MISSOURI S&T

CENTER FOR TRANSPORTATION INFRASTRUCTURE AND SAFETY

Missouri S&T Hydrogen Transportation Test Bed Equipment & Construction

by

John Sheffield

NUTC RE254

A National University Transportation Center
at Missouri University of Science and Technology

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16. Abstract

Investments through the National University Transportation Center at Missouri University of Science and Technology have really scored on the Center's mission areas and particularly Transition-state fuel vehicle infrastructure leading to a hydrogen economy. Already this investment has produced three programs, Hydrogen Fueling Station, the EcoCAR Garage and the Renewable Energy Transit Depot, that have led to a new 2008 Missouri S&T major strategic theme. Chancellor Carney calls it "E3=C" Challenge, i.e., Energy, Environment, and Education equals Civilization. With the strong start empowered by NUTC funds, a new transportation test bed at Missouri S&T, coined "E3 Commons," is being constructed to develop, demonstrate and deploy hydