for some period of time after engine shutdown. **Always turn off the engine and relieve the circuit pressure before opening the fill port.**

7.6.3.4 Lubrication Oil

Level Check

The bus lubrication oil level check is normally done with reference to a dipstick. The engine must be off for an accurate level indication, but the oil must be hot or cold. Do not allow any dirt or foreign matter to enter the oil while removing or re-inserting the dipstick. If it is necessary to lay the dipstick down, ensure that it lies on a clean surface.

Lubrication oil may be added directly through a fill port. Use the specified lubrication oil only. Record the amount of oil added.

The lubrication oil circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

Inspection

The bus lubrication oil sump is fitted with a magnetic drain plug in order to collect metal filings or debris. Material accumulation of this sort indicates component wear or damage, and provides useful diagnostic information when troubleshooting or anticipating power train problems.

The magnetic drain plug has a two-part nut, such that you can remove the inner nut without draining the oil, or remove both to drain the oil.

All collected materials should be retained for future analysis and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately if significant material has collected and return the debris on their request. The plug must be clean before re-insertion.

Sample

Bus lubrication oil samples can provide useful diagnostic information when troubleshooting or anticipating power train problems. Oil samples can be drawn directly from the

Key Points & Notes



oil sump drain plug. Samples should be collected in sealable containers of approximately ½ CUP (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

Key Points & Notes

7.6.3.5 Hydraulic Fluid

Level Check

The bus hydraulic fluid level check is normally done with reference to a header tank sightglass. The engine must be off for an accurate level indication, but the fluid may be hot or cold.

Hydraulic fluid may be added directly through a fill port. Use the specified hydraulic fluid only. Record the amount of fluid added.

The hydraulic fluid circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

*Sample*

Bus hydraulic fluid samples can provide useful diagnostic information when troubleshooting or anticipating power train problems. Fluid samples can be drawn directly from the hydraulic circuit drain plug. Samples should be collected in sealable containers of approximately ½ CUP (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

7.6.3.6 Transmission Fluid

Presence Check

The transmission fluid presence check is normally done with reference to a dipstick. The engine must be off, but the fluid may be hot or cold.

The transmission fluid presence check does not give accurate level information when performed cold, but it provides a quick indication of massive fluid loss prior to starting the engine.

Level Check

Key Points & Notes

The bus transmission fluid level check is normally done with reference to a dipstick, or using an electronic method specific to the transmission manufacturer. Where an electronic method is available, it is preferable to the manual method since it is more reliable and provides more information. The engine must be off for an accurate level indication, but the fluid must be at its normal operating temperature.

Transmission fluid may be added directly through a fill port. Use the specified automatic transmission fluid only. Record the amount of fluid added.

The transmission fluid circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

*Sample and Inspection*

Bus transmission fluid samples can provide useful diagnostic information when troubleshooting or anticipating transmission problems. Fluid samples can be drawn directly from the transmission drain plug. Samples should be collected in sealable containers of approximately ½ CUP (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings.

Check the fluid for the following:

- **Dirt:** Investigate source of dirt and eliminate.
- **Water:** Some condensation appears in the transmission fluid during operation. For obvious water contamination, inspect and pressure test the transmission cooler. Replace leaking coolers.
- **Glycol:** Glycol in the transmission hydraulic system requires immediate action to prevent malfunction and serious damage. Completely disassemble, inspect and clean the transmission. Remove all traces of glycol and varnish deposits resulting from glycol contamination. Replace friction clutch plates contaminated with glycol.
- **Metal Particles:** Metal particles in the transmission fluid indicates internal transmission damage. If metal particles are found in the sump, the transmission must be disassembled and closely inspected for the source of the metal. Clean all internal and external hydraulic circuits, cooler, and all other areas where the metal particles could lodge.

Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

Key Points & Notes

7.6.3.7 HVAC Compressor Oil

Inspection

The HVAC compressor oil inspection can provide useful diagnostic information when troubleshooting or anticipating compressor or refrigerant circuit problems. The oil is self-contained within the compressor and can be viewed through a sightglass. Check the oil for the following:

- **Colorless or Light Yellow Oil:** Good.
- **Brown Oil:** Indicates copper plating caused by moisture in the system or acidic oil. Return the compressor to the manufacturer for oil replacement.
- **Black Oil:** Indicates carbonization caused by air in the system or the presence of wear particles that contain iron. Return the compressor to the manufacturer for oil and filter replacement.
- **Green Oil:** Indicates water in the system, and that copper plating may have occurred. Return the compressor to the manufacturer for inspection of shaft seals, bearings, gears and rotors, and oil and filter replacement.
- **Gray or Silver (Metallic) Particles:** Indicates the presence of wear particles that contain aluminum. This is usually caused by bearing wear or piston scoring. Return the compressor to the manufacturer for inspection of worn or damaged components, and oil and filter replacement.

Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids.

7.6.4 Turbocharger Oil Trap Drain

Lubrication oil becomes infused with air as it interacts with the turbocharger. This air must be removed to prevent the oil from turning into a froth. This is accomplished using a separator vessel on the oil return line, which directs the air stream to an oil trap. This air stream carries a small amount of oil with it that collects in the oil trap while the air escapes through an air vent.

The turbocharger oil trap drain consists of opening a drain port on the bottom of the oil trap and removing any accumulated oil.

Key Points & Notes

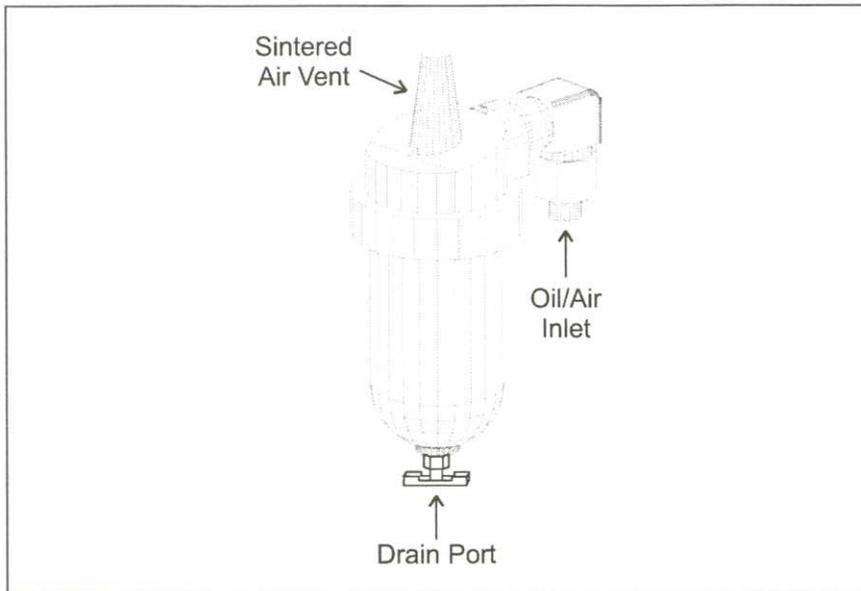


Figure 7-40 Typical Oil Trap

7.6.5 Fire Suppression System Inspections and Tests

The fire suppression system must be inspected for damage and tested for functionality. If any part of the system is damaged or not functioning, the system may fail to detect or suppress fires. The bus may not be operated without a fully functional fire suppression system.

Key components of the fire suppression system include a system controller, fire sensors, nozzles and hoses, and retardant tanks.

7.5.5.1 Sensor Inspections

The fire sensors detect fire presence and are located at key locations throughout the bus. These sensors must be undamaged for the fire suppression system to operate properly. Typically, the fire sensors are only active when the bus battery knife switches are closed (connected).

Each fire sensor includes two windows, an LED, and a pair of electrical connectors. The windows pass infrared energy into the sensor electronics. The LED provides a power and fault indication. The electrical connectors pass power and signals to and from each sensor. The sensors of a given zone are arranged in a serial fashion so that the output of one sensor is the input of the next. The output connector associ-

ated with the terminating sensor of each zone contains an "end-of-line" resistor.

The sensor inspections consist of a visual confirmation that all sensors are powered (LED on), operating without fault indication (LED not flashing), and free of damage, cracks, distortion, dirt or obstruction. Clean the sensor windows using water and non-abrasive towels or rags as required.

Do not attempt to clean the sensor with steam, solvents or other cleaning solutions.

Key Points & Notes

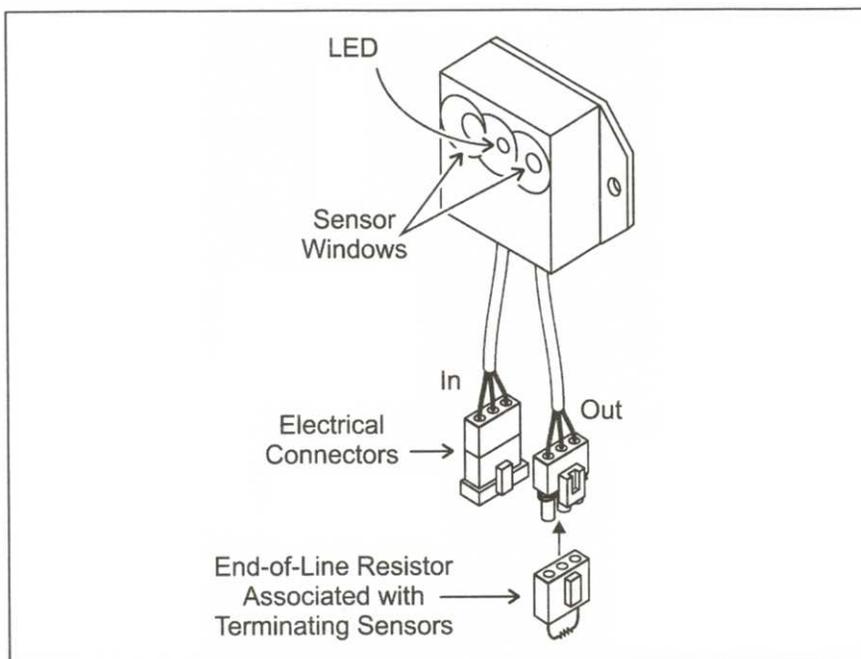


Figure 7-41 Typical Fire Sensor

7.5.5.2 Hose, Nozzle and Retardant Tank Inspections

The hoses and nozzles distribute and discharge the contents of the fire retardant tanks in the event of a fire.

Hose inspections consist of a visual confirmation that all accessible distribution hoses are free of cuts, tears, abrasion, cracks or damage. Remove sources of abrasion.

Nozzle inspections consist of a visual confirmation that all nozzles are functional, undamaged and unobstructed. Nozzles are of two styles, depending on their mounting location. For nozzles with a hinged cap, ensure that the hinged nozzle cap is normally closed but opens easily. For nozzles with a blow-off cap, ensure that the cap is seated on the end of the nozzle.

Retardant tank inspections consist of a visual confirmation that all tanks are undamaged and at the correct charge pressure. A tank is fully charged if its valve pressure gauge pointer is within the green arc at room temperature. (If the tank is cold, allow it to warm up to room temperature). If the pointer is outside the green arc, replace the retardant tank and have it charged or serviced.

Key Points & Notes

Replace damaged components as required.

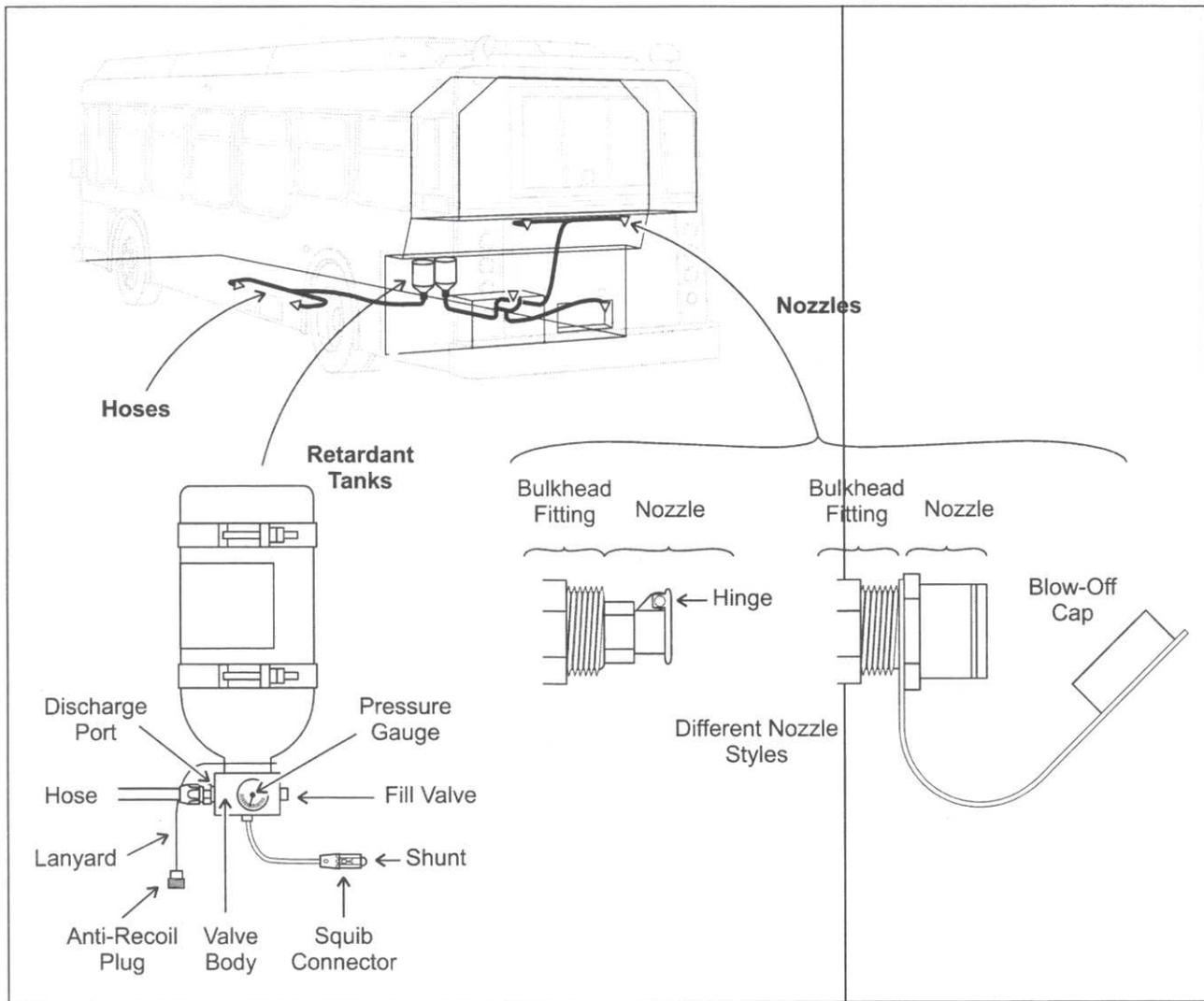


Figure 7-42 Typical Fire Retardant Distribution Equipment

7.5.5.3 System Tests

The fire suppression system must be tested periodically for functionality.

System tests consist of disconnecting each fire retardant tank and substituting an electronic device that indicates

whether the tank *would have* discharged under the test conditions. Different test conditions are simulated using a second electronic device in contact with each fire sensor. The simulated test conditions comprise:

- False Alarm Immunity Test (all sensors)
- Fire Response Test (all sensors)
- Engine Shutdown Test (1 sensor only)
- Fault Test (all zones)

Typical fire suppression system test equipment is illustrated in Figure 7-43 and must include the following:

- one source simulator
- one extinguisher valve simulator per fire retardant tank

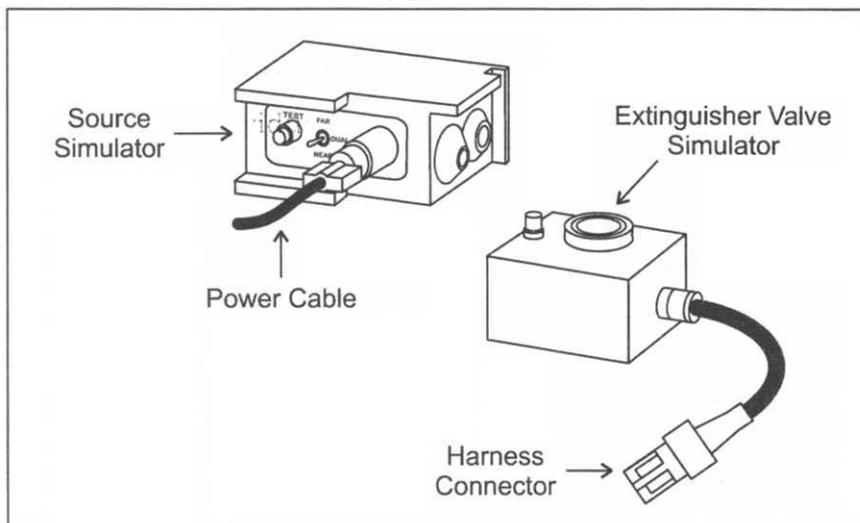


Figure 7-43 Typical Fire Suppression System Test Equipment

Fire suppression system tests usually require two people. One person operates the source simulator while the other person monitors the extinguisher valve simulators. Test results are normally recorded on a test record that indicates the date, the hourmeter and odometer readings, and a pass or fail indication for each test.

Specific test procedures depend on the fire suppression system manufacturer but generally involves the following steps.

Preparation

Prepare to test:

1. Disconnect the squib connector from the electrical wiring harness at the tank valve of each tank. **Failure to dis-**



connect all fire retardant tanks will result in retardant discharge during testing.

Key Points & Notes

2. Connect a valve simulator to the harness disconnected from each fire retardant tank as shown in Figure 7-44.
3. Connect the source simulator power cable to the bus batteries.
4. Ensure the bus control system is active.
5. Ensure that the fire suppression system is powered and operating without fault indication.

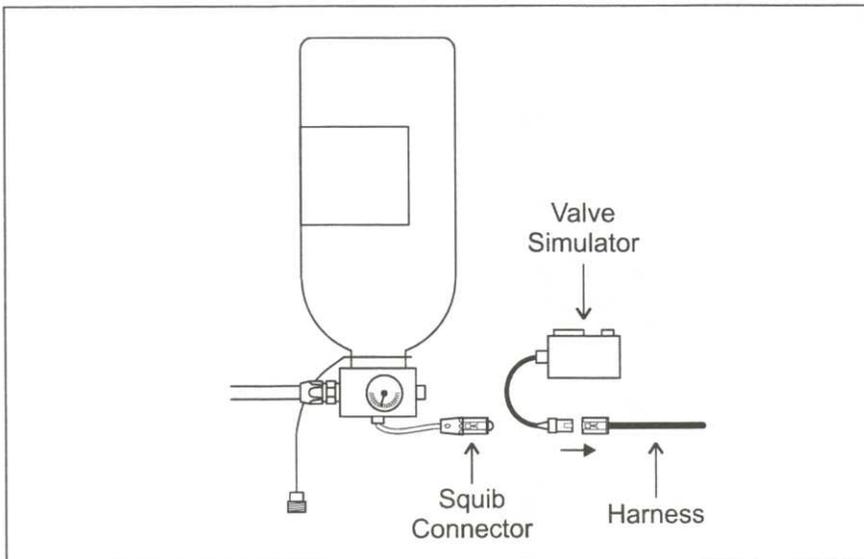


Figure 7-44 Extinguisher Valve Simulator in Use

False Alarm Immunity Test (Bus Off)

For each fire sensor:

1. Ensure the bus engine is off.
2. Align the source simulator with the fire sensor face as shown in Figure 7-45.

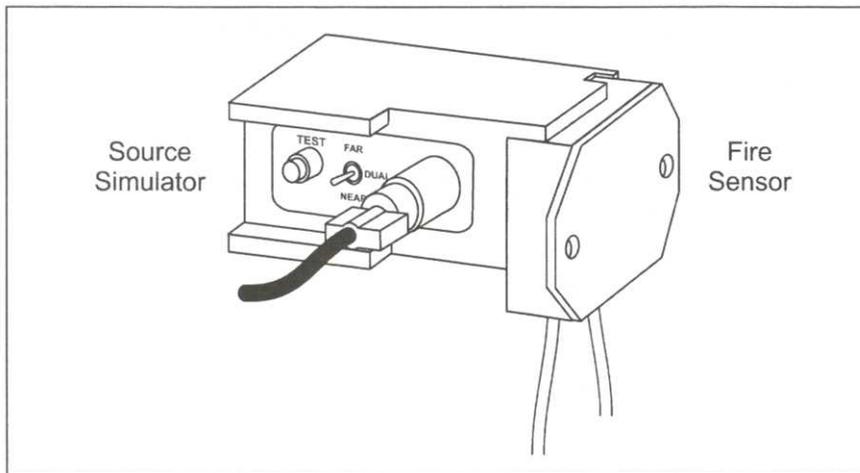


Figure 7-45 Source Simulator in Use

3. Set the source simulator to its *near* false alarm test mode and operate. Confirm that the bus control system *does not* register a fire alarm and the valve simulator associated with the current zone *does not* trip.
4. Repeat step 3 with the source simulator set to its *far* false alarm test mode.

Key Points & Notes

If a sensor false triggers, reset the fire suppression system controller and repeat the test. If the fault persists, replace the sensor.

Fire Response Test (Bus Off)

For *each* fire sensor:

1. Ensure the bus engine is off.
2. Align the source simulator with the fire sensor face as shown in Figure 7-45.
3. Set the source simulator to its fire test mode and operate. Confirm that the bus control system *does* register a fire alarm and the valve simulator associated with the current zone *does* trip after a period of time (as defined by the bus manufacturer).
4. Reset the fire suppression system controller.

If a sensor does not trigger, clean the sensor windows, check alignment with source simulator, and repeat the test. If the fault persists, replace the sensor.

Engine Shutdown Test (Bus On)

For *one* fire sensor:

1. Start the bus.
2. Align the source simulator with the fire sensor face as shown in Figure 7-45.
3. Set the source simulator to its fire test mode and operate. Confirm that the bus control system *does* register a fire alarm and that the engine *shuts down* automatically after a period of time (as defined by the bus manufacturer). Confirm that the valve simulator associated with the current zone *does* trip soon after the engine shuts down (the time period as defined by the bus manufacturer).
4. Reset the fire suppression system controller.

Key Points & Notes

If the engine does not shut down, it is incorrectly connected with the fire suppression system.

Fault Test (Bus Off)

For each zone:

1. Ensure the bus engine is off.
2. Disconnect the terminating connector with the end-of-line resistor. Confirm that the bus control system registers a *system fault* but the valve simulator associated with the current zone *does not* trip.
3. Reset the fire suppression system controller.
4. Re-install the end-of-line resistor.

If the bus does not register a system fault, the bus is incorrectly connected with the fire suppression system.

Post-Test Checks

Once all tests are complete:

1. Disconnect the source simulator and valve simulators, and reconnect the fire retardant tank squib connectors.
2. Ensure that the fire suppression system is powered and operating without fault indication.

7.6.6 Mechanical Inspections

Mechanical inspections relate to the general condition of the fuel cell engine and related components. Specific checks include hose, radiator, transmission, belt and vibration mount inspections.



7.6.6.1 Hose and Tube Inspections

Key Points & Notes

Hoses transfer fluids throughout the fuel cell engine. Hoses and tubes are constructed of a variety of materials, depending on the fluid they convey. Standard materials (typical of hydraulic systems) are used to convey oil, hydraulic fluid, automatic transmission fluid, coolant and water. Teflon tubes are used to convey hydrogen, air or water. Silicone hose is used to convey hydrogen.

Hose inspections consist of a visual confirmation that all visible hoses and tubes are free of cuts, tears, abrasion or damage. Inspect all hose/tube interfaces with sections of metal tubing. If damaged, replace as required using the same hose material. Remove any sources of abrasion.

7.6.6.2 Radiator Inspection

The radiator transfers waste heat to the environment. The cooling capacity of a radiator is directly related to its surface area. Any material that clogs the radiator fins reduces the effective surface area and thereby reduces the effectiveness of the radiator.

The radiator inspection consists of a visual inspection for radiator obstructions, including dust, dirt, plant matter and bugs. Vacuum or air blow the radiator face as required. Do not use pressurized water to clean the radiator if there is any chance of the water contacting the fuel cell stacks or membrane humidifiers.

In addition, visually check the fan blades and other components for damage. Replace as required.

7.6.6.3 Transmission Inspection

The transmission is subject to standard inspections as defined by the transmission manufacturer. Typical inspections check for:

- loose mounting bolts
- fluid leaks
- damaged or loose hoses
- worn, frayed or improperly routed electrical harnesses
- worn, damaged, loose or corroded electrical connectors or motor speed pick-up
- worn or out-of-phase driveline U-joints

In addition:

- Visually inspect the transmission air breather for cleanliness, damage or obstruction. The air breather cap should move freely. Remove the air breather cap and clean using soap and water or replace as required. Do not spray steam, water or cleaning solution directly at the air breather.

Key Points & Notes

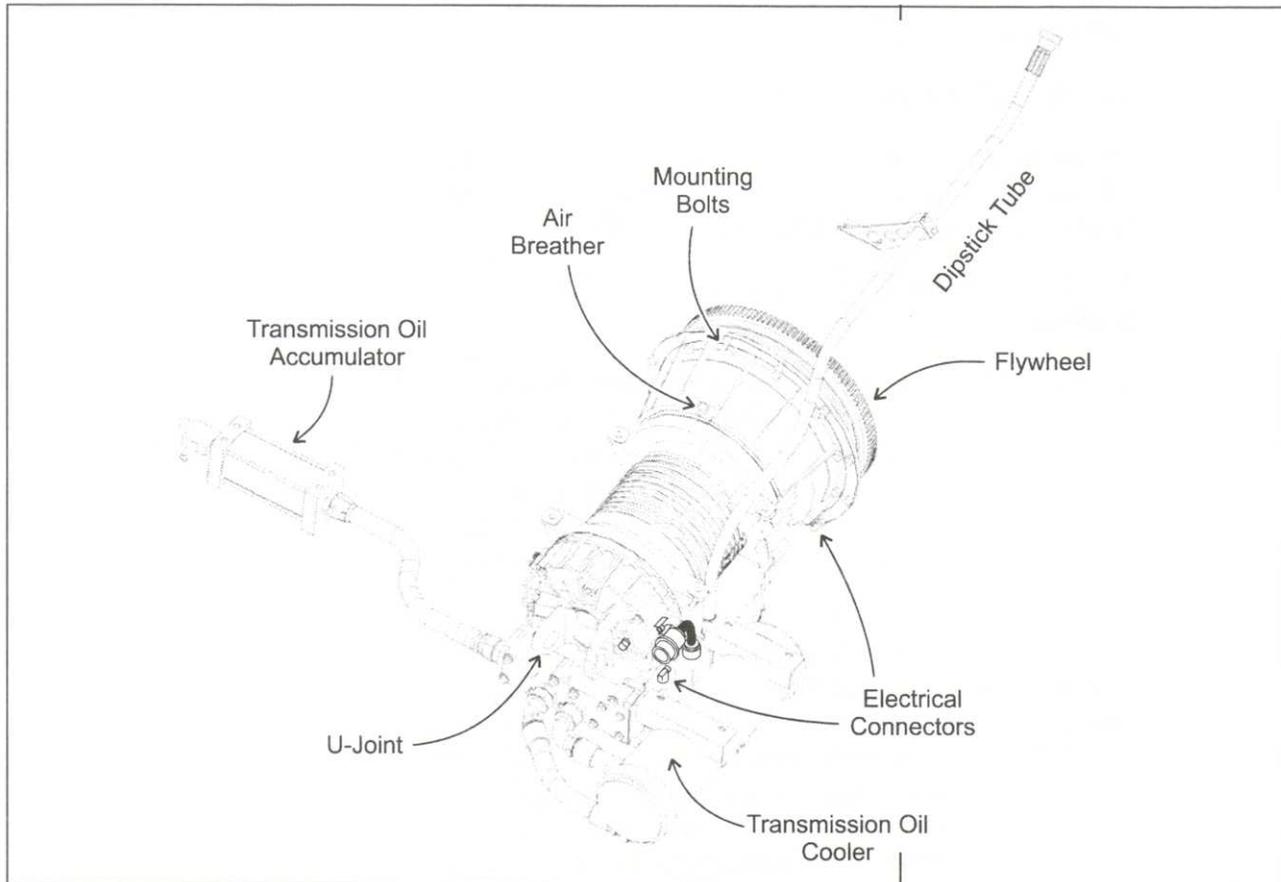


Figure 7-46 Typical Transmission Inspections

7.6.6.4 Belt Inspections

Key Points & Notes

The belts transfer power to the alternator and HVAC compressor.

The belt inspections consist of a visual check for alignment, looseness, cracks, wear or damage. Replace belts or repair belt systems as required. Some belts are permanently aligned (by design) and others use special alignment jigs. Generally, belts are self-tensioned using automatic tensioner devices.

7.6.6.5 Vibration Mount Inspections

The vibration mounts minimize the transfer of vibrations from the bus chassis to the power train and stack modules.

The vibration mount inspections consist of a visual check for missing components (bolts, nuts, etc.), cracks, distortion or other damage. Replace mounts as required. Vibration mounts are designed to accept a high torque to ensure a

solid installation. Use a torque wrench to ensure that the mounting torque of each mount meets the bus manufacturer's specification.

Key Points & Notes

7.6.7 Filter Inspections and Replacement

Filters collect particulate and/or liquid debris from the circuits in which they are installed. Filters impede flow as they clog and must be cleaned or replaced periodically.

7.6.7.1 Stack Air Inlet Filter Inspection and Conditional Replacement

The stack air inlet filters are installed specifically to trap oil particles (originating from the air compressor or turbo-charger lubrication circuits) before they can enter the fuel cell stacks. Oil can seriously damage or destroy fuel cells. Some bus designs use two filters (each installed on half of the air stream) while other buses use a single filter (installed on the whole air stream).

The stack air inlet filters must be inspected for oil presence, and replaced whenever oil is detected. However, oil presence is a serious situation and has greater ramifications than just replacing the filter: alert the bus manufacturer immediately and do not operate the bus until repairs are completed. At a minimum, repairs include tracing and eliminating the oil leak and thoroughly cleaning all contaminated air system components.

The stack air inlet filters are of cartridge design, and are accessed by removing a cover. Cartridges can then be inspected and exchanged directly. Replacement cartridges must be installed in the correct orientation. When replacing a filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.2 Stack Fan Filter Cleaning and Replacement

The stack fan filters accompany the stack vent fans that provide positive pressure to the fuel cell stack enclosures. These fans prevent any potential hydrogen accumulation in the event of fuel cell stack leakage.

The stack fan filters consist of a foam or fine mesh material that is clamped or screwed in place. This filter material can

be removed and cleaned using soap and water, and must be replaced if damaged.

Key Points & Notes

7.6.7.3 Air Intake Filter Minder Inspection and Conditional Filter Replacement

The air intake filter removes particulate debris from the process air stream inlet. This filter is usually accompanied by a standard filter minder.

The filter minder monitors the absolute gauge pressure just downstream of the air inlet filter and thereby provides a visual indication of filter condition. When the filter is clean, there is little gauge pressure. As the filter clogs, the pressure downstream of the filter decreases (drawing a vacuum) and the absolute gauge pressure indication increases accordingly.

The filter minder visual indicator is latched, to show the highest recorded differential pressure, and changes from yellow to red when the filter needs replacement. A reset button resets the indicator.

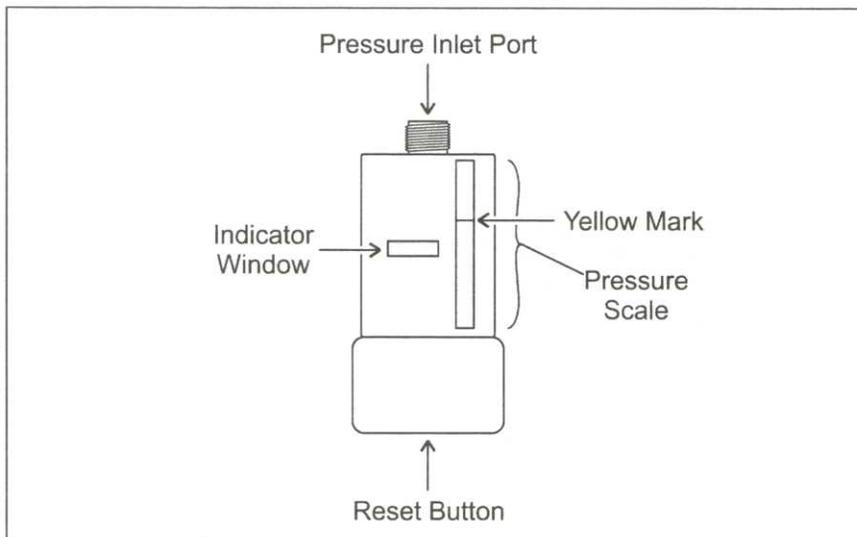


Figure 7-47 Typical Filter Minder

Inspect the filter minder pressure scale and record the pressure reading. If the indicator window is red instead of yellow, replace the filter element. The air intake filter is of cartridge design, and is typically replaced by removing a cover and exchanging the cartridge directly. The replacement cartridge must be installed in the correct orientation.

When replacing the filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required. After filter

element replacement, press the reset button on the filter minder and check that the yellow indicator mark shows 0.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.4 Sintered Air Vent Inspection and Cleaning

Sintered air vents accompany various components that either vent air to atmosphere, or are vented to atmosphere at all times in order to prevent pressure buildup. Typical components with sintered air vents include the air compressor, alternator and variable vane controller. (The term “sintered” refers to a powder that has been coalesced into a solid by heating.)

Inspect all sintered air vents for cleanliness, damage or obstruction. Remove and clean using soap and water or replace as require.

7.6.7.5 Bus Chassis Air Intake Filter Replacement

The bus chassis air intake filter removes particulate debris from the *bus chassis* air stream inlet.

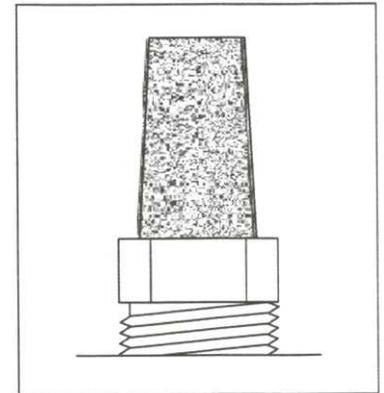
The bus chassis air intake filter is of cartridge design, and is typically replaced by removing a cover and exchanging the cartridge directly. The replacement cartridge must be installed in the correct orientation. When replacing the filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.6 Strainer Inspection and Cleaning

The water strainers remove particulate debris from the humidification water and stack coolant circuits. These strainers are installed to trap any resin beads that may escape from the de-ionizing filters that could otherwise migrate into and clog the fuel cell stacks. As a result, these strainers tend to be installed at the inlet and outlet of each bank of de-ionizing filters, and sometimes at the outlet of the water and/or stack coolant header tanks.

Key Points & Notes



Sintered Air Vent

Each strainer consists of an element mounted within a body. Water or coolant flows through the strainer in such a fashion that any debris collects within the element. The element can be accessed by way of a removable end cap.

Inspect each strainer with the engine off by draining the water or coolant as required (to prevent it from gushing out of the strainer while open) and removing the end cap. Check each strainer for debris, particularly de-ionizing resin beads: if present, alert the bus manufacturer immediately and do not operate the bus until repairs are completed. At a minimum, repairs include tracing and eliminating the source of debris. Retain all collected material and clean the strainer with water prior to re-installation.

Label any collected material with the bus identifier, strainer location, date and odometer reading and return to the bus manufacturer on their request.

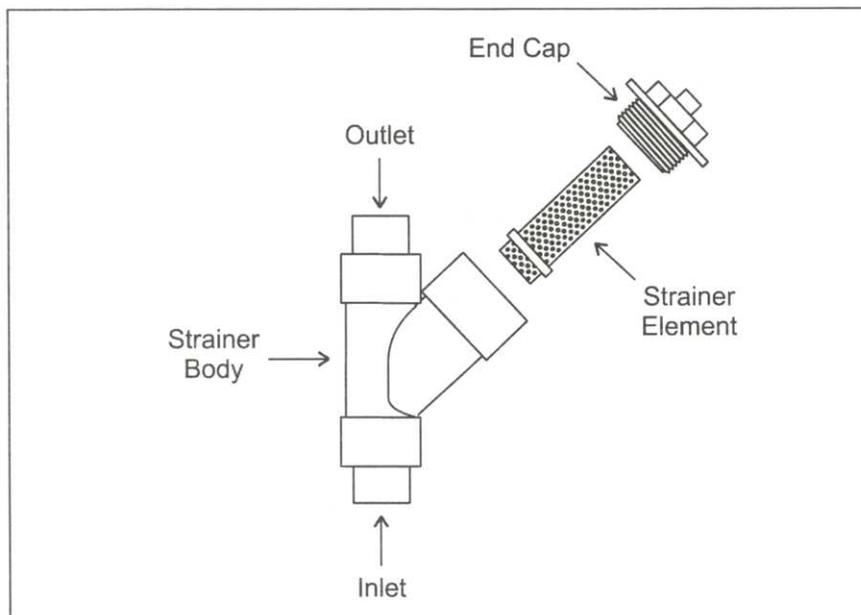


Figure 7-48 Typical Strainer

Key Points & Notes

7.6.7.7 Lubrication System Filter and Oil Replacement

The lubrication system filter removes particulate debris from the lubrication circuit.

The lubrication oil is usually changed in conjunction with the filter. This is convenient since the oil must be drained prior to removing the filter in order to avoid spillage. Drain the oil by way of the oil sump drain plug; retain a sample and inspect as described in Section 7.6.3.4.

The lubrication oil filter consists of a replaceable canister, much like a standard automotive oil filter. Unscrew the used filter, wet the sealing surfaces of the new filter with oil, and use a filter wrench to install a half-turn past hand-tight. Use only the specified replacement part. Once installed, fill the lubrication oil circuit and check the level as described in Section 7.6.3.4.

Label the used filter element with bus identifier, filter location, date and odometer reading and return with any accumulated material to the bus manufacturer at their request.

7.6.7.8 Hydraulic System Filter and Fluid Replacement

The hydraulic system filter removes particulate debris from the hydraulic circuit.

The hydraulic fluid is usually changed in conjunction with the filter. This is convenient since the fluid must be drained prior to removing the filter in order to avoid spillage. Drain the fluid by way of the circuit drain plug; retain a sample and inspect as described in Section 7.6.3.5.

The hydraulic system filter consists of a replaceable canister, much like a standard automotive oil filter. Unscrew the used filter, wet the sealing surfaces of the new filter with fluid, and use a filter wrench to install one-half turn past hand-tight. Use only the specified replacement part. Once installed, fill the hydraulic circuit and check the level as described in Section 7.6.3.5.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.9 Transmission Filter and Fluid Replacement

The transmission filters remove particulate debris from the transmission fluid.

The transmission fluid is usually changed in conjunction with the filter although it may not be necessary to drain the fluid in order to change the filters (depending on the transmission). If changing the fluid, drain by way of the transmission drain plug; retain a sample and inspect as described in Section 7.6.3.6.

The transmission filters consist of replaceable elements. Exchange the elements according to the transmission manufacturer's instructions. Use only the specified replacement

parts. Once installed, fill the transmission and check the level as described in Section 7.6.3.6.

Key Points & Notes

Label the used filter elements with the bus identifier, filter location, date and odometer reading and return with accumulated material to the bus manufacturer on their request.

7.7 Diagnostics

Key Points & Notes

Diagnostics pertains to methods of troubleshooting bus faults that fall outside of routine maintenance.

The following diagnostic interface information is based on the pre-production Phase 4 fuel cell bus designed and built by XCELLSiS Fuel Cell Engines, Inc., and represents the most advanced approach to fuel cell diagnostics currently available. Fuel cell technology is evolving rapidly, and no two bus designs are identical. With this in mind, the diagnostic interface information is intended to be representative of the type of equipment used, although details vary from one bus model to another.

7.7.1 Diagnostics Interface

Bus diagnostics are performed using a portable diagnostics interface that provides real-time access to transducer and control signals. The diagnostics interface:

- displays individual bus systems schematically with instantaneous analog and digital signal state indications
- displays individual fuel cell and overall stack voltages
- provides a fuel cell and stack voltage data capture utility
- indicates abnormal and near-abnormal states of analog signals
- indicates abnormal states of digital signals
- calculates important operating values instantaneously
- provides an alarm history

Concurrent with the diagnostics interface, the on-board data acquisition computer monitors and stores transducer signal values at one-second intervals whenever the bus operates. This data is stored on a memory card that may be downloaded to a host computer for later analysis.

The diagnostics interface is designed either to operate on a portable computer, or on a touch screen monitor. Portable computer screen objects are selected using a mouse. Touch screens objects are manipulated by pressing the touch-sensitive cells associated with that object.

Touch screen cells are organized in a grid pattern as shown in Figure 7-49; these cells are combined to form push buttons and other screen objects. In both portable computer and touch screen configurations, color and shape are used to distinguish between the different button functions, and

between buttons that cause an action to occur, and those that are inactive.

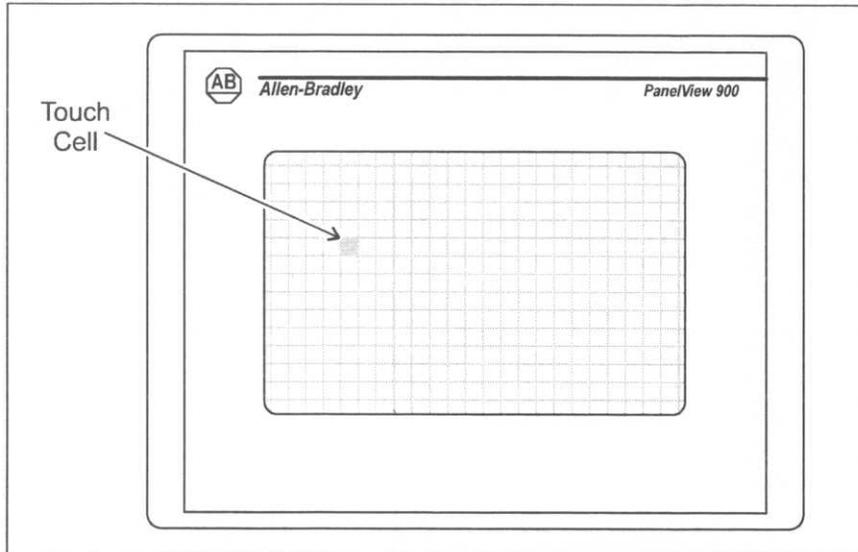


Figure 7-49 Touch Screen Active Cells

7.7.2 Diagnostic Interface Screens

The diagnostics interface is started by plugging it into the corresponding bus connector and, in the case of the portable computer version, running a program. The menu screen appears after the diagnostics interface initializes. A sample menu screen is shown in Figure 7-50.

Key Points & Notes

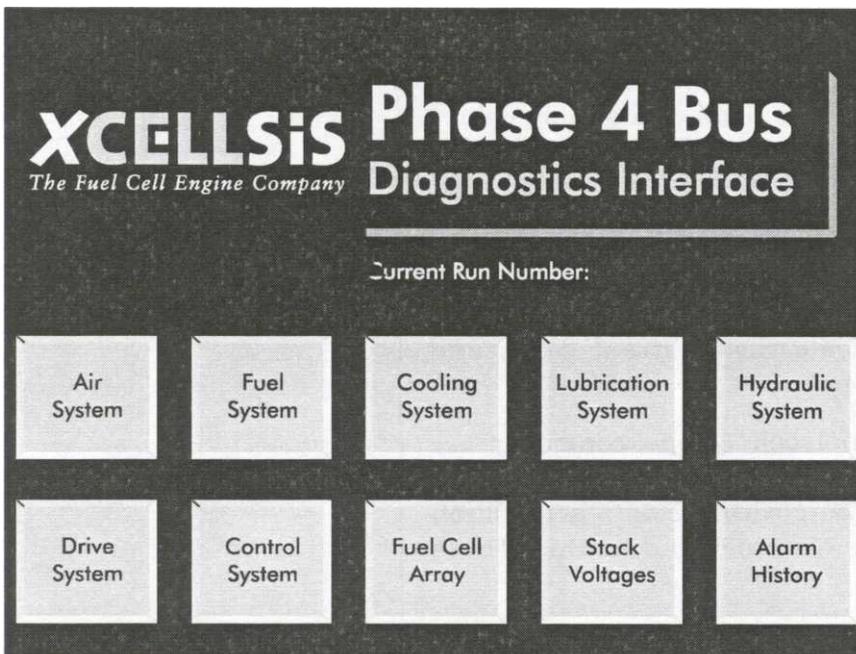


Figure 7-50 Sample Menu Screen

ble. These data items are for display only and do not change color.

Key Points & Notes

Where a numeric value appears next to an icon, the icon is for an analog signal and the value shown is the current value. Analog signals result from transducers like pressure sensors, temperature sensors, flow meters, etc. Analog signal icons have four color states used to represent *undefined* (white), *normal* (green), *warning or near-abnormal* (yellow) and *alarm or abnormal* (red) operation. Additionally, a flashing red color indicates a diagnostic system error (such as if the signal cable is unplugged).

Where a numeric value does not appear next to an icon, the icon is for a digital signal. Digital signals result from devices such as pressure switches, level switches, solenoid valves, cell voltage alarms, etc. Digital signal states are represented by icon color: green icons indicate *open, on, or normal operation* as appropriate; red, blue, purple or yellow icons indicate *closed, off or abnormal operation*, as appropriate.

As a troubleshooting aid, each schematic screen is accompanied by a table that indicates the normal operating range, warning threshold, and alarm threshold for each signal.

7.7.2.2 Control Screens

The control screens present a sequential representation of all control system inputs and outputs, upon which are displayed analog values for each transducer and state representations for each digital signal. Much of the data presented in the control screens is represented elsewhere within the schematic screens, but the control screens are organized according to the physical layout of the controller.

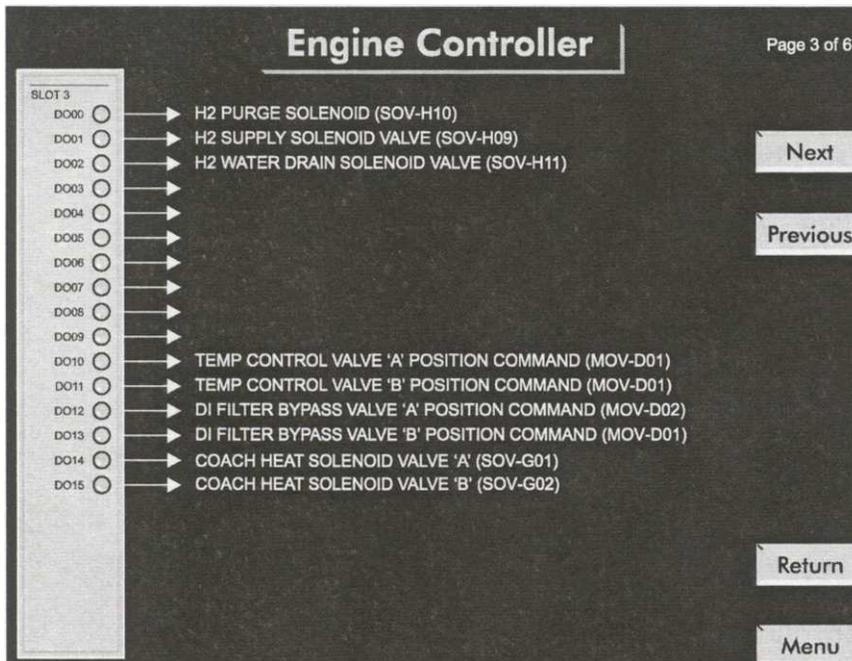


Figure 7-52 Sample Engine Controller Screen

Typically, each controller input or output card is represented on a separate control screen page. A sample engine controller screen is illustrated in Figure 7-52.

The control screen shows a list of signals with its full name and corresponding tag identifier.

Analog signals display their current value after the signal name. The values are updated once per second. The colors of the analog values do not change.

Digital signals have a light to the left of the signal name. The light illuminates green or red depending on the signal state in the same manner as within the schematic screens. If no signal is received, the light remains gray.

7.7.2.3 Voltage Screens

The voltage screens display fuel cell operating information and are divided into a stack voltages screen and a series of cell voltages screens.

Stack Voltage Screen

The stack voltages screen displays the overall voltage of each fuel cell stack. A sample stack voltages screen is illustrated in Figure 7-53.

Key Points & Notes

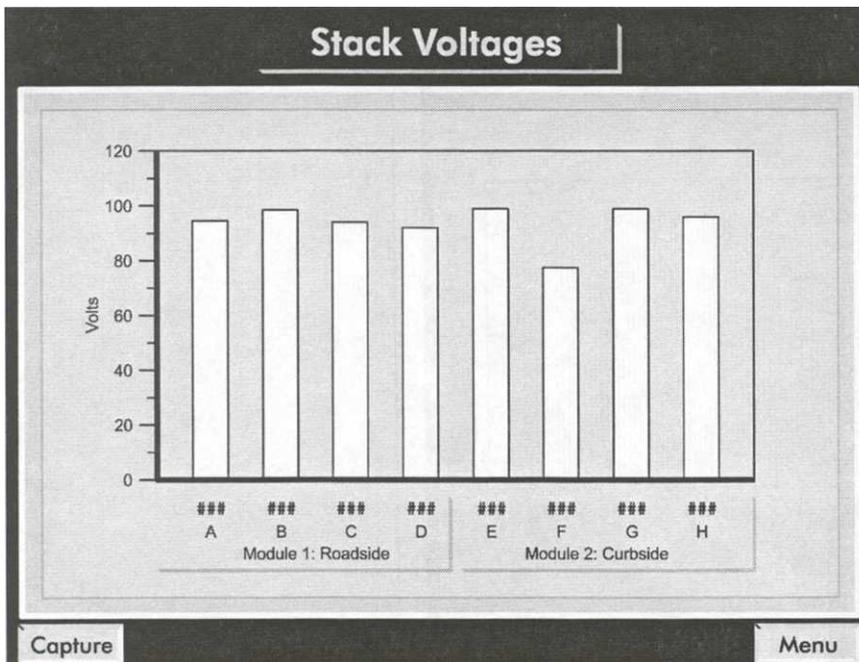


Figure 7-53 Sample Stack Voltages Screen

The stack voltages screen displays the voltage of each fuel cell stack as a bar graphs. Specific voltage levels are indicated beneath the bar for each stack. Pressing any bar displays the cell voltages screen for that stack.

The stack voltages screen includes a capture button that saves the previous 30 seconds of all fuel cell voltage data at half-second intervals when pressed. Each time the button is pressed, the data is stored to the data acquisition computer memory card using sequential file names. This data may be downloaded to a host computer for later analysis.

Cell Voltages Screens

The cell voltages screen displays individual fuel cell voltages within a given stack. A sample cell voltages screen is illustrated in Figure 7-54.

Key Points & Notes

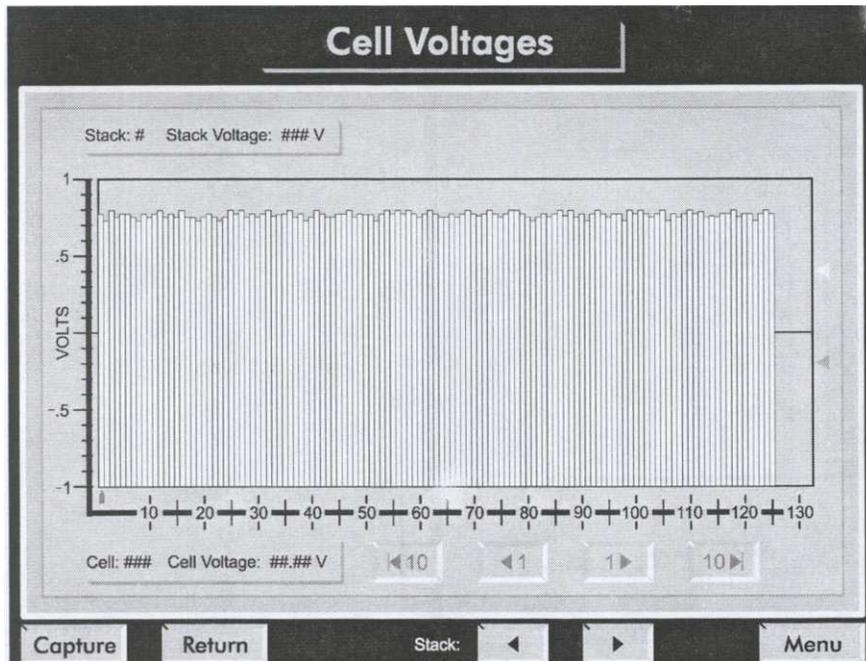


Figure 7-54 Sample Cell Voltages Screen

Key Points & Notes

The cell voltages screen displays individual fuel cell voltages within a given stack as a bar graph. The stack identifier, and total stack voltage is indicated at the top left hand corner. The right and left arrow keys select other stacks.

A cursor (illustrated beneath cell 1) denotes the selected fuel cell. The selected fuel cell number and voltage is displayed at the bottom left hand corner. The 10- and 1- right and left arrow keys next to the cell voltage display change the cursor position.

The upper arrow at the right indicates the cell voltage monitor warning threshold. The lower arrow at the right indicates the cell voltage monitor alarm threshold. An intermediate cell voltage monitor alarm threshold, at 0 V, is not shown graphically.

The capture button saves cell voltage data in the same manner as the capture button on the stack voltages screen.

7.7.2.4 Alarm History Screen

The alarm history screen displays sequential warning and alarm messages. A sample alarm history screen is illustrated in Figure 7-55.

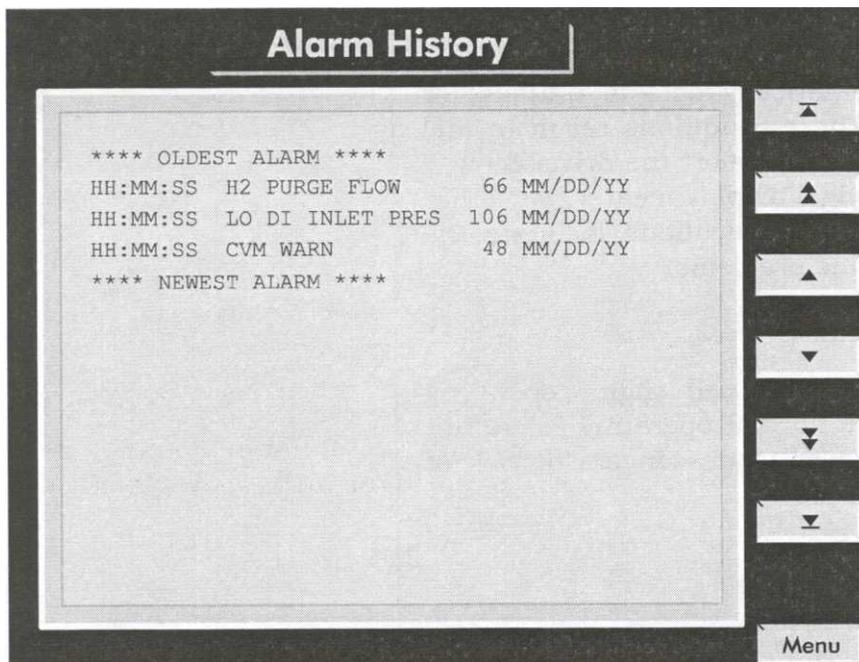


Figure 7-55 Sample Alarm History Screen

Key Points & Notes

The alarm history screen displays bus warnings and alarms in chronological order with the oldest fault displayed at the top of the list. New faults append to the bottom of the list as they are received. The cursor keys scroll through the list.

Each entry contains an HH:MM:SS time code (24-hour clock), the fault code, the sequential bus run number, and a MM/DD/YY date code. The fault list is contained on the data acquisition computer hard drive in an alarm file. Once 998 entries have been received, a new file is created.

Alarm codes cannot be logged when the data acquisition computer hard drive is removed from the bus. Once installed, fault entries are appended to the existing alarm file, or if non-existent, a new alarm file is created.

7.8 Faults

Key Points & Notes

The bus control system automatically detects unusual or unsafe operating conditions. These conditions result in fuel cell engine warnings and alarms that alert the driver by way of dashboard lights, a message display center, or other means. Cumulatively, these fault indications facilitate the process of troubleshooting engine problems.

7.8.1 Warnings

Warnings occur in response to fuel cell engine operating conditions that are outside the normal operating range but do not pose an immediate danger to passengers or risk of component damage.

When a warning occurs:

- an instrument panel light comes on
- a fault message appears on the driver's message display center (if installed), and is registered within the data acquisition computer (accessible through the diagnostics interface)
- the fuel cell engine controller automatically tries to correct the fault
- the engine does not shut down
- available power may be reduced

Warnings are not latched, and therefore clear automatically when the fault condition disappears. If the warning persists, or the fault condition worsens, an alarm may occur. If the warning does not clear, the bus should be returned to the maintenance facility for repair.

7.8.2 Alarms

Alarms occur in response to fuel cell engine operating conditions that are outside the normal operating range and may potentially pose a danger to passengers or risk of component damage. In practice, only fire and gas leak alarms indicate a potential threat to passenger safety and all other alarms conditions are designed to protect the fuel cell engine or other equipment from damage.

The bus engine must shut down in the event of an alarm. Control strategies vary as to whether the shutdown is immediate, delayed, or at the discretion of the operator. In any event, the bus should be steered to a safe location and shut down manually as soon as it is safe to do so, even if the de-

lay associated with automatic shutdown has not fully passed.

Key Points & Notes

When an alarm occurs:

- an instrument panel light comes on and a buzzer may sound
- a fault message appears on the driver's message display center (if installed), and is registered within the data acquisition computer (accessible through the diagnostics interface)
- the fuel cell engine controller automatically tries to correct the fault
- the engine either shuts down immediately or within a short period of time
- available power until shutdown may be reduced
- in the event of a fire alarm, fire retardants (if a fire suppression system is installed) discharge into the appropriate zones soon after shutdown

Alarms are latched and are reset by turning the engine off and on. The engine will not start if an alarm condition persists.

7.8.3 Fault Messages

Each warning and alarm is accompanied by a specific fault message. These fault messages are visible either through a driver's message display center, if installed, and/or the diagnostic interface (alarm history screen; Section 7.7.2.4). Fault messages are typically alphanumeric in nature and help clarify the exact nature of the fault as opposed to the generic indication that results when an instrument panel light comes on.

Supplemental fault codes may be generated by specific components, such as the inverter, transmission or leak indicators. These fault codes can be monitored and interpreted using manufacturer specific diagnostic equipment and documentation.

Multiple Faults

When an engine problem occurs, multiple warnings and alarms often result in rapid succession much like a domino effect. When a single-line driver's message display center is used, some method of prioritizing the messages is programmed into the control system. Typically:

- alarms take precedence over warnings
- messages scroll
- messages clear once the fault condition clears
- there is a limit to the total number of messages

Key Points & Notes

Fault Record

Fault messages that appear on a driver's message display center are transitory in nature, and are only visible as long as the control system is powered. In addition, the occurrence of multiple faults can obscure the initial cause of a sequence of faults. To compensate, all fault messages are stored in a permanent chronological record with the data acquisition computer. This record can be viewed on the alarm screen of the diagnostics interface, or downloaded to a host computer for later analysis.

Fault List

Fault messages are cryptic due to memory and processing requirements and may consist of only a code instead of words. The specific conditions, thresholds and controller responses associated with each fault message are cross-referenced within a fault list. The fault list may include operational messages in addition to warnings and alarms. A portion of a sample fault list is shown in Table 7-4.

An essential part of every message is the delay that occurs before the message is activated. The delay allows the controller to confirm the signal, and to let momentary conditions pass without activating the alarm. Serious faults that pose a threat to humans or equipment are given the shortest delay.

Fault conditions that do pose little or no threat to humans or equipment have longer delays. Fault conditions that are active prior to startup are given the longest delays in order for conditions to stabilize as components energize.

**Hydrogen Fuel
Cell Engines**
MODULE 7: FUEL CELL BUS MAINTENANCE

Key Points & Notes

Message	Fault Class	Condition
OK TO START	Message	No faults exist
OK TO DRIVE	Message	The engine has warmed up and bus is ready to drive
BUS SHUTTING OFF	Message	Voltage bleed-down is underway
STARTUP FAILED	Alarm	Startup failure
LOW FUEL PRESSURE	Warning	Low-pressure in hydrogen cylinder(s); bus is low on fuel
MODERATE GAS LEAK	Warning	Moderate hydrogen leak has been detected
SIGNIFICANT GAS LEAK	Alarm	Significant hydrogen leak has been detected
GAS SENSOR FAIL	Warning	A hydrogen sensor has failed
CHECK TRANSMISSION	Warning	A transmission fault
ALTERNATOR FAIL	Alarm	An alternator fault
FIRE ALARM	Alarm	Fire is detected
FIRE SENSOR FAIL	Warning	A fire sensor has failed
LOW OIL PRESSURE	Warning	Low oil pressure

Table 7-4 Sample Fault List (Portion)

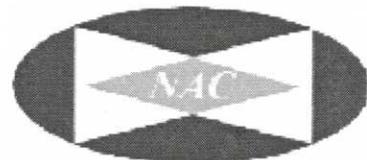
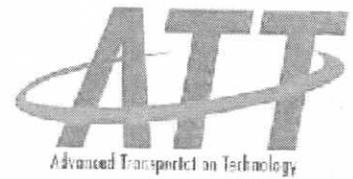
MODULE 8:

Fuel Cell Hybrid Electric Vehicles

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

8.1	HYBRID ELECTRIC VEHICLES	8-1
8.1.1	SERIES HYBRIDS	8-1
8.1.2	PARALLEL HYBRIDS	8-2
8.2	MAJOR COMPONENTS OF HYBRID VEHICLES	8-4
8.2.1	ELECTRIC DRIVE MOTORS	8-4
8.2.2	AUXILIARY POWER UNITS	8-7
8.2.3	GENERATORS	8-12
8.2.4	ENERGY STORAGE SYSTEMS	8-13
8.2.5	REGENERATIVE BRAKING	8-15
8.2.6	CONTROL SYSTEMS	8-15

OBJECTIVES

At the completion of this module, the technician will understand the types and uses of:

- hybrid electric vehicles
- electric motors
- auxiliary power units
- generators
- energy storage systems
- regenerative braking
- control systems

8.1 Hybrid Electric Vehicles

A hybrid electric vehicle (HEV) augments an electric vehicle (EV) with a second source of power referred to as the alternative power unit (APU).

Pure electric vehicles currently do not have adequate range when powered by batteries alone, and since recharging requires several hours, the vehicles are viewed as impractical for driving extended distances. If air conditioning or heating is used, the vehicle's range is further reduced. Accordingly, the hybrid concept, where the alternative power unit is used as a second source of energy, is gaining acceptance and is overcoming some of the problems of pure electric vehicles.



Courtesy of Jo Borck

1916 Range & Lang Electric

More electric vehicles were in use in 1915 than there are at present.



Courtesy of Jo Borck

Figure 8-1 Electric Vehicles

The hybrid electric vehicle operates the alternative power unit to supply the power required by the vehicle, to recharge the batteries, and to power accessories like the air conditioner and heater. Hybrid electric cars can exceed the limited 100 mile (160 km) range-per-charge of most electric vehicles and have the potential to limit emissions to near zero. A hybrid can achieve the cruising range and performance advantages of conventional vehicles with the low-noise, low-exhaust emissions, and energy independence benefits of electric vehicles. Two types of hybrid vehicle configurations are the series and the parallel hybrids.

8.1.1 Series Hybrids

A series hybrid is similar to an electric vehicle with an on-board generator. The vehicle runs on battery power like a

Key Points & Notes

pure electric vehicle until the batteries reach a predetermined discharged level. At that point the APU turns on and begins recharging the battery. The APU operates until the batteries are charged to a predetermined level.

Key Points & Notes

The length of time the APU is on depends on the size of the batteries and the APU itself. Since the APU is not directly connected to the drive train, it can be run at its optimal operating condition; hence, fuel economy is increased and emissions are reduced relative to a pure IC engine vehicle. A schematic of a series hybrid is shown in Figure 8-2.

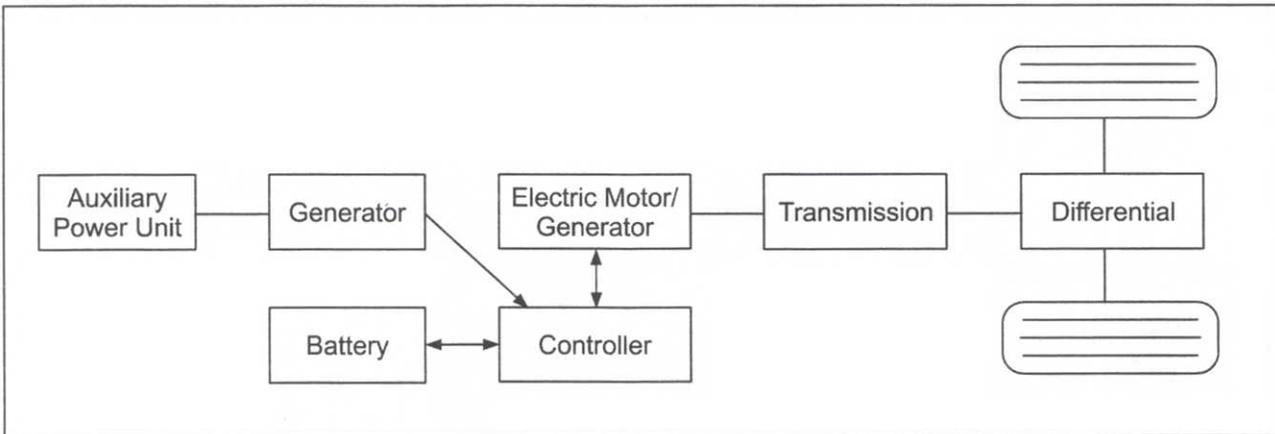


Figure 8-2 Schematic of a Series HEV

8.1.2 Parallel Hybrids

In the parallel hybrid configuration, an APU capable of producing motive force is mechanically linked to the drive train. This approach eliminates the generator of the series approach. When the APU is on, the controller divides energy between the drive train (propulsion) and the batteries (energy storage). The amount of energy divided between the two is determined by the speed and driving pattern.



L3 Research Aeris Parallel Hybrid

For example, under acceleration, more power is allocated to the drive train than to the batteries. During periods of idle or low speeds, more power goes to the batteries than the drive train.

When the APU is off, the parallel hybrid runs like an electric vehicle. The batteries provide electricity to the electric motor where it is converted to mechanical energy to power the vehicle. The batteries also provide additional power to the drive train when the APU is not producing enough and to power auxiliary systems such as the air conditioner and heater.

The drive train for a parallel hybrid is more complex than that of a series hybrid as both the electric motor and the APU must be mechanically linked to the driveshaft. Since parallel hybrids only work with APU's that produce a mechanical output, fuel cells cannot be used for this option. Figure 8-3 shows a schematic of a parallel hybrid.

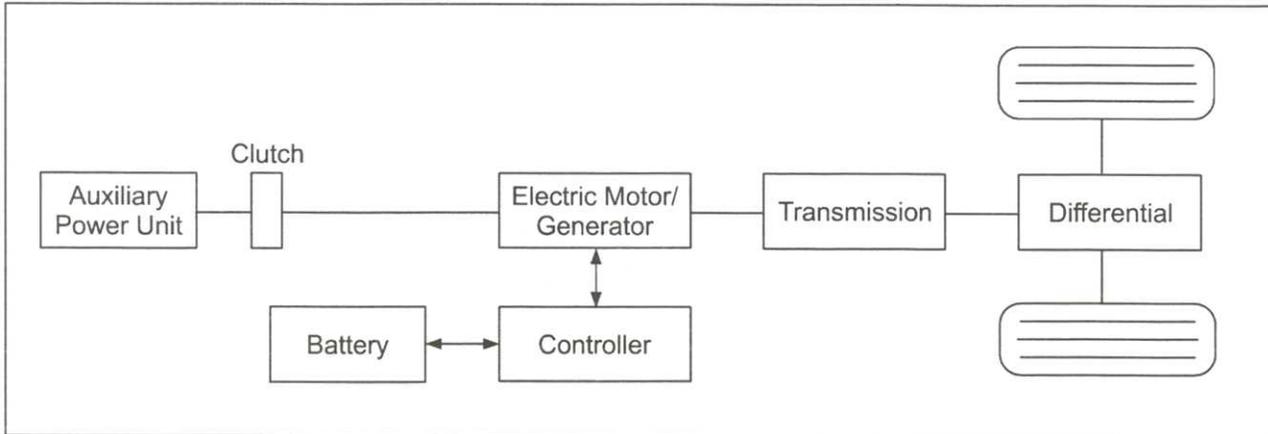


Figure 8-3 A schematic of a Parallel HEV

Key Points & Notes

8.2 Major Components of Hybrid Vehicles

Key Points & Notes

8.2.1 Electric Drive Motors

Hybrid electric vehicles use an electric driveline and motor to provide the power for propulsion. The electric motor is a simple, efficient and durable device that is used every day in all sorts of applications. Electric motors range from those with fractional horsepower that run small appliances, to 5000-horsepower giants used in paper mills and other industries.

An electric motor converts electric energy to mechanical energy (motion) to drive the hybrid vehicle. Every motor can be used as a generator by rewiring it to transform mechanical energy into electrical current, but not all motors make efficient generators. For this dual use, the hybrid may use the electric motor to start the engine and then switch to generating electricity to keep the batteries charged. This reduces both the weight and cost of having two separate devices for engine starting and battery recharging.

In conventional vehicles, engine size determines the total power available to a moving vehicle. Hybrids, on the other hand, have electric motors that provide additional power when needed by the vehicle.

Both electric motors and engines can be rated in kilowatts (kW) — the preferred international standard — or in horsepower (hp). One hp equals 0.746 kW. When comparing horsepower ratings of a motor to an engine, it appears that electric vehicles are drastically under-powered. However, internal combustion engines are rated at the *maximum* power output, while electric motors are rated at their continuous power capabilities. A motor that can produce 10 hp continuously can easily produce three or four times that much power for a few minutes. Unlike internal combustion engines, electric motors emit zero harmful emissions.

The electric motor changes electric energy into mechanical power for work. Operation of the motor is based on three concepts:

- an electric current that produces a magnetic field
- the direction of current in an electromagnet that determines the location of the magnet's poles
- and the magnetic poles attraction or repulsion to each other

An electric motor consists chiefly of a rotating electrical conductor situated between the north and south poles of a stationary magnet. It also contains a conductor known as an armature, a stationary magnet called the field structure, and a commutator.

The field structure establishes a constant magnetic field in the motor. The armature rotates and becomes an electro-magnet when a current passes through it. Connection to the driveshaft allows it to drive the load. The commutator reverses the direction of the current in the armature and helps transmit current between the armature and the power source.

There are two types of motors: direct current and alternating current.

8.2.1.1 Direct Current Motors

In the direct current (DC) motors, the current always flows in the same direction. There are three types of DC motors: series, shunt and compound.

In the series motor, the armature and the field magnet are connected electrically in series. Current flows through the field magnet to the armature, increasing the strength of the magnets. The motor can start quickly under a heavy load, but such a heavy load decreases the motor speed.

The shunt motor connects the magnet and armature in parallel. Part of the current goes through the magnet while the rest goes through the armature. It runs at an even speed regardless of the load, but if the load is too heavy, the motor is difficult to start.

In the compound motor, two field magnets are connected to the armature, one in series and the other in parallel. The compound motor has the benefits of both the series and the shunt. It starts easily with a heavy load and maintains a relatively constant speed even when the load is increased.

Key Points & Notes

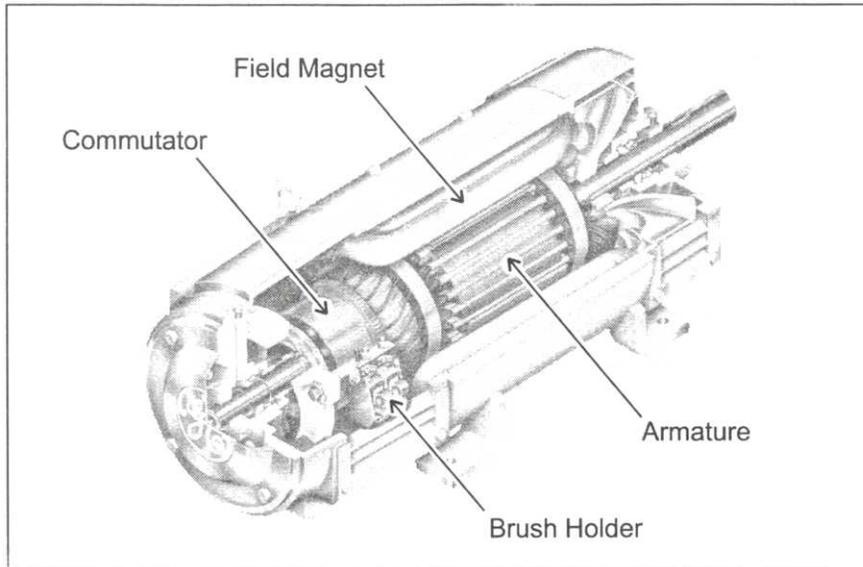


Figure 8-4 Direct Current Motor

8.2.1.2 Alternating Current Motors

Alternating current (AC) motors regularly reverse current flow direction. The reversal is typically 60 times per second or 60 Hz in North America and 50 Hz in Europe. Two changes of direction completes one cycle. The number of cycles per second is called the frequency of the alternating current.

The AC motor has many advantages over the DC motor. It is easy to build and convenient to use. Most AC motors do not require commutators because the current reverses its direction automatically. Those that use commutators do so to conduct the current from the external power source to the moving part of the motor and back.

The two types of AC motors are the induction and the synchronous motors.

In the induction motor, the rotor has no direct connection to an external source of electricity. The current flows around the field coils in the stator and produces a rotating magnetic field. This field induces an electric current in the rotor resulting in another magnetic field. The magnetic field from the rotor interacts with the magnetic field from the stator causing the rotor to turn.

Key Points & Notes

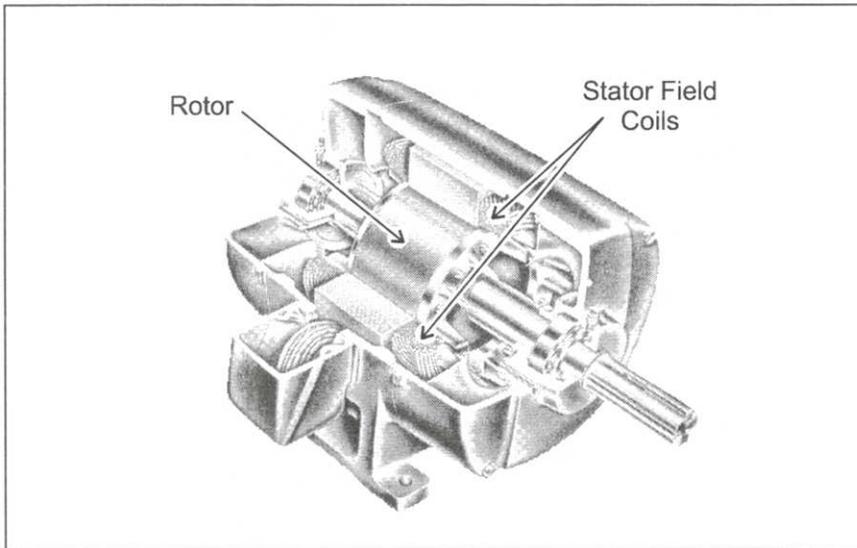


Figure 8-5 Alternating Current Induction Motor

In a synchronous motor, the stator also produces a rotating magnetic field. However, the rotor receives current directly from the power source instead of relying on the magnetic field from the stator to induce an electric current. The rotor moves at a fixed speed in step with the rotating field of the stator. Therefore, the synchronous motor maintains a fixed speed and uses less energy than an induction motor.

Key Points & Notes

8.2.1.3 Electric Motor Configurations

The two possible configurations of electric drive motors in a hybrid vehicle are a single electric motor connected to the wheels through a drive train, or multiple electric motors, one located at each wheel.

The electric motor connected to the wheels through the drive train is the simplest design and is the present design of conventional vehicles.

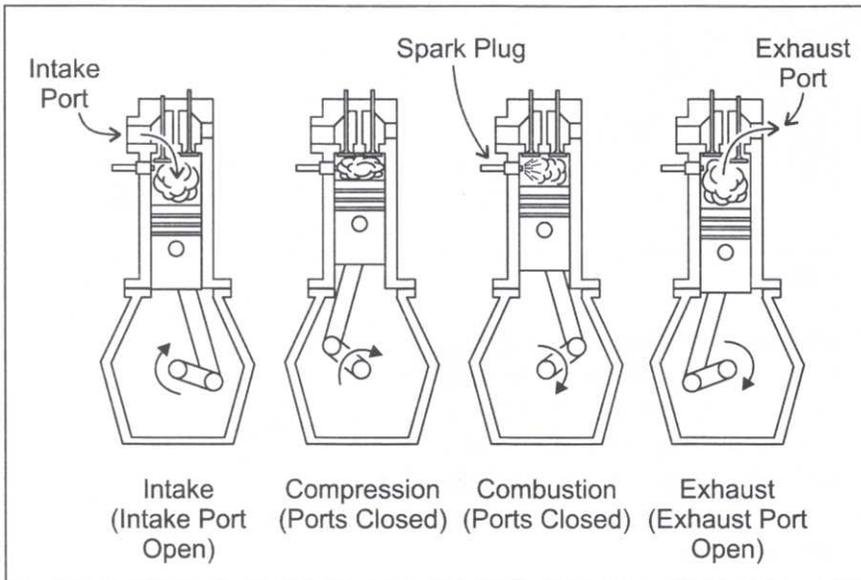
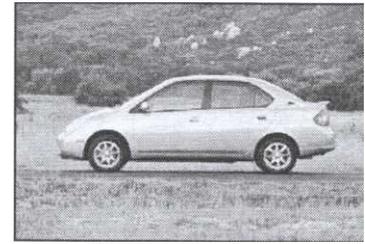
Multiple electric motors, however, produce better traction and regenerative braking at each wheel, allow more room for other parts, and continue to function even when one or more motors malfunction. This configuration has been used in some all-terrain vehicles.

8.2.2 Auxiliary Power Units

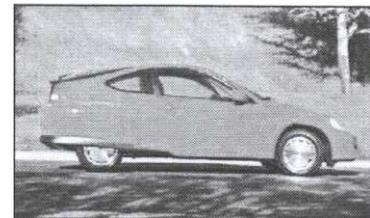
The auxiliary power unit (APU) of a hybrid vehicle supplies the baseline power required to the vehicle, recharges the batteries and powers accessories such as the air conditioner and heater. The APU can consist of a mechanical type engine or a fuel cell. A mechanical type engine can be a spark ignition, compression ignition, rotary, turbine or Stirling engine.

8.2.2.1 Spark Ignition Engine

In 1862, Beau de Rochas proposed a sequence of operations that remains typical of most spark ignition engines. The four-stroke cycle requires two revolutions of the crankshaft for each power stroke and allows the piston to slide back and forth in the cylinder while transmitting the power to the drive shaft.



Toyota Prius Hybrid



Honda Insight Hybrid

Figure 8-6 Four-Stroke Engine Operation

The spark ignition engine has a simple, mature, well understood design, a good power-to-weight ratio, and the ability to burn gasoline, methanol, ethanol, natural gas, propane or hydrogen. It also has well developed emission controls. The disadvantages, however, are poor part-load efficiency and relatively high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen.

In order to produce a higher output from the same size engine and to obtain some valve simplification, the two-stroke cycle was developed by Dugald Clerk in 1878. This cycle is applicable both to compression ignition and to spark ignition operation, but has been primarily successful only with the latter.

The two-stroke engine's combustion cycle is completed in two strokes (one revolution) of the crankshaft as opposed to the four strokes (two revolutions) required by the four-stroke engine.

Key Points & Notes

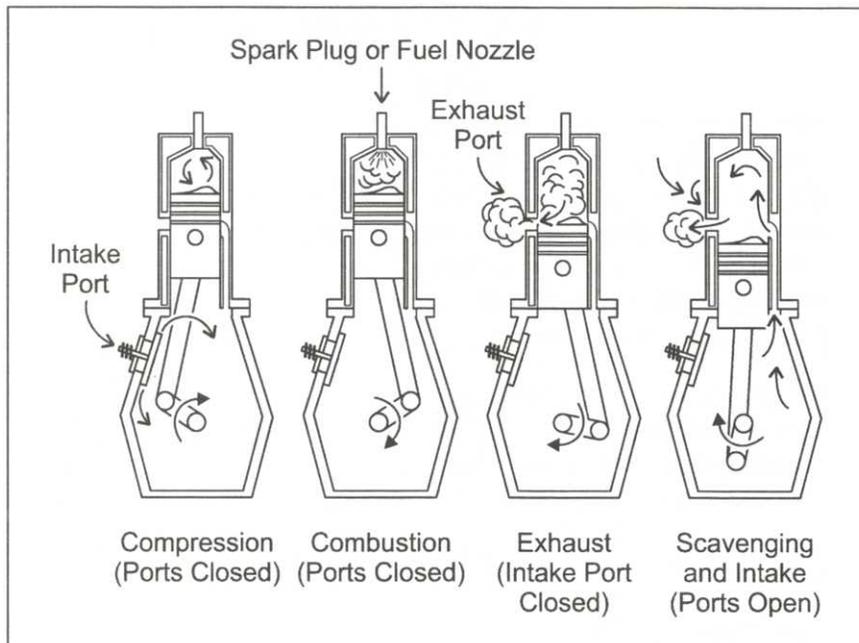


Figure 8-7 Two-Stroke Engine Operation

Key Points & Notes

Compared to the four-stroke, the two-stroke engine has a higher power-to-weight ratio, a simpler design, lower manufacturing costs, and is lightweight. The emissions, however, are a major problem. There are relatively high uncontrolled hydrocarbons and carbon monoxide emissions, and emission control systems have not been sufficiently developed. Two-stroke engines are common in small gasoline motors, such as on chainsaws and smaller motorcycles.

8.2.2.2 Compression Ignition Engines

The compression ignition engine is typified by the diesel engine. The diesel cycle is similar to the Otto cycle except that a high compression ratio and air are required instead of a combustible mixture. Air is admitted to the engine on the intake stroke and the rapid compression of the air raises the temperature to such a point that a fuel, when delivered into the combustion chamber, ignites spontaneously. There is no requirement for a spark to initiate the combustion, or for a homogeneous mixture to propagate the flame.

The advantages of Compression Ignition engines are efficiency at high compression ratios, they are well developed and dependable, and have low carbon monoxide and hydrocarbon emissions. The disadvantages, however, are a high levels of carbon particulate and oxides of nitrogen emissions.

8.2.2.3 Wankel (Rotary) Engines

Key Points & Notes

In 1954, Felix Wankel found that an engine could be made of three variable-volume chambers formed between a stationary epitrochoid-shaped housing and a rotating equilateral triangular rotor. (A epitrochoid is a curve like an epicycloid, but generated by any point on a radius. An epicycloid is a curve described by a point on the circumference of a circle rolling on the outside of the circumference of another circle. Basically, the housing is circular, and the action is rotational.)

Together with proper arrangement of intake, exhaust and ignition mechanisms, this variation of volume in the three chambers makes it possible to carry out the four main events of the Otto cycle within each of the three chambers.

Wankel engines have a compact design, a high power-to-weight ratio, are lightweight, and use the same emission control systems as the four-stroke SI engines. However, they have relatively poor efficiency and high uncontrolled emissions of hydrocarbons, carbon monoxide and oxides of nitrogen. Wankel engines were produced commercially for Mazda cars in the 1980's, but were eventually replaced by conventional spark ignition engines.

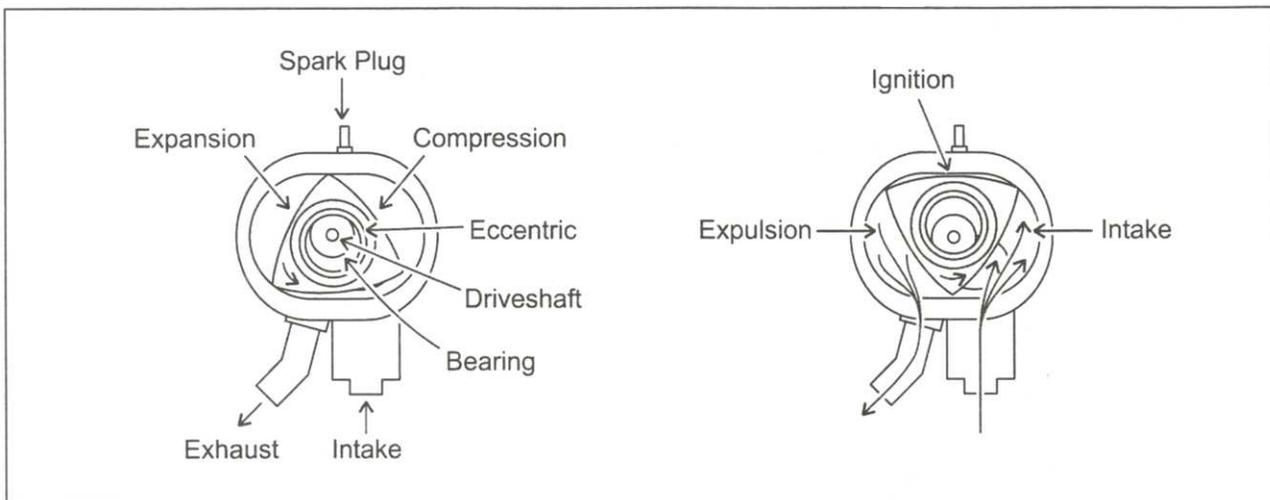


Figure 8-8 Wankel (Rotary) Engine Operation

8.2.2.4 Stirling Engines

An alternative to the internal combustion engine is an external combustion engine known as the Stirling engine. The Stirling cycle has two isothermal processes and two constant-volume processes. The thermal efficiency of the Stirling cycle with perfect regeneration is equal to that of the Carnot cycle for the same temperature range. The Stirling engine has low emissions, good efficiency, and operates quietly. The

disadvantages are a complicated design, a low power-to-weight ratio, high cost and a large cooling requirement.

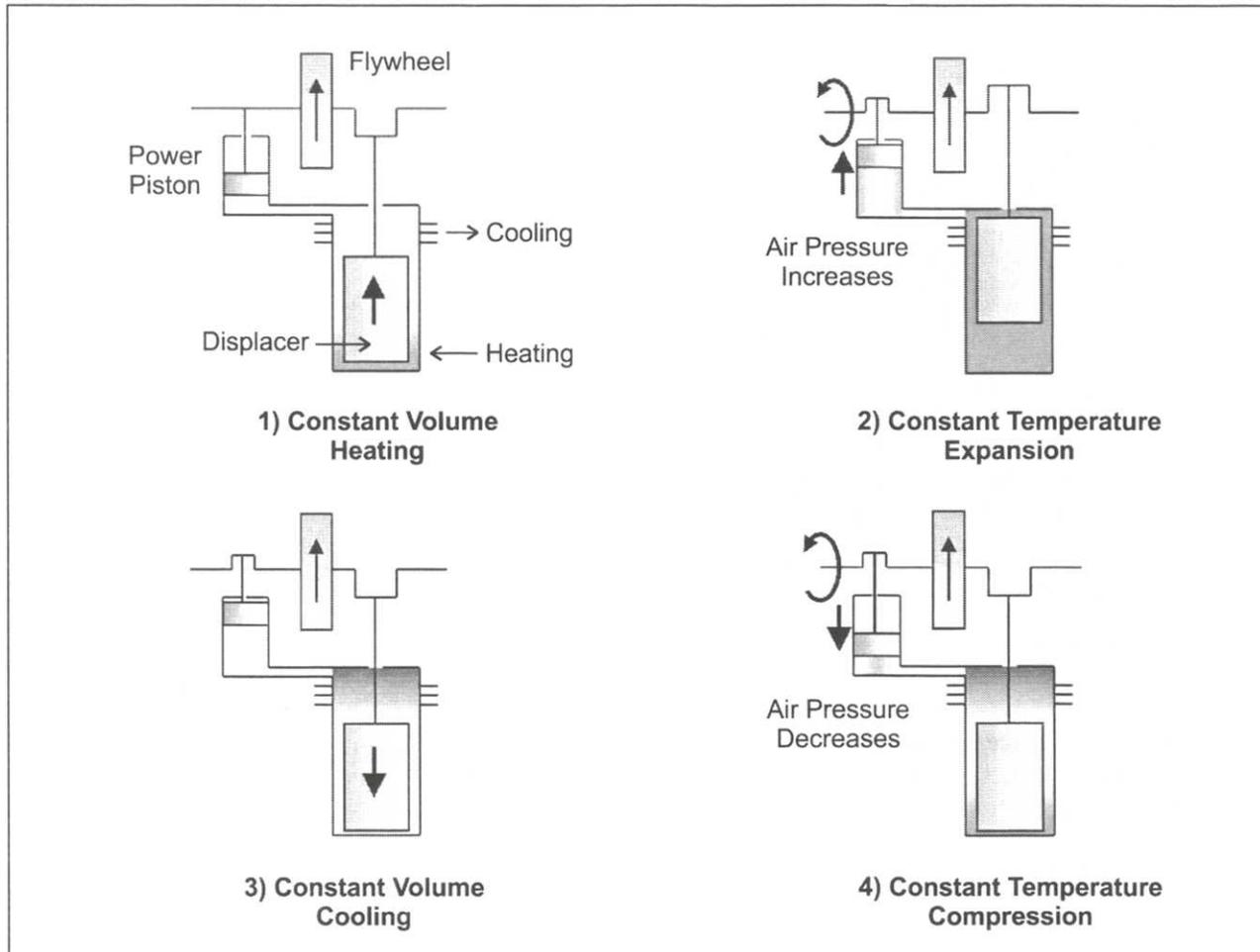


Figure 8-9 Stirling Engine Operation

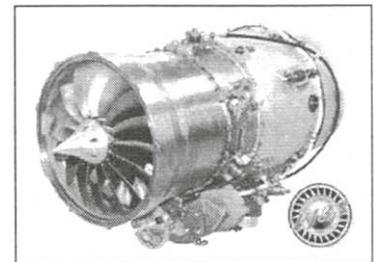
8.2.2.5 Gas Turbines

Gas turbines, one of the oldest forms of combustion engines, are composed of a turbine, a combustion chamber and an air compressor.

The turbine has a rotor that is turned by moving fluid such as water, steam, gas or wind. It changes kinetic energy (energy of movement) into mechanical energy (energy in form of mechanical power). The mechanical energy is transmitted by the turbine through the spinning motion of the rotor's axle.

A gas turbine burns fuels such as oil, natural gas or kerosene. Gas turbines are small, lightweight, smooth running, have good power-to-weight ratios and low emissions. The fundamental problem with them, however, is their expense, poor efficiency at part load and their high operating tempera-

Key Points & Notes



Williams Gas Turbine Engine

ture. Gas turbines engines are used on jet aircraft and burn jet fuel, which is a kind of kerosene.

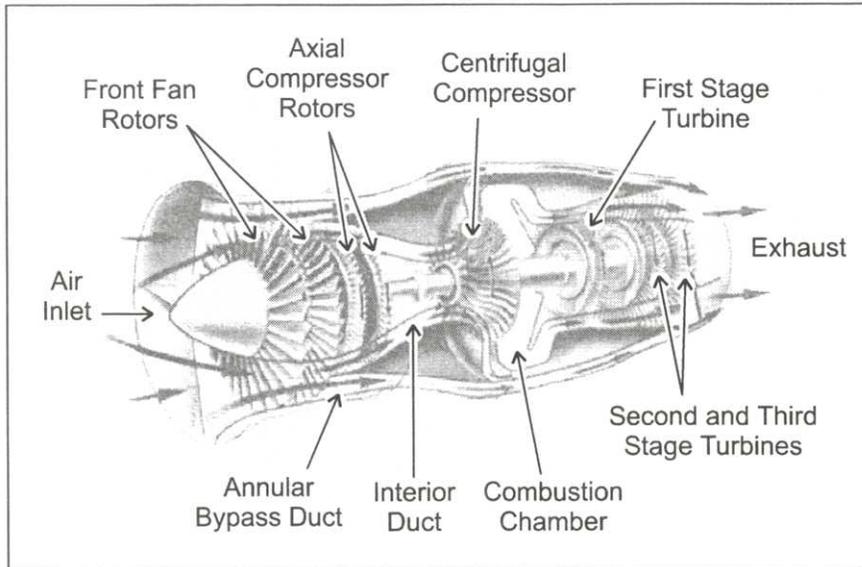


Figure 8-10 Gas Turbine Engine Major Components

8.2.2.6 Fuel Cells

Fuel cells are discussed in detail in other modules of this course. Fuel cells are convenient in electrical hybrid applications since they can be used in tandem with other electricity generating devices.

8.2.3 Generators

All the power systems described above, except for the fuel cell, require a generator to convert the mechanical power into electrical power when used in a series hybrid. Generators, like electrical motors, are either AC or DC.

8.2.3.1 AC Generators

An AC generator (or alternator) produces an electric current that reverses direction many times per second. It is also called a synchronous generator because it generates a voltage containing a high frequency proportional to, or synchronous with, the speed of the rotor.

A simple AC generator has each end of its wire loop, or armature, attached to a slip ring. A carbon brush connected to the outside circuit rests against each of the slip rings. As the armature rotates, the current moves in the direction of the arrows. The brush at the first slip ring conducts the current out of the armature, and the brush at the second slip ring brings it back in.

Key Points & Notes

When the armature rotates parallel to the magnetic field, no current is generated for a moment. When the armature rotates into the magnetic field again, the current reverses direction. It then flows out of the armature through the second slip ring and back into the armature at the first slip ring.

Key Points & Notes

8.2.3.2 DC Generators

A DC generator produces an electric current that always flows in the same direction. It is different from the AC generator in both the way it is built and how it is used.

The commutator rotates with a loop of wire just as the slip rings do with the rotor of an AC generator. Each half of the commutator ring is called the commutator segment and is insulated from the other half. Each end of the rotating loop of wire is connected to a commutator segment. Two carbon brushes connected to the outside circuit rest against the rotating commutator. One brush conducts the current out of the generator and the other brush feeds the current back in.

The commutator is designed so that no matter how current in the loop alternates, the commutator segment containing outward-going current is always against the “out” brush at the proper time.

8.2.4 Energy Storage Systems

The peak power required in hybrid vehicles is met by devices like batteries, capacitors or a flywheel. These devices store energy and readily release it when needed.

8.2.4.1 Batteries

Batteries are one of the most important parts of a hybrid vehicle. A battery produces electricity by means of chemical action. It consists of one or more electric cells. Each cell has all the chemicals and parts needed to produce an electric current.

There are two types of batteries: primary and secondary (or storage) batteries. Primary batteries discharge and must be discarded after one or more of the chemicals is used up. Secondary batteries, on the other hand, can be recharged after they have delivered their electrical energy. Consequently, secondary batteries are ideal for hybrid application. They are able to supply power to the vehicle and be re-used.

The criteria used for battery selection are: temperature, energy density, power density, service life, shelf life, cost, reliability, cell configuration, charge/discharge cycle, safety,

operating environment, recycling, minimal memory effect and efficiency.

8.2.4.2 Capacitors

A capacitor is a device that stores electrical energy in the form of an electrical charge.

A capacitor consists of two metal plates with an insulating material called a dielectric between them. Wires usually connect the plates to a source of electric current such as a battery. When an electric charge flows through the wires from one plate of the capacitor to the other, both plates become charged — one with a positive charge, and the other with a negative charge. The two plates then have potential difference in energy — a voltage — between them.

The plates release their charge when their wires are disconnected from the source and touched together. The ability of the capacitor to store electric energy is its capacitance. The main difference between a battery and a capacitor is that a capacitor can be rapidly charged and discharged.

8.2.4.3 Flywheels

The flywheel is an alternative energy storage system that is capable of replacing chemical batteries in conventional electric vehicles.

A flywheel is a balanced mass spinning around a constant axis that stores energy as rotational kinetic energy. Simply put, a flywheel is a mechanical battery that is capable of delivering multi-kilowatt-hours of energy to the drive system of an electric vehicle.

Flywheel energy storage (FES) systems have been researched for many decades, but their application has been limited due to the high cost of inefficient materials. However, recent advancement in fiber-composite materials, control electronics, and frictionless magnetic bearings have led researchers to believe that modern FES systems could be used to power efficient non-polluting electric vehicles.

The FES systems have been shown to theoretically rival chemical batteries in terms of power, energy density, cycle life, charge time, operating temperature range, environmental friendliness and maintenance needs.

The FES systems are now a viable technology for regenerative braking, for averaging peak power demands, and for storing energy on electric and hybrid vehicles. In hybrids, for example, FES systems can replace expensive ultra-

Key Points & Notes



Capacitors

capacitors for energy storage energy and to average out power demands.

Key Points & Notes

8.2.5 Regenerative Braking

Brakes are devices that slow or stop the movement of a wheel, engine or entire vehicle. Most brakes have a fixed part called a brake shoe or block that presses against a turning wheel to create friction (heat) that causes the wheel to stop or slow down.

In regenerative (or dynamic) braking, some of the energy is converted into electrical energy and stored. Pressing on the brake pedal first activates the regenerative braking system, and then the conventional friction brake. The rotational energy of the braking mechanism generates electrical power and stores it in the batteries.

Electric and hybrid vehicles are well suited to use regenerative braking, as the captured electricity can power the drive motor. This electricity can be used in place of, or to supplement the APU, further reducing fuel use and improving fuel economy.

8.2.6 Control Systems

The electronic control system regulates the high-intensity current, helping it work with the APU counterparts. It controls the power flow between the battery and the motor as well as regenerative braking. A control system contains two main components, namely the command and power components. The command component manages and processes the driver's instructions. The power component chops power flows to control the motor's power intake.

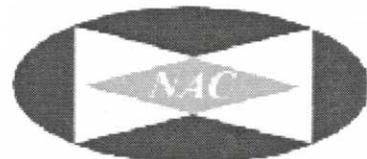
There are two choppers to manage this power flow. The primary chopper is the startup phase and works at low motor speeds. The excitation chopper regulates the motor at medium and high motor speeds.

MODULE 9:
**Acts, Codes, Regulations,
and Guidelines**

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

9.1	MANDATING OF ALTERNATIVE FUEL VEHICLES IN THE U.S.	9-1
9.1.1	INTRODUCTION	9-1
9.1.2	THE CLEAN AIR ACT, 1963	9-1
9.1.3	ALTERNATIVE MOTOR FUELS ACT, 1988 (AMFA)	9-4
9.1.4	ENERGY POLICY ACT, 1992 (EPACT)	9-4
9.1.5	STATE IMPLEMENTATION PLAN (SIP)	9-6
9.1.6	CALIFORNIA	9-6
9.2	CODES AND STANDARDS	9-9
9.2.1	INDUSTRIAL USE OF HYDROGEN	9-9
9.2.2	NON-INDUSTRIAL USE OF HYDROGEN	9-12
9.3	HYDROGEN PUBLICATIONS	9-14
9.4	REGULATORY ORGANIZATIONS	9-15
9.4.1	USA	9-15
9.4.2	CANADA	9-16
9.4.3	JAPAN	9-17
9.4.4	INTERNATIONAL	9-17
9.5	RESEARCH ORGANIZATIONS	9-18

OBJECTIVES

At the completion of this module, the technician will:

- understand the mandating of alternative fuel vehicles in the US
- understand the codes, regulation and guidelines concerning the use of hydrogen
- know where to look for additional information on hydrogen standards

9.1 Mandating of Alternative Fuel Vehicles In The U.S.

Key Points & Notes

Alternative fuels for vehicles has been mandated through Federal and State laws in the US in response to the need to reduce air pollution, particularly in major cities. This section is a review of pertinent acts and regulations that were passed to instigate the development of alternative fuels for transportation uses. The following information is not all-inclusive since new acts, regulations and political initiatives continue to evolve.

9.1.1 Introduction

Air pollution is not a new problem in the nation or the world. In 1955, the Department of Health, Education and Welfare was authorized to begin a study of air pollution. Before this time, no one knew the extent to which automobiles contributed to the problem. By 1962, vehicle engines were determined to be responsible for over 40% of all airborne emissions—the single largest source of air pollution.

Legislation has been passed to mandate efforts to reduce these toxic and polluting emissions. A number of these regulations offer financial incentives to assist the transition to alternative fuel vehicles.

The major laws and policies are:

- Clean Air Act of 1963
- Alternative Motor Fuels Act of 1988
- Clean Air Act Amendments of 1990
- Energy Policy Act of 1992
- Federal Executive Order 12759-1991
- Federal Executive Order 12844-1993
- California Air Resource Board Regulations

9.1.2 The Clean Air Act, 1963

The U.S. Congress passed the original Clean Air Act (CAA) in 1963. This act required compliance with the National Ambient Air Quality Standards (NAAQS) by December 31, 1982. From then until the present, Congress has amended the act several times. Since the original Clean Air Act has failed to clean the air to the desired standard, Congress has made each new revision to the act more stringent.

9.1.2.1 1970 Clean Air Act Amendments

The Clean Air Act Amendments (CAAA) of 1970 required that the concentration of pollutants in exhaust gases from transportation vehicles be reduced below the previously prescribed pollution limits. To ensure this

reduction, specific emission standards for different types of vehicles were established under the Act for carbon monoxide, hydrocarbons, and oxides of nitrogen.

These amendments also required states that had areas in which pollutant concentrations exceeded the NAAQS (non-attainment areas) to develop State Implementation Plans (SIPs). These plans had to detail how the state planned to control emissions and reduce ambient air concentrations to the federally required levels.

9.1.2.2 1988 Clean Air Act Amendments

The 1988 amendments to the Clean Air Act were significant because they gave the Environmental Protection Agency (EPA) the power to enforce regulations such as:

- Withholding federal funds from states with non-attainment areas. These funds include federal grants, highway trust funds, and new sources of construction money.
- Preparing and enforcing a Federal Implementation Plan (FIP) where states have failed to develop an adequate SIP for attaining NAAQS.
- Requiring non-attainment states to have revised SIPs filed with the EPA by May, 1991. In 1991, nearly 100 urban areas still failed to comply with NAAQS for at least one automotive pollutant.
- Providing manufacturers with CAFE (Corporate Average Fuel Economy) incentives to develop alternative fueled vehicles.

9.1.2.3 1990 Clean Air Act Amendments

The 1990 Clean Air Act Amendments are among the most far-reaching environmental initiatives ever passed by the U.S. Congress, containing eleven separate titles under which the EPA issues regulations.

The 1990 CAAA Tier I standards began with vehicles produced in model year (MY) 1994. The proposed EPA phase-in for Tier I standards were:

Year	Vehicles
1994	40% of all new vehicles
1995	80% of all new vehicles
1996	100% of all new vehicles

Tier II standards are required for vehicles produced in MY 2004 and later. In order to reduce the amount of emissions from mobile sources, the only viable options are to reduce private travel or to use cleaner fuels and vehicles. Since it is nearly impossible to mandate a reduction in private travel, the Title II mobile source reduction program has three major components that deal with cleaner fuels and vehicles:

- Conventional gasoline and diesel powered vehicles sold throughout the U.S. after 1993 must meet tougher emission standards.

- In the country's nine smoggiest cities, all conventional gasoline must be replaced by reformulated gasoline. A program to promote the use of clean vehicular fuels as an alternative to gasoline is required.
- The federal program also mandates that fleets in 22 urban non-attainment areas must purchase clean fuel vehicles along with a pilot alternative program for California.

Key Points & Notes

The CAAA 1990 also extends the useful life requirements for passenger car emission control systems to comply with 5 years/50,000 miles to 10 years/100,000 miles. The law also establishes similar standards for all other types of vehicles.

From 1995 through 2005, the CAAA 1990 is estimated to result in 4.5 to 9.7 million vehicles operating on alternative fuels.

9.1.2.4 1990 CAAA-Fleet Requirements

Fleets covered by this mandate include those with 10 or more vehicles that are capable of central refueling. The following fleet types are excluded:

- emergency vehicles
- rental vehicles
- demonstration vehicles
- off-road vehicles
- privately garaged vehicles

The CAAA 1990 covers vehicles with weight classifications from zero to 26,000 pounds GVW (gross vehicle weight) and applies to fleets located in the serious, severe, and extreme ozone non-attainment areas with 1980 populations of over 250,000. It also includes vehicles in one CO non-attainment area-Denver. The air quality standards compliance deadlines for the 96 non-attainment areas with populations over 250,000 range from three to 20 years, depending on the severity of their air quality. The most polluted non-attainment areas have the longest amount of time to achieve compliance.

In Phase I of the program, the percentages of passenger cars and light-duty trucks (up to 6000 GVW), which must be clean fuel vehicles (CFVs) are:

30% by MY 1998
50% by MY 1999
70% by MY 2000

For heavy-duty trucks (above 8,500 GVW and below 26,000 GVW), 50% must be CFVs by MY 1998.

The 1990 CAAA allows fleet owners to earn credits from early or extra purchases of CFVs or by acquiring vehicles that are certified to stricter emission standards than required, beginning in MY 1998. These stricter emission standards can be met by purchasing new vehicles that meet the

clean fuel fleet vehicle standards of LEV (low emission vehicle), ULEV (ultra low emission vehicle) or ZEV (zero emission vehicle), or by converting conventional vehicles to cleaner fuels, or by redeeming credits.

Key Points & Notes

9.1.3 Alternative Motor Fuels Act, 1988 (AMFA)

The Alternative Motor Fuels Act of 1988 (AMFA) encourages the development and use of alternative transportation through the development and widespread use of natural gas, methanol, and ethanol as transportation fuels and the production of alternative fuel powered vehicles. Three programs have been established to fulfill this goal.

The **Alternative Light Duty Vehicle Program** requires the federal government to purchase a "practical number" of alternative fueled passenger automobiles and light-duty vehicles. These vehicles must be powered by natural gas, alcohol or dual energy and must be purchased from original equipment manufacturers (OEM). The Department of Energy is also designated to conduct studies between standard passenger automobiles/light-duty trucks and alternative fueled vehicles that compare fuel economy, safety, emissions, operating and maintenance cost, and performance in cold weather and at high altitude.

The **Truck Commercial Application Program** conducts commercial application projects for alternative fueled vehicles in real-world operation environments in cooperation with heavy-duty engine manufacturers and other federal agencies.

The **Alternative Fuels Bus Testing Program** assists state and local government agencies in comparison testing of natural gas and diesel buses in urban areas. These tests include emissions levels, durability, safety and fuel economy.

Data collected from these projects are submitted to the Alternative Fuels Data Center (AFDC) which is operated and managed by the National Renewable Energy Laboratory in Golden, Colorado. The data is available to the public on-line and through the **National Alternative Fuels Hotline**.

9.1.4 Energy Policy Act, 1992 (EPACT)

The Energy Policy Act of 1992 (EPACT) was designed to establish a firm energy policy for the United States to reduce America's dependence on foreign oil and to increase energy security through the use of domestically produced alternative fuels. EPACT includes a combination of mandates, incentives, funding for research and development, public information dissemination, and purchasing requirements for alternative fueled vehicles for the nation's largest fleets.

EPACT defines alternative fuels to include methanol, ethanol, natural gas, propane, hydrogen, coal-derived liquids, biological materials, electricity or any other fuel that the Secretary of Energy finds to be substantially not petroleum and that would yield substantial energy security benefits and

substantial environmental benefits. Under this definition traditional liquid fuels such as gasoline and diesel are not considered to be alternative fuels.

Key Points & Notes

EPACT is designed to facilitate the development and implementation of alternative fuel technologies. Federal agencies and fuel providers (gas and electric utilities) are required to purchase AFVs beginning in fiscal year 1993. The law also encourages the purchase of more alternative fuel vehicles for federal fleets in order to accelerate the development of an OEM market. The goals for the following decade include:

- 5000 vehicles
- 7500 vehicles
- 10,000 vehicles
- 25% operating with clean fuels
- 33% operating with clean fuels
- 50% operating with clean fuels
- 75% operating with clean fuels

Executive Order No. 12448 (Nov. 1993) increased by 50% the number of alternative fuel vehicles mandated by the 1992 EPA for MY 1993-95.

EPACT also provides the following financial incentives:

- \$25 million per year for transit and school bus fleets to develop a clean-fuels urban bus program.
- \$30 million to provide low-interest loans.
- Income tax incentives including deductions from \$2000 to \$50,000 for buying clean-fuel vehicles.
- \$100,000 for clean-fuel refueling stations.

The U.S. Department of Defense and other research and development institutions also receive financial support.

9.1.5 State Implementation Plan (SIP)**Key Points & Notes**

States with ozone non-attainment areas must include a Clean Fuel Vehicle Support Program that contains measures necessary to ensure the effectiveness of the Clean Fuel Vehicle Program established under Tier II of the 1990 CAAA. This program must be in their SIP.

9.1.6 California**9.1.6.1 California Federal Pilot Program, 1996**

The California Pilot Program started in MY 1996. This program mandated the production and sale of 150,000 clean fuel vehicles (CFV) per year for model years 1996 through 1998. For model years 1999 and beyond, the mandate increased to 300,000 vehicles per year. In addition, other states may voluntarily opt into the program. Vehicles must comply with low emission vehicle (LEV) standards.

The California federal pilot program is postponed if the CFVs are not available from original equipment manufacturers. The fleet operators are permitted, but not required, to purchase vehicles converted by a non-OEM.

9.1.6.2 The California Air Resources Board (CARB)

California is the most proactive state in the U.S. for establishing stringent vehicle emission standards. The air quality in many regions in California is so poor that the California Air Resources Board decided not to wait until federal mandates take effect. The standards developed by CARB are more stringent than those called for by the CAAA. Many states have adopted or are adopting legislation similar to California's. If standards have not been established by federal agencies pertaining to LPG kits and conversions, the standards adopted by the CARB are recommended. Refer to 1994 Progress.

9.1.6.3 California Non-Attainment Areas

The following California cities have been identified as non-attainment areas for ozone and/or carbon monoxide.

**Hydrogen Fuel
Cell Engines**
**MODULE 9: ACTS, CODES, REGULATIONS, AND
GUIDELINES**

City	Severity
Ozone Non-Attainment	
Los Angeles (including LA County, Anaheim and Riverside)	Extreme
Oakland	Moderate
San Diego	Severe
Santa Barbara	Moderate
Bakersfield	Serious
San Francisco	Moderate
Fresno	Serious
San Jose	Moderate
Sacramento	Serious
Visalia	Moderate
CO Non-Attainment	
Los Angeles (including LA County, Anaheim and Riverside)	Serious
Sacramento	Moderate
Chico	Moderate
San Diego	Moderate
Fresno	Moderate
San Francisco	Moderate
Modesto	Moderate
San Jose	Moderate
Oakland	Moderate
Stockton	Moderate

Key Points & Notes

Table 9-1 California Non-Attainment Areas

9.1.6.4 California LEV Phase-In Program

California legislation allows Air Quality Management Districts (AQMDs) to mandate the purchase of LEV's by fleets having 10 or more vehicles if the state's air quality standards are not met. The law also required retail fuel suppliers to provide 90 alternative fuel fueling locations by 1994 and 400 refueling locations by 1997. Passage of SB 135 in late 1991 required all passenger vehicles for hire in non-attainment areas to use alternative fuels. Twenty-five percent of vehicles purchased by the Department of General Services must be LEVs. AQMDs in non-attainment areas can mandate fleet purchases of LEVs.

A minimum number of LEVs, ULEVs, and ZEVs have been mandated for new car sales. The California LEV Phase-in program mandates the following percentage of vehicles for every model year.

Hydrogen Fuel Cell Engines

MODULE 9: ACTS, CODES, REGULATIONS, AND GUIDELINES

Model Year	STD. (0.39)	STD. (0.25)	TLEV	LEV	ULEV	ZEV
1994	10%	80%	10%			
1995		85%	15%			
1996		80%	20%			
1997		73%		25%		
1998		48%		48%		
1999		23%		73%	2%	2%
2000				96%	2%	2%
2001				90%	5%	5%
2002				85%	10%	5%
2003				75%	15%	10%

Key Points & Notes

Table 9-2 Mandated California Vehicle Types

9.2 Codes and Standards

Key Points & Notes

Standards, rules, regulations and guidelines affecting alternative fuel vehicles are still changing. As a result, the following summary is not all-inclusive and may not reflect the most recent information. Transportation businesses for each country, state or county should have an understanding of the most recent codes and standards.

US Department of Transportation (DOT) Regulations

The US Department of Transportation establishes rules and regulations governing interstate transportation of materials. These regulations are covered by Title 49 of the Code of Federal Regulations (CFR), entitled Transportation. The DOT regulations have been adopted from specifications and regulations, which evolved from existing industry standards.

National Fire Protection Agency (NFPA) Regulations

The National Fire Protection Association (NFPA) is a non-profit, voluntary association devoted solely to fire prevention and safety. Since 1896, the NFPA has published guidelines for fire prevention, fire fighting procedures, and fire protection for many different industries. Motor vehicle fuel storage, fuel dispensing, and engine operation are covered by NFPA guidelines. These guidelines are generally accepted as minimum requirements.

The NFPA provides various services including fire prevention training programs for use in public education programs and technical publications on fire prevention and safety. One of the most important services provided by NFPA is the coordination of the development of fire safety codes for specific industries. The latest edition was published in 1995.

Your shop safety policy should reflect the appropriate local and state laws that apply. If there is no other standard to follow, refer to relevant National Fire Protection Association publication.

9.2.1 Industrial Use Of Hydrogen

Current codes, standards and guidelines for hydrogen were developed for industrial applications. The following list includes hydrogen-specific and related codes and standards used for a long time in industrial applications.

9.2.1.1 U.S. Codes and Standards for Industrial Use of Hydrogen

American Petroleum Institute

API 941	Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants
---------	---

American Society for Mechanical Engineers

Key Points & Notes

- ASME Boiler and Pressure Vessel Code
- ASME B31.3 American National Standard Code for Chemical Plant and Petroleum Refinery Piping

Compressed Gas Association

- CGA G-5 Hydrogen, Fourth Edition
- CGA G-5.3 Commodity Specification for Hydrogen, Fourth Edition
- CGA G-5.4 Standard for Hydrogen Piping Systems at Consumer Locations
- CGA G-5.5 Hydrogen Vent Systems
- CGA P-6 Standard Density Data, Atmospheric Gases & Hydrogen, Fifth Edition
- CGA S- 1.1 Pressure Relief Device Standards, Part 1 - Cylinders for Compressed Gases
- CGA S-1.2 Pressure Relief Device Standards, Part 2 - Cargo and Portable Tanks for Compressed Gases
- CGA S-1.3 Pressure Relief Device Standards, Part 3 - Compressed Gas Storage Containers

Dept. of Transportation — National Highway Transportation Safety Administration (NHTSA)

- FMVSS 301 Fuel System Integrity
- FMVSS 303 Fuel System Integrity of CNGVs
- FMVSS 304 CNG Fuel Containers
- 49 CFR Regulations for Transportation Equipment and the Transport of Hydrogen (Parts 100-199, 3 01-398)

Department of Labor — Occupational Safety and Health Administration (OSHA)

- 29 CFR 1910.103 Hydrogen

Federal Specification

- BB-H-866 Gaseous Hydrogen Grades for Cutting and Welding and as a Lifting Medium for Balloons
- ZZ-H-461 D Hose and Hose Assembly, Rubber, Gas (Acetylene-Hydrogen, Air and Oxygen)

Hydrogen Fuel Cell Engines

MODULE 9: ACTS, CODES, REGULATIONS, AND GUIDELINES

National Fire Protection Association**Key Points & Notes**

NFPA 10	Standard for Portable Fire Extinguishers
NFPA 30A	Automotive & Marine Service Station Code
NFPA 50A	Standard for Gaseous Hydrogen Systems at Consumer Sites
NFPA 50B	Standard for Liquefied Hydrogen Systems at Consumer Sites
NFPA 52	CNG Vehicular Fuel Systems
NFPA 54	National Fuel Gas Code. This code is a safety code that applies to the installation of fuel gas piping systems, fuel gas utilization equipment and related accessories.
NFPA 55	Compressed & Liquefied Gases in Portable Cylinders
NFPA 58	Storage & Handling of Liquefied Petroleum Gases
NFPA 70	National Electric Code. Practical safeguarding of persons and property from the hazards arising from the use of electricity.
NFPA 88A	Standards for Parking Structures. Covers the construction and protection of, as well as the control of hazards in, open, enclosed, basement and underground parking structures. It does not apply to one- and two-family dwellings.
NFPA 88B	Standards for Repair Garages. Covers the construction and protection of, as well as the control of hazards in garages used for major repairs and maintenance of motorized vehicles and any sales and servicing facility associated therewith.
NFPA 496	Purged & Pressurized Enclosures for Electrical Equipment
NFPA 497A	Classification of Class I Hazardous Locations. Applies to locations where flammable gases or vapors, flammable liquids or combustible liquids are processed or handled and where their release to the atmosphere may result in their ignition by electrical systems or equipment.
NFPA 497M	Classification of Gases, Vapors and Dusts for Electrical Equipment in Hazardous Locations
NFPA 513	Standard for Motor Freight Terminals
NFPA 853	Installation of Stationary Fuel Cell Power Plants
NFPA MY-HLH-88	Electrical Installations in Hazardous Locations

Natural Gas Vehicle Coalition

Key Points & Notes

NGV1 CNGV Fueling Connection Devices

NGV2 Basic Requirements for CNGV Fuel Containers

**9.2.1.2 Canadian Codes, Standards and Regulations for
Industrial Use of Hydrogen**

Canadian Electrical Code

Canadian Electrical Code Part 1, C22.1, Safety Standard for Electrical Installations

Electrical Systems in Hydrogen Installations

Transport Canada

Regulations for the Transportation of Hydrogen

Transportation of Dangerous Goods Act and Regulations

Transportation of Liquid Hydrogen

Transportation of Portable Hydrogen Containers and Cylinders

Canadian Standards Association International (CSA)

CSA B51 Code for Boilers, Pressure Vessels and Pressure Piping
Code Containing Hydrogen

CSA B51-M Construction and Inspection of Boilers and Pressure
Vessels

9.2.2 Non-Industrial Use Of Hydrogen

A variety of organizations have been working on codes, standards and guidelines for the design and operation of non-industrial hydrogen applications, including fueling stations and fuel cell vehicles.

Prominent are the role played by the International Standards Organization Technical Committee 197 (ISO), the National Hydrogen Association (NRA), and the Canadian Hydrogen Association (CHA). These organizations used the Natural Gas Vehicle Coalition codes as a model.

American National Standards Institute (ANSI)

ANSI Z21.83 Fuel Cell Power Plants

American Society for Mechanical Engineers

ASME PTC 50 Performance Testing for Fuel Cells

Institute of Electrical and Electronics Engineers (IEEE)

IEEE SCC.21 Standard for Instrumentation

International Standards Organization — Published

Key Points & Notes

ISO 13984 Liquid Hydrogen - Land vehicle fueling system interface

ISO 14687 Hydrogen Fuel - Product specification

International Standards Organization — Under Development

ISO/CD 13985 Liquid hydrogen - Land vehicle fuel tanks.
Part 1: Design, fabrication, inspection and testing.
Part 2: Installation and maintenance.

ISO/WD 13986 Tank containers for multi-modal transportation of liquid hydrogen

ISO/WD 15594 Airport hydrogen fuelling facility

ISO/WD 15866 Gaseous hydrogen blends and hydrogen fuel - Service stations

ISO/WD 15869 Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks.
Part 1: General Requirements.
Part 2: Particular requirements for metal tanks.
Part 3: Particular requirements for hooped wrapped composite tanks with a metal liner.
Part 4: Particular requirements for fully wrapped composite tanks with a metal liner.
Part 5: Particular requirements for fully wrapped composite tanks with a non-metallic liner.

ISO/WD 15916 Basic requirements for the safety of hydrogen systems

ISO/AWI 17268 Gaseous hydrogen - Land vehicle filling connectors

National Hydrogen Association — Working Groups

WG1 Connectors

WG2a. Tanks and Containers

WG2b. Hydrides

WG3 Refueling Stations

WG4 (Disbanded)

WG5/6 Codes and standards for self-service refueling of vehicles with hydrogen and certification program for hydrogen vehicle fuel systems

WG7 Codes and standards for maritime unique applications of hydrogen

9.3 Hydrogen Publications

Key Points & Notes

The Sourcebook for Hydrogen Applications

By the Canadian Hydrogen Association (CHA) and the National Hydrogen Association (NHA) for the Department of Natural Resources Canada and the U.S. Department of Energy. 1998.

This sourcebook is a single-volume reference on the safe use of hydrogen, including applicable codes, standards, regulations, guidelines and prevailing practices. It provides an outline of key safety considerations for non-industrial applications. A content outline is posted on the NRA website. The sourcebook comes as both paper and CD-ROM. It is available from the CHA, the NHA or the publisher:

TISEC Inc. 2113A St. Regis Boulevard
Dollard, Montreal, Quebec, Canada H9B 2M9
514-684-9096 or 800-531-2863
sourcebook@tiseec.com

Safety Standards for Hydrogen and Hydrogen Systems

By the National Aeronautics and Space Administration, Office of Mission Assurance, Washington, DC, NSS 1740.16, February 1997

These standards establish a "uniform agency process for hydrogen system design, materials selection, operation, storage and transportation." It includes the minimum guidelines for NASA. For a copy, contact:

Director, Safety and Risk Management Division, NASA
Office of the Associate for Safety and Mission Assurance
Washington, DC 20546 USA. Phone 202-358-2406

Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System for Transportation Applications. Hydrogen Vehicle Safety Report

By Directed Technologies, Inc., and the Ford Motor Company for the U.S. Department of Energy DOE/CE/50389-502, May 1997

This report presents a detailed review of the safety characteristics of a hydrogen-fueled fuel cell vehicle. Emphasis is given to on-board high-pressure gaseous hydrogen storage methods. The analysis includes the normal operation of a vehicle, its fueling, indoor storage, collisions and tunnel operation. The report identifies risks and failure modes with potential hazardous conditions, as well as potential countermeasures for prevention and harm reduction. The risks are compared to vehicles powered by gasoline, propane and natural gas. For a copy, contact:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161 USA
www.ntis.gov

9.4 Regulatory Organizations

Key Points & Notes

9.4.1 USA**American Gas Association (AGA)**

1515 Wilson Blvd.
Arlington, VA 22209 USA
703-841-8574
www.aga.org

American National Standards Institute (ANSI)

11 W. 42nd St., 13th Floor
New York, NY 10036 USA
212-642-4900
www.ansi.org

American Society of Mechanical Engineers (ASME)

Three Park Avenue
New York, NY 1001 6-5990 USA
800-THE-ASME
www.asme.org

Compressed Gas Association (CGA)

Suite 1004 - 1725 Jefferson David Hwy.
Arlington, VA 22202-4102 USA
703-412-0900
www.cganet.com

International Code Council, Inc. (ICC)

5203 Leesburg Pike, Suite 708
Falls Church, VA 22041 USA
703-931-4533
www.inticode.org

National Fire Protection Association (NFPA)

1 Batterymarch Park
Quincy, MA 02269-9101 USA
617-770-3000
www.nfpa.org

National Hydrogen Association (NHA)

1800 M Street N.W. Suite 300
Washington, DC 20036-5802 USA
202-223-5547
www.hydrogenus.com

Society of Automotive Engineers (SAE)

400 Commonwealth Dr.
Warrendale, PA 15096-0001 USA
724-776-3760
www.sae.org

U.S. Department of Labor

Occupational Safety & Health Administration (OSHA)
Office of Public Affairs - Room N3647
200 Constitution Avenue
Washington, D.C. 20210 USA
202-693-1999
www.dol.gov

Key Points & Notes

U.S. Department of Transportation (DOT)

400 7th Street, SW
Washington, DC 20590 USA
202-426-4000
www.dot.gov

U.S. Environmental Protection Agency (EPA)

National Vehicle and Fuel Emissions Laboratory
2565 Plymouth Rd.
Ann Arbor, MI 48105 USA
313-668-4275
www.epa.gov

California Air Resources Board (CARB)

9528 Telstar Ave.
El Monte, CA 91731-2900 USA
818-575-6800
www.arb.ca.gov

South Coast Air Quality Management District (AQMD)

21865 E. Copley Dr.
Diamond Bar, CA 91765-4182 USA
909-396-2000
www.aqmd.gov

9.4.2 Canada

Canadian Gas Association (CCA)

20 Eglinton Avenue West
Suite 1305, P.O. Box 2017
Toronto, Ontario, Canada M4R 1 K8
416-481-1828
www.cga.ca

Canadian General Standards Board (CGSB)

CGSB Sales Centre
Ottawa, Ontario, Canada K1A 1G6
819-956-0425 or 800-665-CGSB (within Canada)
www.pwgsc.gc.ca/cgsb

**Hydrogen Fuel
Cell Engines**

**MODULE 9: ACTS, CODES, REGULATIONS, AND
GUIDELINES**

Canadian Hydrogen Association (CHA)

5 King's College Road
Toronto, Ontario, Canada M5S 3G8
416-978-2551
www.h2.ca

Key Points & Notes

Canadian Standards Association International (CSA International)

604-244-6652
www.cssinfo.com

Canadian Standards Organization (CSO)

178 Rexdale Blvd.
Etobicoke, Ontario, Canada M9W 1 R3
416-747-4000
www.csa.ca

Transport Canada

330 Sparks Street
Ottawa, Ontario, Canada K1A 0N5
613-990-2309
www.tc.gc.ca
For Transportation of Dangerous Goods Act and Regulations

9.4.3 Japan

High-pressure Gas Safety Institute of Japan

Sumitomo Shin Toranomom Bldg.
4-3-9, Toranomom, Minato-ku
Tokyo, Japan 105-8447
81-3-3436-6103
www.khk.orjp

Japan Industrial Gases Association (JIGA)

3-2-6, Kasumigaseki, Tiyoda-ku
Tokyo, Japan 100-0013
81-3-3580-0886
www.jiga.gr.jp

9.4.4 International

International Standards Organization (ISO)

Ms. Sylvie Gingras,
Secretary of ISO/TC 197
Bureau de normalisation du Quebec
333, rue Franquet
Sainte-Foy, Quebec
Canada G1P 4C7
418-652-2238
www.iso.ch/iso/en

or
Dr. Tapan K. Bose
Hydrogen Research Inst., UQTR
P.O. Box 500
Trois-Rivieres, Quebec
Canada G9A 5H7
819-376-5139
Tapan-Bose@UQTR.UQuebec.ca

9.5 Research Organizations

Key Points & Notes

Contact the following organizations for more information on hydrogen powered and fuel cell vehicles:

Alternative Fuels Data Center

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393 USA
303-231-1288

Daimler-Chrysler Corporation

FFVs and NGVs
800 Chrysler Dr. East
Auburn Hills, MI 48326-2757 USA
313-576-4991

Ford Motor Company

Alternative Fuels Division
14310 Hamilton Ave.
Highland Park, MI 48203 USA
800-258-3835

Gas Research Institute

8600 Bryn Mawr Ave.
Chicago, IL 60631 USA
312-399-8170

General Motors Corp.

Alternative Fuels Division
30500 Mound Rd., ARMB 336
Warren, MI 48090 USA
313-986-5719

Idaho National Environmental Engineering Laboratory

Institute of Gas Technology
3424 S. State Street
Chicago, IL 60616-3896 USA
312-567-3877

National Alternative Fuels Hotline

P.O. Box 70879
Washington, DC 20024 USA
800-423-1363

U.S. Department of Energy (DOE)

Office of Domestic and Energy Policy
Mail Stop EP (PE-50)
1000 Independence Ave., SW
Washington, DC 25085 USA
202-586-4456
www.doe.gov

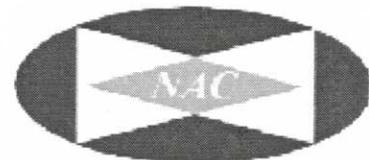
MODULE 10:

Maintenance and Fueling Facility Guidelines

College of the Desert
Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

10.1	MAINTENANCE FACILITY GUIDELINES	10-1
10.1.1	LEAK DETECTION SYSTEMS	10-1
10.1.2	FIRE DETECTION SYSTEMS	10-2
10.1.3	ELECTRICAL CLASSIFICATION FOR HAZARDOUS LOCATIONS	10-3
10.1.4	POSITIVE VENTILATION	10-3
10.1.5	EMERGENCY STOP EQUIPMENT	10-3
10.1.6	DESIGNATED PARKING AND STORAGE	10-4
10.1.7	HEATING EQUIPMENT	10-4
10.2	FUELING FACILITY GUIDELINES	10-5
10.2.1	MECHANICAL DESIGN	10-5
10.2.2	ELECTRICAL DESIGN	10-7
10.2.3	CLEARANCES	10-7
10.2.4	SAFETY PROVISIONS	10-7
10.2.5	MATERIALS	10-8
10.2.6	SECURITY	10-8
10.2.7	MAINTENANCE	10-9
10.2.8	LIQUID HYDROGEN FUELING FACILITIES	10-9

OBJECTIVES

At the completion of this module, the technician will:

- understand safety guidelines for hydrogen safe maintenance facilities
- understand safety guidelines for hydrogen fueling facilities

10.1 Maintenance Facility Guidelines

Key Points & Notes

The maintenance facility guidelines detailed in the following sections are representative of those used in current fuel cell bus applications and are intended as guidelines only. Specific guidelines may vary depending on facility location and application. At all times, the maintenance facility must conform to all pertinent government regulations and comply with all local, state and federal building codes and hydrogen related regulations.

Maintenance facilities for hydrogen fueled buses must include:

- leak detection systems
- fire detection systems
- electrical classification for hazardous locations
- positive ventilation
- emergency stop equipment
- designated parking and storage areas
- ignition-free space heating equipment

The specifications for each guideline are detailed in the following sections.

10.1.1 Leak Detection Systems

The facility must include appropriate hydrogen gas leakage detectors with a minimum of two detector heads mounted over the maintenance area. These detectors must be interlocked with the facility so that:

Upon detection of 20% LFL hydrogen:

- an audible alarm sounds inside and outside the maintenance area
- a red light flashes inside and outside the maintenance area
- a 20% LFL alarm sounds and indicator light illuminates at the monitoring station
- all gas supplies shut off
- all bay doors open
- room ventilation increases from 6 to 12 air changes/hour

Upon detection of 40% LFL hydrogen (as above, plus):

- a 40% LFL alarm sounds and indicator light illuminates at the monitoring station
- all electrical power to the test lab is disconnected, with the exception of the ventilation fan and other explosion proof equipment (such as emergency equipment, lights and signs)
- the fire department is notified automatically

- the fire alarm sounds for building evacuation

Key Points & Notes

The leak detection system *on-board* the bus may not be operational during parking or maintenance activities.

Hand-Held Leak Detectors

Portable hand-held hydrogen leak detectors should be accessible at the indoor maintenance and parking areas. Hand-held leak detectors are used for routine leak tests, and can locate small leaks that do not trigger the facility leak detection system.

Emergency Response Plan For Hydrogen Leaks

A proper written response plan for various sizes and locations of hydrogen leaks must be part of the facility's safety plan. The plan should include evacuation plans for personnel within and nearby the facility, and the safe withdrawal of all compressed gas buses. Other responses to a gas leak may include opening the bay doors, increasing the ventilation fan rate, alerting or evacuating other personnel, ceasing nearby operations, moving the bus outdoors, etc.

The length of time that a hydrogen fueled bus can be run inside the facility should be limited as larger quantities of gas may be released when the bus is operating. Repairs should not be carried out in an area designated for parking only.

10.1.2 Fire Detection Systems

The facility must include appropriate fire (IR- or LTV-type) detectors, with a minimum of two detector heads mounted over the maintenance area. These detectors must be interlocked with the facility so that:

Upon fire detection for <15 seconds:

- An audible alarm sounds inside and outside the lab area
- A red light flashes inside and outside the lab area

Upon fire detection for > 15 seconds, as above, plus:

- All gas supplies shut off
- All electrical power to the test lab is disconnected, with the exception of the ventilation fan and other explosion proof equipment (such as emergency equipment, lights and signs)
- The fire department is notified
- The building is evacuated (fire alarm sounds)

Proper maintenance facility fire detection systems are essential.

Flammable gas mixtures of hydrogen in air are easily ignited by electrical discharges or other ignition sources. Once ignited, a hydrogen flame is almost invisible in daylight due to the absence of soot.

The fire suppression system *on-board* the bus may not be operational during parking or maintenance activities.

Emergency Response Plan For Hydrogen Fires

A proper written response plan for various sizes and locations of hydrogen fires must be part of the facility's safety plan. The plan should include evacuation plans for personnel within and nearby the facility, and an appropriate fire fighting strategy for the emergency response team.

10.1.3 Electrical Classification For Hazardous Locations

All electrical equipment and machinery that have a potential for exposure to hydrogen should conform to NFPA 70, National Electrical Code requirements. According to NFPA 50A, all equipment within 15 ft (4.6 m) of hydrogen equipment must be classified Class I, Div 2. All equipment within 4.9 ft (1.5 m) must be classified Class I, Div 1.

In the US, the electrical installation must conform to the National Electrical Code, Article 500 and supplements pertinent to "Hazardous Locations: Class I Installations".

In Canada, the electrical installation must conform to the Canadian Electrical Code Part 1, Section 18, which describes electrical equipment classification for hazardous locations.

In general, these classifications dictate that all electrical power must be interrupted during a facility alarm condition except power that feeds explosion proof equipment.

10.1.4 Positive Ventilation

A maintenance facility must have positive ventilation that can operate at a normal rate of 6 air changes per hour, and increase automatically to 12 air changes per hour when hydrogen is detected. Ventilation flow should be designed such that any hydrogen leaks is exhausted to the outside without dispensing throughout the maintenance shop or accumulating below the ceiling.

10.1.5 Emergency Stop Equipment

The facility must have an automatic emergency stop capability to shut down all facility hydrogen flow and electrical power. At least one emergency stop button should be located away from the immediate shop area so that personnel can evacuate the area in an emergency prior to pressing the button.

Key Points & Notes



10. 1.6 Designated Parking and Storage

Key Points & Notes

Indoor areas where a hydrogen fueled bus is parked *while fueled* must contain the same hydrogen safety equipment described for maintenance facilities. In addition, vehicles fueled with liquid hydrogen must be attached to a dedicated vent so that any fuel bleed-off discharges directly outdoors. Indoor parking or maintenance bays should be situated to make it easy to quickly move the vehicle outdoors should a leak occur.



Any vehicle that is known to be leaking hydrogen must not be brought indoors.

Outdoor areas where the bus is parked *while fueled* must be free of sources of ignition (such as operating electrical equipment) and overhead obstructions (such as wires or overpasses).

The bus can be parked in any indoor or outdoor location provided the fuel storage system has been vented to 10 psig (0.7 barg). This slightly above atmospheric pressure prevents air from entering the system. As a matter of course, the fuel storage system should always be vented if a vehicle is stored for one month or longer.

10. 1.7 Heating Equipment

Facility heating equipment must not use electrical elements, generate sparks, or present open flames within the electrical classification area. This applies equally to systems used to heat the facility at large, and local systems used to prevent the fuel cell stacks from freezing (whether indoor or outdoor). To comply with this, heat must be ducted into the area using hot air, hot water, or steam. No surface should exceed 800 °F (426 °C).

10.2 Fueling Facility Guidelines

Key Points & Notes

The fueling facility guidelines detailed in the following sections are representative of those used in current fuel cell bus applications and are intended as guidelines only. Specific guidelines may vary depending on facility location and application. At all times, the fueling facility must conform to all pertinent government regulations and comply with all local, state and federal building codes and hydrogen related regulations.

The fueling facility must be located outdoors away from any operating electrical machinery or overhead wires. A weather awning or structure over portions of the fuel dispensing area is allowed, provided it does not interfere with the venting or diffusion of hydrogen gas.

Fueling facilities for hydrogen fueled buses must provide:

- appropriate mechanical design
- appropriate electrical design
- adequate clearances
- adequate safety provisions and equipment
- appropriate use of materials
- appropriate security arrangements
- appropriate maintenance procedures

The specifications for each guideline are detailed in the following sections.

10.2.1 Mechanical Design

For safe operation, the mechanical design of the fueling facility must meet the following guidelines:

- The dispensing hose, compressors, tanks, piping manifold and other hydrogen containing portions of the fueling facility must be grounded together by a dedicated cable.
- During fueling, the fueling facility dispensing equipment and the bus must be grounded together using a dedicated cable. A positive grounding interlock system may be used to prevent access to the bus fueling receptacle until a positive ground connection has been made.
- Check valves must be installed within the fuel dispensing station and inside the bus fill port to ensure that there is no backflow during any transfer of hydrogen.
- All storage tanks must have pressure relief devices that release on overpressure or when exposed to fire.
- The compressors must be explosion proof and designed for hydrogen compression.

- | | |
|--|-------------------------------|
| <ul style="list-style-type: none"> • The lines from the compressor, storage tanks and bottles must have automatic fast closing valves and manual shutoff valves at both the storage and dispenser ends. • The fuel dispenser must have a breakaway connection on each hose that limits the breakaway force to 150 lb (660 N). A manual isolation valve must be installed immediately upstream of this breakaway connection. A bleed-off device must be located between the manual isolation valve and the breakaway connection. The breakaway connection must incorporate double shutoff features that isolate both sides of the connection when uncoupled. • The excess-flow and normal hydrogen shutoff valves at the fueling station should be positioned and anchored so that they will not be disturbed if the fuel hose and/or piping are strained or torn apart. • Hoses must have retractors or counterweights to prevent fueling connections from hitting the ground. • The fueling receptacle must be approved for hydrogen use. • The fueling receptacle must have a sealed vent-back connection. This connection must be designed to convey the vent gas to a safe area. The hose or pipe used in this line must de-couple so that it cannot interfere with the breakaway on the dispenser hose. • The fueling system (hoses, lines and receptacle) must prevent the entry of air into the vehicle fuel system and fueling station equipment. • Fuel transfer must be automatically interrupted when the bus fuel tank contains low-pressure (15 psig; 1 barg). Low tank pressure may indicate that the tank contains air. The pressure relief device may have leaked the hydrogen out of the tanks and air may have diffused into the tanks. • The fuel dispenser must have a temperature compensation system. This system must either adjust the fill pressure to compensate for variations in ambient temperature and the heating of the tanks during fueling, be calibrated to prevent tank overtemperature, or operate with reference to a temperature transducer located inside one of the bus tanks. • The fuel dispenser must automatically shut down when the vehicle storage system is full and must prevent tank overpressure at all temperatures. • Automatic electronic systems must interrupt fueling both during overtemperature or overpressure conditions (as above) or during other fueling station faults. The automatic shutdown must interrupt all electrical power to the fueling apparatus including compressors and other equipment. • The fueling station must include a vent provision capable of discharging the entire contents of the vehicle fuel storage to the atmosphere in a safe location and manner. The fueling station may include an optional defueling system, capable of capturing the hydrogen for re-use. | <p>Key Points & Notes</p> |
|--|-------------------------------|

- All safety relief valves vent ports must discharge in a safe location and manner.
- The structural foundation must be adequate to support all components including the bus. The fueling area must be level.

Key Points & Notes

10.2.2 Electrical Design

For safe operation, the electrical design of the fueling facility must meet the following guidelines:

- All electrical equipment and machinery that have a potential for exposure to hydrogen should conform to NFPA 70, National Electrical Code requirements. According to NFPA 50A, all equipment within 15 ft (4.6 in) of hydrogen equipment must be classified Class I, Div 2. All equipment within 4.9 ft (1.5 in) must be classified Class I, Div 1.
- Electrical equipment that produces sparks may not be used. Unclassified electrical equipment must be located away from the fuel dispensing and fuel delivery equipment.
- All hydrogen-bearing equipment and all electrical equipment must be grounded to the facility (including the dispensing station and hose).
- A lightning arrestor must be connected to the facility. The cable and its footing must be correctly sized to ensure proper grounding.
- Electric and open flame heaters may not be used. Any required heat must be supplied convectively by way of hot air, hot water, steam or some other indirect method.

10.2.3 Clearances

The fueling facility must include the following clearances:

- The facility may not be located under overhead wires, roadways or other obstructions.
- The facility must provide adequate space to access the bus.

10.2.4 Safety Provisions

The fueling facility must include the following safety features:

- The fueling facility must be outdoors.
- No ignition sources may be present at any time.
- An infrared or ultraviolet flame sensor is required in the vicinity of the fueling facility. The flame sensor must interrupt all electrical power to the fueling apparatus and shut off the gas flow when triggered.
- Emergency stop buttons are required at each fuel dispenser and at each exit from the fueling area.

- Only non-sparking tools may be used to operate or maintain the facility. Key Points & Notes
- Fire extinguishing equipment and procedures must be in place.
- All personnel must be trained in emergency procedures and an evacuation plan.
- A fueling and maintenance record must be kept.
- All certifications and permits must be in place.

Regulatory signs must be included as required. In the absence of specific regulations, signs should indicate:

- that no smoking is permitted at any time
- that the bus must be grounded to the fueling facility and the ignition must be off
- that only non-sparking tools are permitted
- the location of fire extinguishers
- the location of the emergency stop buttons
- the location of manual shutoff valves

10.2.5 Materials

The fueling facility must use materials that are non-combustible, resistant to hydrogen embrittlement and compatible with fuel cell systems. Specifically:

- Materials must meet fuel cell system requirements as detailed in Section 7.1.5.
- Hoses must be made of synthetic material with stainless steel braid and be certified for compressed hydrogen gas use. Hoses must be electrically conductive. The hose ends should be installed by the hose manufacturer and the hose assembly must be pressure tested to 1.5 times the rated pressure. Hoses should be documented with serial number, test pressure, test date and first date of service.

The design of hydrogen facilities should include use of low tensile strength steels wherever possible, proper annealing and welding procedures, and the avoidance of notches, rapid temperature changes, an temperature excursions above and below ambient temperature wherever possible.

10.2.6 Security

The fueling facility should provide adequate security.

10.2.7 Maintenance

Key Points & Notes

The fueling facility instruments and equipment must be regularly maintained. A maintenance record must be kept. This maintenance should include, as a minimum:

- regular testing and calibration of hydrogen flame detectors.
- regular testing and calibration of gas dispenser temperature compensation systems.
- regular testing and calibration of gas dispenser excess flow valve.
- regular testing and calibration of low-pressure shut off valve.
- regular testing and calibration of all pressure relief devices.
- regular compressor service as required by the manufacturer.
- regular leak tests.
- regular inspection of all components for damage, wear or corrosion.
- hoses should be discarded after 12 months of use or immediately after any mechanical abuse such as a breakaway incident.

Facilities should undergo regular fire prevention inspections. This fire prevention inspection includes all devices that are commonly inspected in transit garages, such as:

- general condition of automatic sprinkler heads, sprinkler valve assemblies, dry pipe valves and locked valve shutoffs
- yard hydrants, hoses and portable fire extinguishers
- water supplies
- operational verification and readiness of automatic systems
- housekeeping issues, including cutting and welding procedures, smoking regulations and emergency procedures

10.2.8 Liquid Hydrogen Fueling Facilities

A liquid hydrogen fueling facility consists of a liquid hydrogen storage tank, a vaporizer, a dispensing unit, and associated piping, tubing and valves. The purpose of the vaporizer is to generate enough vapor pressure to initiate liquid flow. The dispensing system must include a vapor return line to the liquid hydrogen storage tank.

A liquid hydrogen fueling facility has the same basic requirements as a gaseous fueling station. In addition:

- Special materials and procedures must be used with respect to cryogenic temperatures. Insulation must be non-combustible and provide a vapor-tight seal in the outer covering to prevent air condensation and subsequent oxygen enrichment within the insulation. The insulation and outside shield must prevent attrition under normal operating con-

**Hydrogen Fuel
Cell Engines**

**MODULE 10: MAINTENANCE AND FUELING
FACILITY GUIDELINES**

ditions. Personnel must wear eye protection, gloves and outerwear made of fire resistant clothing designed for use with cryogenic materials.

Key Points & Notes

- Equipment must not be installed above asphalt surfaces or other combustible materials in order to prevent the contact of liquid air with these surfaces. Concrete is ideal. Drip pans are suitable where required.
- Bleed-off gas must vent in a safe manner
- All vent lines must discharge safely without impingement on the storage container, adjacent structures or personnel.
- A high-pressure air or nitrogen supply needs to be available at the dispenser to clean ice and frost from the receptacle. The nozzle's mating surface must be clean and free of dust, frost, or other solid particles before use.
- Air leaks into the liquid systems must not occur. Helium must be used to purge cold liquid systems since all other gases will condense and freeze at liquid hydrogen temperatures.

MODULE 11:

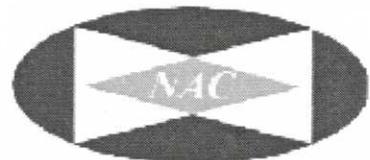
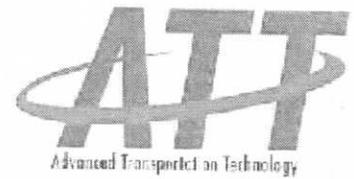
Glossary and Conversions

College of the Desert

Revision 0, December 2001

XCELLSiS
The Fuel Cell Engine Company

BALLARD



CONTENTS

11.1 GLOSSARY 11-1
11.2 MEASUREMENT SYSTEMS 11-31
11.3 CONVERSION TABLE 11-33

OBJECTIVES

This module is for reference only.

11.1 Glossary

This glossary covers words, phrases, and acronyms that are used with fuel cell engines and hydrogen fueled vehicles. Some words may have different meanings when used in other contexts.

There are variations in the use of periods and capitalization for abbreviations, acronyms and standard measures. The terms in this glossary are presented without periods.

ABNORMAL COMBUSTION – Combustion in which knock, pre-ignition, run-on or surface ignition occurs; combustion that does not proceed in the normal way (where the flame front is initiated by the spark and proceeds throughout the combustion chamber smoothly and without detonation).

ABSOLUTE PRESSURE – Pressure shown on the pressure gauge plus atmospheric pressure (psia). At sea level atmospheric pressure is 14.7 psia. Use absolute pressure in compressor calculations and when using the ideal gas law. See also psi and psig.

ABSOLUTE TEMPERATURE – Temperature scale with absolute zero as the zero of the scale. In standard, the absolute temperature is the temperature in °F plus 460, or in metric it is the temperature in °C plus 273. Absolute zero is referred to as Rankine or r , and in metric as Kelvin or K. Use absolute temperature in compressor calculations, and when using the ideal gas law.

ABSORPTION – To draw into the surface of. See also adsorption.

AC – Alternating Current.

AC GENERATOR (or ALTERNATOR) – An electric device that produces an electric current that reverses direction many times per second. Also called a synchronous generator.

ACTUAL CAPACITY – The quantity of gas actually compressed and delivered by a compressor cylinder. This is cylinder displacement (PD) times volumetric efficiency (VE). This is the capacity normally quoted on air compressors only, expressed in ACFM (actual cubic feet per minute).

ADP – Advanced Digital Processor

ADSORPTION – To stick to the surface of. See also absorption.

AIR-FUEL RATIO (A/F) – The proportions, by weight, of air and fuel supplied for combustion.

AIR POLLUTION – Any contamination of the air that is harmful to humans, animals or plants.

ALCOHOLS – A group of colorless organic compounds, each of which contains a hydroxyl (OH) group. The simplest alcohol is methanol CH_3OH .

ALGORITHM – A process or procedure used to solve a problem. Generally synonymous with “programs” or “software” in a computer system.

ALTERNATING CURRENT (AC) – A type of current that flows from positive to negative and from negative to positive in the same conductor.

ALTERNATIVE FUEL – An alternative to gasoline or diesel fuel that is not produced in a conventional way from crude oil, for example CNG, LPG, LNG, ethanol, methanol and hydrogen.

AMPERES (Amps or A) – Unit of current flow. One Amp equals one coulomb of charge passing by a point per second.

ANALOG SIGNAL – An electrical signal that varies in voltage within a given parameter.

ANION – A negatively charged ion.

ANODE – The electrode at which oxidation (a loss of electrons) takes place. For fuel cells, the anode is electrically negative; for the opposite reaction of electrolysis, the anode is electrically positive.

ANSI – American National Standards Institute

AROMATICS – Chemical compounds added to natural gas in order to impart odor. Aromatics cannot be added to hydrogen for fuel cell use.

ASME CODE – The American Society of Mechanical Engineers’ Boiler and Pressure Vessel Code.

ASME CONTAINER – Any container/cylinder manufactured to the specifications of the American Society of Mechanical Engineers in effect at the time of fabrication.

ATMOSPHERIC PRESSURE – The absolute pressure above a perfect vacuum at any geographic location or temperature. The atmospheric pressure at sea level is 29.92 "Hg or 14.74 psi at 59 °F. Any change in altitude, temperature or movement of atmospheric air masses alters this figure.

AUTOIGNITION TEMPERATURE – The minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of a source of ignition. (Also known as self-ignition temperature.)

AUTOMOTIVE AIR POLLUTION – Evaporated and unburned fuel and other undesirable by-products of combustion that escape from a vehicle into the atmosphere, mainly carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), sulfur oxides (SOx) and particulates.

BACKFIRE – The accidental explosion of an overly rich mixture in the exhaust manifold of a spark-ignition engine. Backfire conditions can also develop if the premature ignition occurs near the fuel intake valve and the resultant flame travels back into the induction system.

bar – Metric unit of pressure equal to one atmosphere. Bar is more correctly indicated as bara — pounds per square inch *absolute*, or the absolute pressure measured relative to a perfect vacuum. Related to this is barg – pounds per square inch *gauge* as measured relative to atmospheric pressure. 0 barg = 1 bara.

BASIC GAS LAWS – The relationships between pressure, temperature and volume/density of gas. See Boyle's Law, Charles' Law and Ideal Gas Law.

BATTERY – An energy storage device that produces electricity by means of chemical action. It consists of one or more electric cells, each of which has all the chemicals and parts needed to produce an electric current.

BENZENE – The simplest aromatic hydrocarbon, consisting of a single aromatic ring. A common constituent of gasoline and gasoline engine exhaust. It is a known carcinogen and is considered a toxic air contaminant.

BI-FUEL – A system that can operate on two fuels, one at a time and not simultaneously, such as gasoline and CNG.

BOILING POINT – The temperature at which a liquid becomes a gas or vice versa.

BOROSCOPE – Apparatus that enables detailed visual inspection of internal cylinder and tube surfaces, and allows for close up inspection of affected areas.

BOYLE'S LAW (First Gas Law) – If temperature remains constant, the volume occupied by a given weight of gas varies with its absolute pressure. As the volume of a gas is reduced, its pressure increases. Named for British physicist Robert Boyle (1627-1691). Also known as Mariotte's Law.

BRITISH THERMAL UNITS (Btu) – The quantity of heat required to raise the temperature of one pound of water 1 °F. Also Btuh: British thermal units per hour.

Btuh - British Thermal Units per Hour

BURST DISK – A safety device commonly used to relieve accidental high-pressure from a circuit. The burst disk is designed to rupture when subjected to a predetermined pressure level.

BURNING SPEED – The speed at which a flame travels through a combustible gas mixture (different from flame speed).

BUTANE – A type of petroleum gas that is liquid below 32 °F (0 °C) at atmospheric pressure.

BYPASS – A separate passage that permits a liquid, gas, or electric current to take a path other than that normally used.

CAA – Clean Air Act

CALIBRATE – To check or correct the initial setting of a test instrument.

CALIFORNIA AIR RESOURCES BOARD (CARB) – The California Air Resources Board certifies alternative fuel systems for adequate emissions performance. Any alternative fuel system conversions should employ only components approved by CARB, otherwise the EPA can require that the vehicle be returned to its original configuration.

CAPACITOR – An energy storage device that stores electrical energy in the form of an electrical charge. A capacitor consists of two metal plates with an insulating dielectric between them.

CAPACITY – The water volume of a container in standard cu ft (cf or ft³) per gallon. (NFPA 52)

CARB - California Air Resources Board; see entry.

CARBON (C) – An atom and primary constituent of hydrocarbon fuels. Carbon is routinely left as a black deposit left on engine parts such as pistons, rings, and valves by the combustion of fuel.

CARBON DIOXIDE (CO₂) – A colorless, odorless gas that results from the complete combustion of carbon with oxygen. Carbon dioxide is a greenhouse gas and is a major contributor to the greenhouse effect.

CARBON MONOXIDE (CO) – A pollutant from engine exhaust that is a colorless, odorless, tasteless, poisonous gas that results from incomplete combustion of carbon with oxygen.

CARBURETION – The actions that take place in the carburetor: converting liquid fuel to vapor and mixing it with air to form a combustible mixture.

CARBURETOR – The device in an engine fuel system that mixes fuel with air and supplies the combustible mixture to the intake manifold for varied speed and load conditions of the engine.

CATALYST – A substance that can speed or slow a chemical reaction between substances, without itself being consumed by the reaction. Platinum is a typical catalyst.

CATALYTIC CONVERTER – A device in the exhaust system containing a catalyst so that reactions can occur that convert undesirable compounds in the exhaust gas into harmless gases.

CATHODE – The electrode at which reduction (a gain of electrons) takes place. For fuel cells, the cathode is electrically positive; for the opposite reaction of electrolysis, the cathode is electrically negative.

CATION – A positively charged ion.

cc – Cubic centimeter; see entry.

CELSIUS – Metric temperature scale and unit of temperature ($^{\circ}\text{C}$). Named for Swedish astronomer Anders Celsius (1701-1744) although the thermometer first advocated by him in 1743 had 100° as the freezing point of water, and 0° as the boiling point, the reverse of the modern Celsius scale. Also called the Centigrade scale, for the Latin for “hundred degrees.”

CENTIMETER (cm) – A metric unit of linear measure. One centimeter equals about 0.4 inch, and one inch equals about 2.5 centimeters. One foot is equal to approximately 30 centimeters.

CENTRAL (FUEL) DELIVERY SYSTEM – This system forms the fuel-air mixture during the intake stroke. The injection is at the inlet of the air intake manifold. A carburetor is a central delivery system.

CETANE NUMBER – An indicator of the ignition quality of diesel fuel. A high-cetane fuel ignites more easily (at lower temperature) than a low-cetane fuel. Cetane numbers for diesel fuels range from 30 to 70 while 40 to 50 is typical.

cf (ft³) – Cubic foot of gas determined at 14.7 psia and 70°F (100 kPa and 21°C).

CHARLES' LAW (Second Gas Law) – Named for French scientist Jacques A.C. Charles (1746-1823). Charles' law states that if pressure remains constant, the volume of a gas increases proportionately with any increase in temperature. Also known as the Gay-Lussac law for French chemist Joseph Louis Gay-Lussac (1778-1850) who published his work in 1802, whereas Charles claimed to have reached his conclusions in 1787 but never published them. Charles was the first to use hydrogen in a balloon, and his work on gas temperature led to the discovery of absolute zero.

CHECK – To verify that a component, system or measurement complies with specifications.

CHECK VALVE – A valve that opens to permit the passage of air or fluid in one direction only, or operates to prevent (check) some undesirable action.

CHEMICAL FORMULA – A chemical formula describes the chemical composition of a molecular compound or substance according to its constituent atoms. Hydrogen, methanol and ethanol are pure substances with a definite formula. Natural gas, commercial propane, gasoline and diesel fuel have variable compositions.

CHEMICAL REACTION – The formation of one or more new substances when two or more substances are brought together.

CLEAN AIR ACT (CAA) – Legislation enacted to regulate emissions and air pollution.

cm – Centimeter; see entry.

CNG – Compressed Natural Gas; see entry.

CNG CYLINDER – A cylinder or other container designed for use or used as part of a CNG system

CO – Carbon Monoxide; see entry.

CO₂ – Carbon Dioxide; see entry.

COALESCING FILTER – A filter designed to separate liquid from gas.

COMBUSTION – Burning, fire produced by the proper combination of fuel, heat, and oxygen. In the engine, the rapid burning of the air-fuel mixture that occurs in the combustion chamber.

COMBUSTION CHAMBER – The space between the top of the piston and the cylinder head, in which the air-fuel mixture is burned.

COMPOUND MOTOR – A type of DC electric motor in which two field magnets are connected to the armature, one in series and the other in parallel.

COMPRESSED HYDROGEN GAS (CHG) – Compressed hydrogen gas is hydrogen compressed to a high-pressure and stored at ambient temperature.

COMPRESSED NATURAL GAS (CNG) – Mixtures of hydrocarbon gases and vapors, consisting principally of methane in gaseous form that has been compressed for use as a vehicular fuel. (NFPA 52)

COMPRESSION – Reducing the volume of a gas by squeezing it into a smaller space. Increasing the pressure reduces the volume and increases the density and temperature of the gas.

COMPRESSION IGNITION (CI) ENGINE – An internal combustion engine in which air is admitted to the engine on the intake stroke and the rapid compression of the air raises the temperature to such a point that the fuel ignites. Typified by the diesel engine.

COMPRESSION RATIO (CR) – The volume of the cylinder when the piston is at BDC, divided by the volume of the cylinder when the piston is at TDC.

COMPRESSION RING – The upper ring or rings on a piston, designed to hold the compression in the combustion chamber and prevent blowby.

COMPRESSION STROKE – The piston movement from bottom dead center to top dead center immediately following the intake stroke, during which both the intake and exhaust valves are closed while the air fuel mixture in the cylinder is compressed.

COMPRESSOR – Equipment that pressurizes air, gas, etc. into a compressed state.

COMPUTER – A programmable electronic device that can store, retrieve and process data.

CONDENSATION – A change of state during which a gas turns to liquid, usually because of temperature or pressure changes.

CONDENSER – A device used to liquefy water from a moist gas stream.

CONSTANT VOLUME INJECTION (CVI) SYSTEM – A type of port injection fuel delivery system in which air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots.

COOLANT – A liquid used to transfer heat to or from engine components. In a fuel cell engine, the coolant consists of either pure de-ionized water, a mixture of de-ionized water with pure ethylene glycol, or standard antifreeze depending on the circuit.

COOLING SYSTEM – A system that removes heat from engine components by the forced circulation of coolant. Fuel cell engines typically have a *bus cooling system* and a *stack cooling system*.

CR – Compression Ratio; see entry.

CRANKCASE – The lower part of the engine in which the crankshaft rotates; includes the lower section of the cylinder block and the oil pan.

CRANKCASE VENTILATION – The circulation of air through the crankcase of a running engine to remove water, blowby and other vapors to prevent oil dilution, contamination, sludge formation and pressure buildup.

CRYOGENIC TEMPERATURES – Temperatures below $-100\text{ }^{\circ}\text{F}$ (200 K ; $-73\text{ }^{\circ}\text{C}$).

CTC - Canadian Transportation Commission.

CUBIC CENTIMETER – A volume of space equal to a cube that is one centimeter on each side. Abbreviated as cc or cm^3 , and equivalent to a milliliter (mL) in capacity.

CYLINDER – A high pressure gas container (constructed, inspected, and maintained according to DOT or CTC regulations, ANSI/AGA NGV2, or CSA B51 standards. (NFPA 52)). Alternatively, a cylinder is also the circular tube-like opening in an engine block or casting in which a piston moves up and down.

DC – Direct Current; see entry.

DC GENERATOR – An electrical device that produces an electric current that always flows in the same direction.

DECELERATION– A decrease in velocity or speed with time; allowing the car or engine to coast to idle speed from a higher speed with the acceleration at or near the idle position.

DEFUELING – The terms depressurizing, venting and defueling all mean the release of gas from a vessel. The term defueling is used to mean the capture of released hydrogen for future use; the reverse of fueling.

DE-IONIZED WATER: Water with its ions removed to make it non-conductive. Also known as distilled water.

DE-IONIZING FILTER: A filter that removes ions from a liquid.

DENSITY – Density is measured as the amount of mass contained per unit volume. Density values only have meaning at a specified temperature and pressure since both of these parameters affect the compactness of the molecular arrangement, especially in a gas. The density of a gas is called its vapor density, and the density of a liquid is called its liquid density.

DETONATION – The very rapid burning of vapor resulting in a self-sustaining shock wave, the pressure behind which is several atmospheres. Detonation waves travel at speeds exceeding the speed of sound in air. In an internal combustion engine, detonation is commonly referred to as spark knock or ping. In the combustion chamber, an uncontrolled second flame front (after the spark occurs at the spark plug) with spontaneous combustion of the remaining compressed air-fuel mixture, resulting in a pinging noise. See pre-ignition and octane.

DEUTERIUM – Heavy hydrogen: containing a neutron in addition to a proton and electron.

DIAGNOSIS – A procedure followed in locating the cause of a malfunction.

DIAGNOSTIC CODE – A code obtained from a computerized diagnostic tool.

DIAPHRAGM – A thin dividing sheet or partition that separates an area into compartments; used in fuel pumps, modulator valves, vacuum advance units and other control devices.

DIELECTRIC – A nonconductive, insulating material.

DIESEL FUEL – Diesel fuel is the most common fuel for heavy-duty engines and is therefore a standard of comparison for other fuels.

DIESEL VOLUME EQUIVALENT (DVE) – The number of standard cubic meter of hydrogen equivalent to a liter of diesel (or, alternatively, scf of hydrogen equivalent to a gallon of diesel on an energy-equivalent basis).

DIPSTICK – An engine fluid level indicator.

DIRECT CURRENT (DC) – A current that flow through a circuit in one direction only. Direct current voltage is designated VDC.

DIRECT CYLINDER (FUEL) INJECTION SYSTEM – A sophisticated system that forms the fuel-air mixture inside the combustion cylinder after the air intake valve has closed.

DIFFUSIVITY – The ability of a gas to diffuse in air.

DISTRIBUTOR PILATE – The plate in the ignition distributor to which the coil switching device (points or pickup coil) is mounted and is usually moved by the vacuum advance.

DOT – US Department of Transportation.

DRY GAS – A gas that does not contain water vapor.

DUAL-FUEL – A system that operates on two fuels simultaneously, such as a fumigated diesel engine that runs on diesel and natural gas.

EFFICIENCY– The ratio between an actual result and the theoretically possible result.

EFFICIENCY, THERMAL – The ratio of the useable work that results from a thermodynamic process (such as a chemical reaction) to the total amount of energy released during the process.

EFFICIENCY, SYSTEM (OR OVERALL) – The ratio of the useable work that results from some series of processes to the total amount of energy used during those processes. System efficiency is only meaningful in relation to a defined series of processes; for example, the system efficiency for an engine at the flywheel is different (and necessarily higher than) the system efficiency at the wheels of a vehicle. The system efficiency for one system is often compared inappropriately to the system efficiency for another system that is defined differently.

EJECTOR – A device used to circulate gas: new gas enters the ejector where it mixes with and drives the recirculating flow by way of suction.

ELECTRONIC FUEL INJECTION (EFI) SYSTEM – A type of port injection fuel delivery system that meters the hydrogen fuel to each cylinder, using individual electronic fuel injectors for each cylinder and plumbed to a common fuel rail. The system uses variable injection timing and constant fuel rail pressure.

ELECTRODE – A conductor through which electricity enters or leaves an electrolyte. Batteries and fuel cells have a negative electrode (the anode) and a positive electrode (the cathode).

ELECTRONIC FUEL INJECTION SYSTEM (EFI) – A system that injects fuel into a spark ignition engine, and uses computer controls to meter and time fuel delivery. (see GFI)

ELECTROLYSIS – The decomposition water into its elemental components (hydrogen and oxygen) through the application of electrical energy.

EMISSION CONTROL – Any device or modification added onto or designed into a motor vehicle for the purpose of reducing air polluting emissions.

EMISSION STANDARDS – Allowable automobile emission levels, set by local, state and federal legislation.

ENCLOSURE – A structure whose purpose is to protect equipment from the environment or to provide noise attenuation. (NFPA 52)

ENDOTHERMIC – A chemical reaction that draws heat inward during the process of reaction.

ENERGY – The quantity of work a system or substance is capable of doing, usually measured in British thermal units (Btu) or Joules (J).

ENERGY CONTENT – Amount of energy for a given *weight* of fuel. Every fuel can liberate a fixed amount of energy when it reacts completely with oxygen to form water. This energy content is measured experimentally and is quantified by a fuel's higher heating value (HHV) and lower heating value (LHV). The difference between the HHV and the LHV is the "heat of vaporization" and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam.

ENERGY DENSITY – Amount of energy for a given *volume* of fuel. Thus, energy density is the product of the energy content and the density of a given fuel.

ENGINE – A machine that converts heat energy into mechanical energy.

ENTHALPY – The thermodynamic measure of heat content. Enthalpy is used as a way to quantify the amount of energy released or absorbed when a system changes from one state to another.

ENTHALPY OF REACTION – The amount of energy released or absorbed during a chemical reaction. When water and oxygen combine to form water, the amount of energy released is equivalent to $-230 \text{ BTU/mole}_{\text{water}}$ ($-242 \text{ kJ/mole}_{\text{water}}$).

ENTROPY – The thermodynamic measure of the relative disorder or randomness of the universe. In any spontaneous process, entropy must always increase. It is this principle that makes perpetual motion machines impossible.

ENVIRONMENTAL PROTECTION AGENCY (EPA) – The independent agency of the United States government that sets standards and coordinates activities related to automotive and stationary emissions and the environment.

EQUIVALENCE RATIO – The actual A/F ratio divided by the stoichiometric A/F ratio. Lean mixtures are described as less than 1.0 and rich mixtures are greater than 1.0.

ETHANOL – An alcohol composed of carbon, hydrogen and oxygen. It is a clear colorless liquid and is the same alcohol found in beer, wine and whiskey. Ethanol is produced by fermenting a sugar solution with yeast.

EVAPORATION – The transforming of a liquid to the gaseous state.

EXHAUST EMISSIONS – Pollutants emitted into the atmosphere through any opening downstream of the exhaust ports of an engine.

EXHAUST GAS RECIRCULATION (EGR) – A thermal dilution and/or NO_x control system that recirculates a portion of the exhaust gases back into the intake manifold.

EXHAUST STROKE – The piston stroke (from BDC to TDC) immediately following the power stroke, during which the exhaust valve opens so that the exhaust gases can escape from the cylinder to the exhaust manifold.

EXHAUST SYSTEM – The system through which exhaust gases leave the vehicle. Consists of the exhaust manifold, exhaust pipe, muffler, tail pipe and resonator.

EXOTHERMIC – A chemical reaction that expels heat outward during the process of reaction.

EXPANSION RATIO – The ratio of the volume at which a gas or liquid is stored compared to the volume of the gas or liquid at atmospheric pressure and temperature.

EXPANSION TANK (SURGE TANK) – A tank that provides room for fuel expansion or heated coolant, giving off any air that may be trapped in the system.

EXPLOSIVE LIMITS – The explosive range of a gas is defined in terms of its lower explosive limit (LEL) and its upper explosive limit (UEL). Between the two limits is the explosive range in which the gas and air are in the right proportions to burn when ignited. Below the LEL there is not enough fuel to burn. Above the UEL there is not enough air to support combustion. An explosion is different from a fire in that for an explosion, the combustion must be contained, allowing the pressure and temperature to rise to levels sufficient to violently destroy the containment.

FAHRENHEIT – Temperature scale and unit of temperature (°F). Named for German physicist Gabriel Daniel Fahrenheit (1686-1736) who was the first to use mercury as a thermometric fluid in 1714.

FAN – The bladed device on the front of the engine that rotates to draw cooling air through the radiator and around the engine.

FILTER – A device through which air, gases, or liquids are passed to remove impurities.

FLAME SPEED – The sum of burning speed and displacement velocity of the unburned gas mixture.

FLAME TEMPERATURE – The temperature of a flame burning a stoichiometric mixture of fuel and air (neither fuel nor air is in excess).

FLAMMABILITY LIMITS – The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited. Below the lower flammability

limit there is not enough fuel to burn. Above the higher flammability limit there is not enough air to support combustion.

FLANGE – A rib or rim added for strength. Also used for guiding or attaching another object (component).

FLASHPOINT – The temperature at which the fuel produces enough vapors to form an ignitable mixture with air at its surface.

FLYWHEEL – An energy storage device in which a balanced mass spinning around a constant axis stores energy as rotational kinetic energy.

FOUR-STROKE CYCLE – The four piston strokes composed of intake, compression, power, and exhaust, that make up the complete cycle of piston movements in the four stroke engine.

FREEZING POINT – The temperature at which crystals of hydrocarbons formed on cooling disappear when the temperature of the fuel is allowed to rise.

FUEL – A substance that releases energy when reacted chemically with oxygen.

FUEL GAUGE – A gauge that indicates the amount of fuel in the fuel tank or cylinder.

FUEL INJECTION SYSTEM – A system (replacing the conventional carburetor) that delivers fuel under pressure into the combustion chamber, pre-combustion chamber, turbulence chamber, or into the airflow just as it enters each individual cylinder.

FUEL INJECTOR – A device for introducing fuel into a piston engine (replacing the carburetor).

FUEL STORAGE SYSTEM – One or more containers, including their inter-connecting equipment designed for use in the mobile containment of fuel.

FUEL SYSTEM – The system (fuel cylinders and lines, gauge, fuel pump, carburetor, and intake manifold) that delivers the combustible mixture of vaporized fuel and air to the engine cylinders.

FUEL TANK – The storage tank for fuel on a vehicle.

FUELING FACILITY – A system of cylinders, pressure vessels, compression equipment, buildings, structures and associated equipment used for storage and dispensing of gaseous engine fuel in vehicle operations. Also known as a refueling facility.

GAS – A state of matter in which the matter has neither a definite shape nor a definite volume. Also an abbreviation for gasoline in North America.

GAS TURBINE ENGINE – A type of internal combustion engine in that the shaft is spun by the pressure of combustion gases flowing against curved turbine blades located around the shaft.

GASKET – A layer of material, usually made of cork or metal or both, that is placed between two machined surfaces to provide a tight seal between them.

GASOHOL – A blend of 90% gasoline and 10% ethanol used as an automotive fuel.

GASOLINE – A liquid blend of hydrocarbons obtained from crude oil, currently used as fuel in most automobile engines.

GAUGE PRESSURE – A pressure read on a scale that ignores atmospheric pressure. Thus, the atmospheric pressure of 14.7 psi absolute is equivalent to 0 psi gauge (PSIG) the pressure above atmospheric pressure — as shown on dial of a pressure gauge in pounds per square inch.

GENERATOR – An electrical device that converts mechanical power into electrical power.

GIBBS FREE ENERGY – The amount of energy available to do useful work resulting from a chemical reaction. When water and oxygen combine to form water, the useful energy is equivalent to $-217 \text{ BTU/mole}_{\text{water}}$ ($-229 \text{ kJ/mole}_{\text{water}}$).

gpm – gallons per minute, or grams per mile.

gps – gallons per second.

GRAMS PER MILE (gpm) – A mixed measure for the weight of pollutants emitted into the atmosphere with the vehicle exhaust gases. Anti-pollution laws set maximum limits for each exhaust pollutant in grams per mile.

GREENHOUSE EFFECT– The tendency for the atmosphere to hold in infrared radiation, or heat, because of increased levels of carbon dioxide (CO₂).

H₂ – Hydrogen; see entry.

H₂O – Water; see entry.

HAZARD – An existing or potential condition that can result in an accident.

HAZARDOUS – A substance or circumstance that may cause injury or damage by reason of being explosive, poisonous, corrosive, oxidizing, or otherwise harmful.

HC – Hydrocarbon; see entry. Also used to represent emissions from an internal combustion engine.

HEAT – A form of energy that is released by the burning of fuel. In an engine, heat energy is converted to mechanical energy.

HEAT OF COMPRESSION – An increase in temperature brought about by the compression of a gas.

HEV – Hybrid Electric Vehicle; see entry.

Hg – Chemical symbol for mercury.

HICE – Hydrogen internal combustion engines

HIGH PRESSURE CYLINDER – Cylinders used for storing high pressure gas with a service pressure of 1000 psig (68 barg) or greater.

HORSEPOWER (hp) – A standard measure of mechanical power, or the rate at which work is done. One hp equals 33,000 ft-lb of work per minute; it is the power necessary to raise 33,000 lb a height of 1 ft in 1 min. One horsepower equals 746 Watt, or 0.746 kW.

HYBRID ELECTRIC VEHICLE (HEV) – A vehicle that is powered by both an electric drive system and a second source of power, such as an internal combustion engine, referred to as the alternative power unit (APU).

HYDROCARBON (HC) – An organic compound containing only carbon and hydrogen, usually derived from fossil fuels such as petroleum, natural gas, and coal: an agent in the formation of photochemical smog.

HYDROGEN (H₂) – The simplest and lightest element in the universe, which exists as a gas except at low cryogenic temperatures. Hydrogen gas is colorless, odorless and highly flammable gas when mixed with oxygen over a wide range of concentrations. Hydrogen forms water when combusted, or when otherwise joined with air, as within a fuel cell. Hydrogen molecules in which both protons have the same spin are known as “ortho-hydrogen”. and those in which the protons have opposite spins are known as “para-hydrogen”.

HYTHANE – A commercial gas product that contains 20% hydrogen and 80% natural gas.

IC Engine (ICE)– Internal Combustion Engine; see entry.

IDEAL GAS LAW (Third Gas Law) – Approximates the behavior of many gases under conditions close to ordinary atmospheric temperatures and pressures.

IDLE (IDLE SPEED) – Engine speed when the accelerator is fully released, and there is no load on the engine.

IGNITION – The action of the spark in starting the burning of the compressed air-fuel mixture in the combustion chamber.

IGNITION ENERGY – The amount of external energy that must be applied in order to ignite a combustible fuel mixture.

IGNITION SYSTEM – In the automobile, the system that furnishes high-voltage sparks to the engine cylinders to fire the compressed air-fuel mix-

ture. Consists of the battery, ignition coil, ignition distributor, ignition switch, wiring, and spark plugs.

INDUCTION MOTOR – A type of AC electric motor in which the rotor has no direct connection to an external source of electricity.

INERTIA – Property of an object that causes it to resist any change in its speed or direction of travel.

INJECTOR – The tube or nozzle through which fuel is introduced into the intake airstream or the combustion chamber.

INSPECT – To examine a component or system for surface condition, or function.

INSULATION – A material that prevents the transfer of electricity or heat.

INTEGRAL – Built into, as part of the whole.

INTERNAL COMBUSTION ENGINE (ICE) – An engine in which the fuel is burned inside the engine itself, rather than in a separate device, such as a boiler on a steam engine.

JOULE (J) – Metric unit of energy, work, heat or torque. Equal to the Newton-meter (Nm). Named for English physicist James Prescott Joule (1818–1889) who pioneered the measurement and understanding of heat.

KELVIN – Metric scale of absolute temperature (K). Named for Scottish physicist (1824–1907) who formulated the second law of thermodynamics in 1850 and introduced the absolute scale of temperature.

KILOGRAM (kg) – Metric unit of weight or mass, equal to approximately 2.2 lb. Related units are the milligram (mg) at 1000 per kg, and the metric tonne at 1000 kg.

KILOMETER (km) – Metric unit of length, equal to 0.62 miles (1.6 km per mile). Related units are the meter at 1000 per kilometer, the decimeter at 10 per meter, the centimeter at 100 per meter, and the millimeter at 1000 per meter.

KILOPASCALS (kPa) – Metric unit of pressure. One psi equals 6.9 kPa. One inch of mercury (HG) equals 3.38 kPa. Related units are the Pascal (Pa) at 1000 per kPa, the bar at 100 kPa and the megapascal at 1000 kPa. See also Pascal.

KILOWATT (kW) – A unit of power equal to about 1.34 hp, or 1000 watts. The Watt is named for James Watt, Scottish engineer (1736-1819), a pioneer in steam engine design.

km/h – Kilometer per hour. Note the use of the slash to indicate “per” instead of the abbreviation “p” as in mph or gps.

KNOCK – A common term that refers to the results of preignition or detonations sound caused by excessive clearance between moving parts in an engine. A knock can be overcome by increasing the octane number of the fuel, retarding ignition timing or by reducing engine load. In diesel engines, knock is caused by excessive pressure within the combustion chamber and abnormal fuel combustion. In diesel engines it is avoided by the use of higher cetane fuels.

kPa – Kilopascal; see entry. Note capitalization.

kW – Kilowatt; see entry. Note capitalization.

LABELED – Equipment or materials to which has been attached a label, symbol or other identifying mark of an organization acceptable to the “authority having jurisdiction” and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner. (NFPA 52)

LAMBDA (λ) – Equal to the stoichiometric F/A ratio divided by the actual F/A ratio. Lambda is the inverse of PHI.

LEAK TESTING – Testing by use of a solution, such as a soap solution, to observe a leak under pressure by the formation of bubbles as gas escapes from the leak.

LEAN MIXTURE – An air-fuel mixture that has a relatively low proportion of fuel in relation to air. For example, an air-fuel ratio of 16:1 indicates a lean mixture, compared to an approximately normal air fuel ratio of 14.7:1 for gasoline.

LEV – Low Emission Vehicle; see entry.

LH2 (Liquefied Hydrogen) – Hydrogen cooled to 20.3 K (–423 °F; –253 °C) and ambient pressure becomes a liquid.

LIGHT-DUTY VEHICLE – A motor vehicle manufactured primarily for transporting persons or property and having a gross vehicle weight of 6000 lb (2720 kg) or less.

LIQUEFIED NATURAL GAS (LNG) – A motor fuel composed of natural gas that has been liquefied. Liquefied natural gas cooled to 111 K (–259 °F; –162 °C) and ambient pressure becomes a liquid.

LIQUEFIED PETROLEUM GAS (LPG) – Any material that is composed predominantly of any of the following hydrocarbons or mixtures of hydrocarbons: propane, propylene, normal butane, isobutylene and butylenes.

LITER (L) – Metric measure of capacity corresponding to a volume of 1000 cm³ (or 1 dm³). One liter is approximately equal to 34 fl oz, 0.26 gal (US) or 61 cubic inches. Related units are the milliliter (mL) at 1000 to the liter, and the kiloliter (kL) at 1000 L. Note use of capital L in abbreviations. Engine

displacement is often given in cubic centimeters (cc) for smaller engines, and in liters for larger engines.

LNG – Liquefied Natural Gas; see entry.

LPG – Liquefied Petroleum Gas; see entry.

LOW-PRESSURE CYLINDER – Those cylinders with a marked service pressure below 900 psi (6205 kPa).

LOWER EXPLOSIVE LIMIT (LEL) – The LEL is the lowest gas concentration that will support an explosion when mixed with air, contained and ignited. The LEL is always higher than the LFL.

LOWER FLAMMABLE LIMIT (LFL) – The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited.

MALFUNCTION – Improper or incorrect operation. See Check Engine light.

MANIFOLD – A device with several inlet or outlet passageways through which a gas or a liquid is gathered or distributed.

MANUAL SHUTOFF VALVE – A hand valve used to isolate a component or circuit.

MANUFACTURER – Any person, firm, or corporation engaged in the production or assembly of products, components, or systems.

MASS AIRFLOW SENSOR (MAF) – A sensor that measures the volume of air entering an engine, usually in grams per second (g/sec). Used in on-board computer systems.

MASS FLOW METER – A device for measuring the mass flow of gases.

MECHANICAL EFFICIENCY – In an engine, the ratio between brake horsepower and indicated horsepower.

MECHANICAL PROPERTIES – Properties of a material that pertain to its elastic and plastic behavior when force is applied: yield strength, ultimate strength, elongation, hardness, etc.

MELTING POINT – The temperature at which a solid becomes a liquid or vice versa.

METER (m) – Basic metric unit of length equal to 3.28 feet, 1.09 yards or 39.37 inches. Related units are the decimeter (dm) at 10 per meter, the centimeter (cm) at 100 per meter, the millimeter (mm) at 1000 per meter and the kilometer (km) at 1000 meters.

METHANE (CH₄) – See Natural Gas.

METHANOL (CH_3O) – Methyl alcohol, , is the simplest of the alcohols. It has been used, together with some of the higher alcohols, as a high-octane gasoline component and is a useful automotive fuel in its own right.

MILES PER HOUR (mph) – Standard measure of speed. Equal to 1.6 km/h.

MILLIGRAM (mg) – Metric unit of weight or mass equal to 1/1000 of a kilogram. The weight of 1 mL or 1 cc of water at atmosphere pressure.

MILLIMETER (mm) – Metric unit of length, equal to 0.04 inch, or 25 min per inch. There are 1000 millimeters in a meter.

mm – Millimeter; see entry.

MODIFICATION – An alteration; a change from the original.

MOLECULAR WEIGHT – Sum of the weights of atoms making up a molecule.

MOLECULE – The smallest particle of a substance that retains all the properties of the substance; it is composed of atoms.

MOTIVE PRESSURE REGULATOR – A pressure regulator that reduces gas pressure from the high pressure conditions within the fuel storage system to an intermediate pressure, typically around 175 psig.

MOTOR – An electric motor. A motor converts electric energy to mechanical energy (motion).

mph – Miles per hour; see entry.

N_2 – Nitrogen; see entry.

NATURAL GAS – Mixtures of hydrocarbon gases and vapors consisting principally of methane in gaseous form. (NFPA 52)

NEWTON (N) – Metric unit of force that, acting on a mass of one kilogram, increases its velocity by one meter per second every second along the direction that it acts. Named for English mathematician Sir Isaac Newton (1642–1727) who had the greatest single influence on theoretical physics until Albert Einstein. He discovered the binomial theorem and differential calculus. In his major treatise *Principia Mathematica* (1687), generally considered the greatest scientific work ever written, he gave a mathematical description of the laws of mechanics and gravitation, and applied these to planetary and lunar motion. He also discovered that white light is made up of a mixture of colors, built the first reflecting telescope and revolutionized the minting of coins to prevent counterfeiting.

NITROGEN (N_2)– A colorless, tasteless, odorless gas that constitutes 78% of the atmosphere by volume and is a part of all living tissues.

NITROGEN OXIDES (NO_x) – Any chemical compound of nitrogen and oxygen. Nitrogen oxides result from high temperature and pressure in the combustion chambers of automobile engines and other power plants during the

combustion process. When combined with hydrocarbons in the presence of sunlight, nitrogen oxides form smog. A basic air pollutant; automotive exhaust emission levels of nitrogen oxides are regulated by law.

NOBLE METALS – Metals (such as gold, silver, platinum, and palladium) that do not oxidize readily or enter into other chemical reactions. These metals will promote reactions between other substances. Platinum and palladium are used as the catalysts in catalytic converters.

NON-COMBUSTIBLE MATERIAL – A material that in the form in which it is used and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat. (NFPA 52)

NO_x – See Nitrogen Oxides; see entry.

NO_x CONTROL SYSTEM – A device or system used to reduce the amount of nitrogen oxides produced in an engine.

NUCLEUS – The positively charged particle that is the center of an atom.

O₂ – Oxygen; see entry.

OCTANE NUMBER – The number used to indicate the octane rating of a gasoline. The octane number describes the anti-knock properties of a fuel when used in an internal combustion engine. Knock is a secondary detonation that occurs after fuel ignition due to heat buildup in some other part of the combustion chamber. When the local temperature exceeds the autoignition temperature, knock occurs.

OCTANE RATING – A measure of the antiknock properties of a gasoline. The higher the octane rating, the more resistant the gasoline is to abnormal combustion.

ODORIZATION – A process of adding a distinctive odor to natural gas so that its presence can be easily detected.

OHM – A unit of electric resistance equal to the resistance of a circuit in which a potential difference of one volt produces a current of one ampere.

OEM – Original Equipment Manufacturer

OHM'S LAW – This law explains the relationship of voltage, current, and resistance in a circuit. One volt of electrical pressure is needed to push one ampere of electrical current through one ohm of resistance ($V = I \times R$).

OHMMETER – An instrument used to measure the amount of resistance (number of ohms) in an electric conductor or circuit.

OIL – A liquid lubricant; made from crude oil and used to provide lubrication between moving parts. In a diesel engine, oil is used for fuel.

OLEFIN – An unsaturated hydrocarbon containing one or more double bonds.

ORIFICE – A small opening, or hole, that controls the flow rate of a gas or liquid into a cavity.

O-RING – A type of sealing ring, made of a special rubber compound. The O-ring is placed into a groove to provide the sealing action.

OTTO CYCLE – The cycle of events in a four-stroke cycle engine. Named for the German inventor, Dr. Nikolaus Otto.

OVERHEAT – To become excessively hot. To operate above the manufacturer's recommended temperature range.

OXIDATION – Burning or combusting; the combining of material with oxygen. Rusting is slow oxidation, and combustion is rapid oxidation.

OXIDES OF NITROGEN (Nox) – See Nitrogen Oxides.

OXYGEN (O₂) – A colorless, tasteless, odorless, gaseous element that makes up about 21% of air. Oxygen is capable of combining rapidly with ALL elements (except inert gases) in the oxidation process called burning (combustion). Oxygen combines very slowly with many metals in the oxidizing process called rusting.

Pa – Pascal; see entry.

PARALLEL HYBRID – A type of hybrid electric vehicle in which the alternative power unit is capable of producing motive force and is mechanically linked to the drive train.

PARALLEL CIRCUIT – The electric circuit formed when two or more electrical devices have their terminals connected together, positive to positive and negative to negative, so that each may operate independently from the same power source.

PARTIAL PRESSURE – The amount of pressure contributed by an individual gas in a mixture of ideal gases toward the overall, total pressure.

PARTICLE – A very small piece of metal, dirt, or other impurity that may be contained in the air, fuel, or lubricating oil used in an engine.

PARTICULATES (PARTICULATE MATTER – PM) – Small particles (generally less than 30 microns) of carbon and other pollutants occurring as solid matter in the exhaust systems of vehicles. These particles generally remain suspended in the atmosphere, causing a major pollution problem in many U.S. cities. Current EPA regulations address only “respirable” or “fine” particles that are less than 10 microns in diameter (PM 10).

PASCAL (Pa) – Metric unit of pressure. Related units are the kilopascal (kPa) at 1000 Pa, the bar at 100,000 Pa and the megapascal at 1,000,000 Pa. The Pascal is named for Blaise Pascal, French mathematician and physicist

(1623-1662) who discovered that air has weight, confirmed that a vacuum could exist and derived the principle that the pressure of fluid at rest is transmitted equally in all directions. He also founded the theory of probability, and developed a forerunner of integral calculus.

PASCAL'S LAW – The pressure of a gas is equal in all directions.

PASSIVATED ELEMENT – A substance that does not readily enter into chemical combination.

PETROLEUM – The crude oil from which gasoline, lubricating oil, and other such products are refined.

PHI (Φ) – Equal to the stoichiometric A/F ratio divided by the actual A/F ratio. Phi is the inverse of LAMBDA.

PHYSICAL PROPERTIES – Characteristics that pertain to the nature and composition of a material or object.

PISTON – A movable part, fitted into a cylinder, that can receive or transmit motion as a result of pressure changes in a fluid. In the engine, that cylindrical part which moves up and down within a cylinder as the crankshaft rotates.

PISTON DISPLACEMENT – The cylinder volume displaced by the piston as it moves from the bottom to the top of the cylinder during one complete stroke.

PISTON RINGS – Rings fitted into grooves in the piston to seal a cylinder assembly. There are two types: compression rings for sealing the compression in the combustion chamber, and oil rings to scrape excess oil off the cylinder wall.

POLARITY – The condition in an electric component or circuit that indicates the direction of current flow. The identification of one point as positive (+) and another point as negative (–) for a voltage.

POLLUTANT – Any substance that adds to the contamination or degrading of the environment. In a vehicle, any substance in the exhaust gas from the engine or evaporating from the fuel system.

POLLUTION – Any gas or substance that makes the environment less fit. Types of pollution include: air, ground water, ocean, noise, etc.

PORT (FUEL) DELIVERY SYSTEMS – This system forms the fuel-air mixture during the intake stroke. It is injected at the inlet port.

POWER OUTPUT – For an engine power output is based on the speed the engine is turning, multiplied by the torque produced.

ppb – Parts per billion

ppm – Parts per million

PREMATURE IGNITION or PRE-IGNITION – This occurs when the fuel mixture in the combustion chamber becomes ignited before ignition by the spark plug, and results in an inefficient, rough running engine.

PRESSURE – The exertion of continuous force on or against a body by another in contact with it, expressed as force per unit area.

PRESSURE DIFFERENTIAL (<P)– The difference between the pressure of the air/fuel mixture in the intake manifold and atmospheric pressure.

PRESSURE RELIEF DEVICE (PRD) – A safety device on a pressure vessel, actuated by either overpressure or overtemperature, that relieves the pressure by opening to vent some or all of the contents of the vessel.

PRESSURE TRANSDUCER – A sensor that converts pressure readings to electrical signals.

PRESSURE VESSEL – A container or other component designed in accordance with the ASME Code. (NFPA 52)

PRESSURIZE – To apply more than atmospheric pressure to gas or liquid.

PROCESS VARIABLE – A sensor used to set the setpoint of any PID control loop. In automotive fuel injection systems, the O₂ sensor is always the process variable.

PROPANE (C₃H₈)– A type of liquid petroleum gas (LPG) that is liquid below – 44 °F (– 42 °C) at atmospheric pressure. Propane gas is heavier than air.

PROTON – A subatomic particle in the nucleus of an atom that carries a positive electric charge, and is not moveable by electrical means.

psi – Pounds per square inch; a unit of pressure. Psi is more correctly indicated as psia – pounds per square inch *absolute*, or the absolute pressure measured relative to a perfect vacuum. Related to this is psig – pounds per square inch *gauge* as measured relative to atmospheric pressure. 0 psig = 14.7 psia.

PULLEY – A metal wheel with a V-shaped groove around the rim that drives, or is driven by, a belt or rope.

PUMP – A device that develops pressure or transfers gas or liquid from one place to another.

PURGE – The use of a gas to flush residual gases and/or liquids from a container.

PYROLYSIS – The chemical decomposition brought about by heat.

QUENCH – During combustion, the removal of heat from the end gas or outside layers of air-fuel mixture by the cooler metallic surfaces of the combustion chamber, thus reducing the tendency for combustion to occur.

QUENCH AREA – The area of the combustion chamber near the cylinder walls that tends to cool (quench) combustion because of the nearby cool water jackets.

RADIATOR – A heat exchanger in the cooling system that removes heat from coolant passing through it, thus returning the coolant to the engine at a lower temperature.

RADIATOR PRESSURE CAP – A type of cap placed on the radiator filler tube that allows for the pressurization of the cooling system for more efficient operation.

RAFFINATE – The gas mixture that results when hydrogen is removed from reformat.

RATIO – Proportion; the relative amounts of two or more substances in a mixture. Usually expressed as a numerical relationship, as in 2:1.

REACTANT – A substance that enters into chemical combination with another substance.

REFORMING – A chemical process that reacts hydrogen-containing fuels in the presence of steam, oxygen, or both into a hydrogen-rich gas stream.

REFORMATE – The hydrogen-rich gas mixture that results from processing hydrogen containing fuels in a reformer.

REGENERATIVE (or DYNAMIC) BRAKING – A energy recovery system in which energy generated by vehicle braking is converting into electricity and stored.

REGULATOR – A device that controls generator output to prevent excessive voltage, excessive current output, or excessive air/gas pressure.

RELAY – An electrical device that opens or closes the high current portion of a circuit or circuits in response to a relatively low voltage signal. An electromagnetically operated switch.

RELIEF VALVE – A valve that opens when a preset pressure is reached. This relieves or prevents excessive pressures.

REMOVE AND REPLACE R AND R) – To perform a series of servicing procedures on an original part or assembly; includes removal, inspection, lubrication, all necessary adjustments, and reinstallation.

REPLACE – To remove a used part or assembly and install a new or rebuilt part or assembly in its place; includes cleaning, lubricating, and adjusting as required.

RESISTANCE (R) – The characteristic of a device to oppose the passage of electrical current. The opposition to a flow of current through an electric circuit or device; measured in ohms. A voltage of 1 volt will cause 1 ampere to

flow through a resistance of 1 ohm. This is known as Ohm's law and can be written in three ways:

RESISTIVE TEMPERATURE DEVICE (RTD) – A device whose electrical resistance changes in proportion to its temperature.

REVOLUTIONS PER MINUTE (rpm) – A measure of rotational speed.

RICH MIXTURE – An air-fuel mixture that has a relatively high proportion of fuel and a relatively low proportion of air.

ROOM TEMPERATURE – A temperature from 68 to 72 °F (20 to 22 °C).

ROTARY – A circular motion of a moving part.

ROTOR – A revolving part of a machine, such as an alternator rotor, disk brake rotor, distributor rotor or Wankel-engine rotor.

rpm – Revolutions per minute; see entry.

SAE – Society of Automotive Engineers; used to indicate a grade or weight of oil measured according to the SAE.

SCAVENGING – The displacement of exhaust gas from the combustion chamber by fresh air.

scf – Standard cubic feet

scfd – Standard cubic feet per day

SCHEDULED DEFUELING/VENTING – The planned removal of hydrogen from a vehicle fuel storage system in order to make repairs or modifications to the bus equipment.

SEAL – A part or material that is used to close off the area of contact between two machine parts, usually to prevent fuel, gases, coolant or oil leakage.

SERIES CIRCUIT – An electric circuit in which the same current flows through all devices; positive terminals are connected to negative terminals.

SERIES HYBRID – A type of hybrid electric vehicle is which runs on battery power like a pure EV until the batteries discharge to a set level, then the alternative power unit turns on to recharge the battery.

SERIES MOTOR – A type of DC electric motor in which the armature and the field magnet are connected electrically in series.

SERVICE PRESSURE - The settled pressure at a uniform gas temperature of 70 OF (21 °C) and full gas content. It is the pressure for which the equipment has been constructed, under normal conditions. (NFPA 52)

SHORT CIRCUIT – A defect in an electric circuit that permits current to take a different path, instead of following the desired one.

SHUNT – A parallel connection or circuit.

SHUNT MOTOR – A type of DC electric motor that connects the magnet and armature in parallel.

SI SYSTEM – The metric system of measurement.

slpm – Standard liters per minute. Used to quantify the flow of gas adjusted to standard temperature and pressure.

SOLENOID – An electromechanical device (a coil of wire wound around a movable core) that, when connected to an electrical source such as a battery, produces a mechanical movement. This movement can be used to control a valve or to produce other movements.

SOLENOID SWITCH – A switch that is opened and closed electromagnetically by the movement of a solenoid core. The core also causes a mechanical action, such as the movement of a drive pinion into mesh with flywheel teeth for cranking. Also solenoid valve.

SOURCE(S) OF IGNITION – Devices or equipment that, because of their modes of use or operation, are capable of providing sufficient thermal energy to ignite flammable compressed natural gas-air mixtures when introduced into such a mixture or when such a mixture comes into contact with them and that will permit propagation of flame away from them. (NFPA 52)

SO_x – Sulfur oxides; see entry.

SPARK PLUG – A device that screws into the cylinder head of an engine, provides a spark to ignite the compressed air-fuel mixture in the combustion chamber.

SPECIFIC GRAVITY – Ratio of the weight of the gas to the weight of air or the ratio of the weight of a liquid to an equal volume of pure water.

SPECIFIC HEAT – Ratio of the amount of heat required to raise the gas temperature one degree compared to the amount of heat required to raise an equal amount of water one degree.

SPECIFICATIONS – Information provided by the manufacturer, describing systems and their components, operations, and clearances. Also, the service procedures that must be followed for a system or component to operate properly.

SPEED – The rate of motion. For vehicles, speed is measured in miles per hour or kilometers per hour.

STANDARD CONDITIONS – Temperature and pressure conditions that correspond to 0 °C (32 °F) and 14.7 psig (1 barg) respectively. Sometimes, standard temperature is taken as room temperature.

STANDARD CUBIC FEET (SCF) – Cubic feet of gas determined at standard conditions.

STATOR – In the torque converter, a third member (in addition to turbine and pump) that changes the direction of a fluid under certain operating conditions (when stator is stationary).

STIRLING ENGINE – A type of internal combustion engine in which the piston is moved by changes in the pressure of a working gas that is alternately heated and cooled. It has two isothermal processes and two constant-volume processes.

STOICHIOMETRIC (STOICH) – A chemically perfect reaction of fuel and air in an engine (the only products of combustion are water and carbon dioxide).

STOICHIOMETRIC AIR-FUEL RATIO – The exact air-fuel ratio required to completely react a fuel into water and carbon dioxide.

STP – Standard temperature and pressure.

STROKE – In an engine cylinder, the distance that the piston moves in traveling from BDC to TDC or from TDC to BDC.

SULFUR OXIDES (SO_x) – Acids that can form in small amounts as the result of a reaction between hot exhaust gas and the catalyst in a catalytic converter.

SWITCH – A device that opens and closes an electric circuit.

SYNCHRONOUS MOTOR – A type of AC electric motor in which the stator also produces a rotating magnetic field.

THERMAL – Of or pertaining to heat.

THERMAL EFFICIENCY – Ratio of the energy output of an engine to the energy in the fuel required to produce that output.

THERMOSTAT – A device for the automatic regulation of temperature: usually containing a temperature sensitive element that expands or contracts to open or close off the flow of a gas, liquid or electricity.

THREE-WAY CATALYTIC CONVERTER (TWC) – A catalytic converter that uses platinum, rhodium, and palladium to reduce vehicle emissions. Three-way catalysts require mixtures extremely close to stoichiometric for effective conversion of NO_x.

TORQUE – The ability of a force to move a load or to do work. Turning or twisting motion; measured in standard in pound-feet (ft-lb), or in metric in the Newton-meter (Nm).

TORQUE WRENCH – A wrench that indicates the amount of twisting effort (rotary motion) being applied with the wrench.

TORRICELLI (torr) – Unit of pressure equal to 1 mm of mercury (1 mm Hg) or 1 atm = 760 torr. Named for the Italian physicist Evangelista Torricelli (1608–1647), who first measured the pressure of the atmosphere using a tube of mercury upended within a dish of mercury, coincidentally producing the first vacuum within the tube.

TRANSDUCER – Any device that converts an input signal of one form into an output signal of a different form.

TROUBLE DIAGNOSIS (TROUBLESHOOTING) – The detective work necessary to find the cause of a problem.

TURBOCHARGER – A supercharger driven by the engine exhaust gas pressure for pressurizing the intake air or air-fuel charge of an engine, so as to increase the mixture delivered to the cylinders thus increasing power output.

UPPER EXPLOSIVE LIMIT (UEL) – The UEL is the highest gas concentration that will support an explosion when mixed with air, contained and ignited. The UEL is always lower than the UFL.

MODULE 11: GLOSSARY AND CONVERSIONS

UPPER FLAMMABLE LIMIT (UFL) – The UFL of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the UFL, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich.

VAC – Volts Alternating Current. See Alternating Current.

VACUUM – Negative gauge pressure, or a pressure less than atmospheric pressure. Vacuum can be measured in psi, but is usually measured in inches or millimeters of mercury (Hg); a reading of 30 in. Hg [762 mm Hg] would indicate a perfect vacuum.

VACUUM GAUGE – A device that measures pressures below atmospheric.

VALVE – A device that can be opened or closed to allow or to stop the flow of a liquid or gas.

VAN DER WAALS – Named after Dutch physicist Johannes Diderick van der Waals (1837–1923) who first worked out the adjustments to the ideal gas law in 1873. Van der Waals equation is $(P+a/V^2)(V-b) = \underline{RT}$. The feeble attractive forces between gas molecules that necessitate the probability adjustment (a/V^2) are called “van der Waals forces.”

VANE – A flat, extended surface that is moved around an axis by or in a fluid: part of the internal revolving portion of a turbocharger.

VAPOR – A gas: any substance in the gaseous state, as distinguished from the liquid or solid state.

VAPORIZATION – A change of state from liquid to vapor by evaporation or boiling; a general term including both evaporation and boiling.

VDC – Volts Direct Current. See Direct Current.

VENT – An opening through which a gas can leave an enclosed chamber.

VENTILATION – The circulating of fresh air through any space to replace impure air.

VENTING – The discharge of hydrogen from a fuel storage system to the atmosphere.

VISCOSITY – A measure of the resistance to flow of a liquid. The lower the viscosity, the thinner the fluid is and the more easily it will flow. This is affected by temperature. At low temperatures, viscosity is high, while at high temperatures viscosity is low.

VISCOUS – Thick; tending to resist flowing.

VOC - Volatile Organic Compounds; see entry.

VOLTAGE (V) – The force that causes electrons to flow in a conductor. One Volt equals one Joule of work per Coulomb of electrons. The difference in electrical pressure (or potential) between two points in a circuit.

VOLTMETER – An electric meter for measuring the voltage or electrical pressure of an electric device, such as a battery or alternator, or for measuring the voltage between two points in an electric circuit.

VOLUME (V) – An area defined by measurement of length, width, and height, and expressed in cubic units such as the cubic feet, cubic centimeter, etc. Volume is constant, being a measurement of space rather than a condition of air or gas.

WANKEL (ROTARY) ENGINE – A rotary engine in which a three-lobe rotor turns eccentrically in an oval chamber to produce power.

WASTE SPARK SYSTEM – An ignition systems that energizes the spark each time the piston is at top dead center whether or not the piston is on the compression stroke or on its exhaust stroke. For hydrogen engines, the waste sparks are a source of pre-ignition.

WATER (H₂O) – A colorless, transparent, odorless, tasteless liquid compound of hydrogen and oxygen. The liquid form of steam and ice. Fresh water at atmospheric pressure is used as a standard for describing the relative density of liquids, the standard for liquid capacity, and the standard for fluid flow. The melting and boiling points of water are the basis for the Celsius temperature system. Water is the only byproduct of the combining of hydrogen and oxygen, and is produced during the burning of any hydrocarbon. Water is the only substance that expands on freezing as well as by heating, and has a maximum density at 4 °C.

WATER INJECTION – A technique for thermally diluting a fuel mixture by injecting water into the hydrogen fuel stream.

WEIGHT AND DENSITY OF AIR – Weight and density of a given volume of air vary proportionally with pressure. An air receiver tank filled with air at atmospheric pressure floats on water, whereas the same tank of air pressurized to 1000 psig contains a denser mass of air, and the increased weight causes it to sink.

WORKING PRESSURE – The pressure at which the equipment was designed to function, or if conditions have changed, the maximum pressure allowed at specified temperatures.

ZEV – Zero Emissions Vehicle

Z-FACTOR – Compressibility factor of a gas; a multiplier that accounts for its deviation from the ideal gas law.

11.2 Measurement Systems

Metric or SI System

The meter is the central unit of the metric system. Other measures, such as for area, volume, capacity, mass, energy, force, power, voltage and others are directly linked to the meter, greatly simplifying calculations. Orders of magnitude are in multiples of ten. The meter was first defined as 1.0×10^{-7} of the distance between the North Pole to the Equator as measured on a line through Paris. It is now defined as the length of the path traveled by light in a vacuum during $1/299,792,458^{\text{th}}$ of a second.

The metric system was first introduced in France in 1793, but was not accepted until after 1837. Since then, the metric or “SI” system has become the official measurement system throughout most of the world.

Prefix	Symbol	Factor	Scientific Notation
exa	E	1,000,000,000,000,000,000	10^{18}
peta	P	1,000,000,000,000,000	10^{15}
tera	T	1,000,000,000,000	10^{12}
giga	G	1,000,000,000	10^9
mega	M	1,000,000	10^6
kilo	k	1,000	10^3
hecto	h	100	10^2
deca	da	10	10^1
		1	10^0
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	③	0.000001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pico	p	0.000 000 000 001	10^{-12}
femto	f	0.000 000 000 000 001	10^{-15}
atto	a	0.000 000 000 000 000 001	10^{-18}
bold = commonly used			

Table 11-1 Metric Prefixes and Their Meaning

Standard, English or Imperial System

The standard/English/Imperial system does not have a central unit. The system grew out of various units that had been established ad hoc over centuries in many countries. Common units, such as the yard, foot and inch, were defined as the king’s reach, the length of his foot and the width of his thumb, and therefore subject to continual change. The mile started as the distance an army could travel in an hour. Dimensions were eventually stan-

standardized by the English and the Imperial system spread throughout the British Empire.

In the US, the Imperial system was adapted in minor ways (as in liquid measure) and is known as the standard, English or US system. While mixed units and fractions are commonly used, it is the decimal measures (or “engineering units”), such as the decimal foot, that are used by scientists, engineers, etc. The foot is now officially defined as a portion of a meter.

Prefix	Symbol	Factor	Scientific Notation
millions	MM	1,000,000	10^6
thousands	M	1,000	10^3

Table 11-2 Standard Prefixes and Their Meaning

Engineering Units

Use engineering units without mixing units of different magnitude. For example, use 1.5' instead of 1'-6". The former can be multiplied with other numbers, while the latter cannot.

Use engineering units as decimals, not as fractions. For example, use 1.5 ft instead of 1 ½ ft. Fractions cannot be multiplied or otherwise manipulated mathematically in a practical way.

Prefixes to units should not be combined. For example, use billion instead of thousand-million, and giga instead of kilo-mega.

Periods, Commas and Plurals

In English-speaking countries, Asia and in many other countries, commas are used to separate thousands, while a period is used to indicate the decimal point. In France, Germany and many other European countries, the practice is the reverse; indicating the decimal point with a comma, and thousands by periods.

A zero should precede numbers that are less than zero, in order to draw attention to the decimal point. For example, write 0.24 rather than .24.

Periods should never be used with metric abbreviations. Standard units are often written with a period, but need not be.

Abbreviations for units should not be pluralized. For example, write 2 lb instead of 2 lbs.

11.3 Conversion Table

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Length (Distance)			
ft or' (feet)	12		in
yd (yards)	3		ft
mi (miles)	5280	5000	ft
in or " (inches)	1000		mill or thou (thousandths of an inch)
in	25.400	25	mm (millimeters)
in	2.540	2.5	cm (centimeters)
ft	0.304 80	0.3	m (meters)
m (meters)	3.280 84	3.3	ft
mi	1.609 344	1.6	km
km (kilometer)	1000		m
m	10		dm (decimeter)
m	100		cm
m	1000		mm
mm	1000		③m (micron)
light-years	9.46×10^{12}		km
light-years	5.88×10^{12}		mi
Speed (Velocity)			
mph (miles per hour)	1.609344	1.6	km/h (kilometers per hour)
fps (feet per second)	0.30480	0.3	m/s (meters per second)
fpm (feet per min)	0.30480	0.3	m/min (meters per minute)
knots	1.151	1.2	mph
mach (speed of sound)	741.455	750	mph
c (speed of light)	186,281.7	1.86×10^5	mi/s (miles per second)
c	299,792,800	3×10^8	m/s (meters per second)

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Acceleration			
mph/s (miles per hour per second)	0.026 823	0.027	km/h-s (kilometers per hour per sec)
ft/s ² (feet per second per second)	0.304 80	0.3	m/s ² (meters per second per second)
ft/s ²	1.097 28	1.1	km/h-s
gravity	32.174 05	32	ft/s ²
gravity	9.806 65	10	m/s ²
Area			
ft ² or sq ft (square feet)	144	150	in ² or sq in (square inch)
yd ² or sq yd (square yards)	9	10	ft ²
in ²	6.45	6	cm ² (square millimeters)
ft ²	0.093	0.1	m ² (square meters)
mi ² or sq mi kilometers)	2.590	2.6	km ² (square (square miles)
acre	43,560	44,000	ft ²
acre	0.404 96	0.4	hectare
hectare	10,000		m ²
Volume, Capacity			
ft ³ or cu ft (cubic inches)	1728	1700	in ³ or cu in (cubic feet)
ft ³	7.480519	7.5	gal
gal	0.133 681	0.13	ft ³
yd ³ or cu yd (cubic yards)	27	30	ft ³
fl oz (fluid ounce)	2		Tb (tablespoon)
fl oz	1.804 688	2	in ³
in ³	0.554	0.5	fl oz
cup	8		fl oz
pt (pint)	2		cup
qt (quart)	2		pt
gal (gallon)	4		qt

Unit	Accurately Multiply By	Roughly Multiply By	To Get
gal	128	130	fl oz
US liquid barrel	31.5	30	gal
US liquid barrel	0.119 24	0.12	m ³
Imperial fl oz	0.960 76	1	fl oz
Imperial pt	2.5		cup
Imperial gal	153.721 7	150	fl oz
Imperial gal	160		Imperial fl oz
in ³	16.387 064	16	cm ³ (cubic centimeter) or mL (milliliter)
ft ³	28,316.85	30,000	cm ³ or mL
ft ³	28.316 85	30	L (liter) or dm ³ (cubic deci- meters)
ft ³	0.028 317	0.03	m ³ (cubic meter) or kL (kiloliter)
fl oz	29.573 53	30	cm ³ or mL
Imperial fl oz	28.413 07	30	cm ³ or mL
gal	3.785 412	4	L or dm ³
Imperial gal	4.546 092	4.5	L or dm ³
cm ³ or mL	0.061 024	0.06	in ³
cm ³ or mL	0.033 813	0.03	fl oz
m ³ or kL	35.314 475	35	ft ³
cm ³ or mL	1000		mm ³
L or dm ³	1000		cm ³ or mL
m ³ or kL	1000		L or dm ³
Mass			
lb(pound)	16		oz (ounce)
ton — short	2000		lb
ton — long	2240	2200	lb
ton — long	1.12	1.1	ton — short
oz	28.350	30	g (gram)
lb	453.592	500	g
lb	0.453 59	0.5	kg (kilogram)
ton - short	0.907 18	0.9	tonne
g	0.035 273	0.035	oz

kg	35.273 368	35	oz
Unit	Accurately Multiply By	Roughly Multiply By	To Get
kg	2.204 586	2.2	lb
tonne (metric)	2205	2200	lb
tonne	1.102 293	1.1	ton — short
tonne	1.016 064	1	ton — long
g	1000		mg
kg	1000		g
tonne	1000		kg
Mt (megatonne)	1,000,000		tonne
Mass Flow			
cfm(ft ³ /min) (cubic feet per minute)	60		cfs (ft ³ /s) (cubic feet per second)
cfh (ft ³ /h)(cubic feet per hour)	24		cfm (ft ³ /min)
gps(gallons per second)	60		gpm
gpm (gallons per minute)	8.020 833	8	cfh (ft ³ /h)
cfs	28.317	30	slps (standard liters per sec.)
cfs	0.028 317	0.03	m ³ /s (cubic meters per second)
cfm	28.316 85	30	slpm (standard liters per minute)
cfm	0.0283 17	0.03	m ³ /min (cubic meters per minute)
cfh	0.472	0.5	slpm
gpm	3.785 412	3.8	slpm
slpm	0.035 315	0.035	cfm
m ³ /min	1000		slpm
slpm	60		slps
Force			
lb _F or lb (pound force)	4.448 222	4.5	N (Newtons) or J/m (Joules per meter)

N	0.224 809	0.22	lb _F
Unit	Accurately Multiply By	Roughly Multiply By	To Get
Pressure			
psi (pound-force per square inch)	16	15	oz per sq in (oz/in ²)
psf (pounds per square ft)	144	150	psi
psi	0.068 046	0.07	atm
psi	2.04	2	in Hg
psi	27.72	28	in of water
atm	14.696	15	psi
in Hg (inches of mercury)	0.491	0.5	psi
in Hg (or "Hg)	13.6	14	in of water
psi	6.894 757	7	kPa
psi	0.068 948	0.07	bar
psi	0.006 895	0.007	MPa
psi	51.715	50	Torr
in Hg	25.4	25	Torr
in Hg	3.386 39	3.4	kPa
in wg (inches of water)	248.84	250	kPa
atm	101.325	100	kPa
atm	1.013 25	1	bar
kPa (kilopascals)	0.145 038	0.15	psi
bar	14.503 77	15	psi
bar	0.986 923	1	atm
bar	0.1		mpa
bar	100		kPa
bar	1000		mbar (millibars)
kPa	1000		Pa
Mpa (megapascals)	1000		kPa
GPa (gigapascals)	1000		mpa
Torr (millimeters of	0.133 322	0.13	kPa

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Energy, Heat, Work, Torque			
mercury)			
ft-lb or ft-lb _F (foot-pounds)	16		in-lb (inch-pounds)
ft-lb	1.355 818	1.4	J (Joules) or Nm (Newton-meters)
Btu (British thermal units)	777.477	800	ft-lb
Btu or W-h (Watts per hour)	10,000		therm
Btu	1055.056	1000	J
Btu	1.055 056	1	kJ (kilojoules)
J	0.947 364	1	Btu
kW-h (kilowatt-hours)	3.6		MJ (megajoules)
kW-h	3600		kJ
Temperature			
°F (degrees Fahrenheit)	-32; x 5/9	-30; x 0.5	°C (degrees Celsius)
°C	x 9/5 + 32	x 2 + 30	°F
<°F	x 5/9	x 0.5	<°C
<°C	x 1.8	x 2	<°F
K	x 1.8		°R
°F	+459.67	460	°R (degrees Rankine)
°C	+273.15	+ 273	K (degrees Kelvin)
Power, Heat Flow Rate			
Btuh (British thermal units per hour)	0.293 07	0.3	W (Watts) or J/s (Joules per second)
hp (horsepower)	0.000 393	0.0004	Btuh
hp – electric	0.746	0.7	kW (kilowatts)
Btuh	0.000 293	0.0003	kW
MBh (thousands of Btuh)	0.293	0.3	kW

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Density			
oz/in ³ (ounces per cubic inch)	1730	1700	kg/m ³ (kilograms per cubic meter)
lb/ft ³ (pounds per cubic foot)	16.018	16	kg /m ³
kg /m ³	0.062 43	0.06	lb/ft ³
Specific Volume			
ft ³ /lb (cubic feet per pound)	0.062 43	0.06	m ³ /kg (cubic meters per kg)
m ³ /kg	16.018	16	ft ³ /lb
Energy Density or Heat Density			
Btu/ft ² (British thermal units per sq. foot)	11.357	11	kJ/m ² (kilojoules per square meter)
Btu/ft ³ (British thermal units per cubic foot)	37.297	37	kJ/m ³ (kilojoules per cubic meter)
Btu/gal (Btus per gallon)	1000.279	1000	kJ/L (kilo- joules per liter)
Power Density			
kW/ft ² (kilowatts per square feet)	10.764	10	kW/m ² (kilowatts per square meter)
Btuh/ft ²	3.1546	3	kW/m ²
Specific Heat			
Btu/lb (British thermal units per pound)	2.326	2.3	kJ/kg (kilojoules per kilogram) or J/g (Joules per gram)
Thermal Capacity			
Btu/lb-°F (Btu per pound-°F)	4.1868	4	kJ/kg-°C (kilojoules per kilogram-°C)

MODULE 11: GLOSSARY AND CONVERSIONS

Unit	Accurately Multiply By	Roughly Multiply By	To Get
Fuel Consumption			
mpg (miles per gallon)	4.251 436	4	km/L (kilometers per liter)
mpg (miles per gallon)	0.235 21	0.25	u100km (liters per 100 km)
gal/hp-hr (gallons per horsepower-hour)	0.079 317	0.08	L/kW-hr (liters per kilowatt-hour)
Humidity Ratio			
grain of moisture per pound of dry air	1/7000 or $1.428\ 57 \times 10^{-4}$		kg of moisture per kg of dry air
Pressure Drop (Water at 68 °F; 20 °C)			
ft/100ft (feet per 100 feet)	98	100	Pa/m (Pascals per meter)
ft/100ft	0.098	0.1	kPa/m (kilopascals per meter)
psi/100ft (psi per 100 feet)	226	230	Pa/m
kPa/m	10.2	10	ft/100ft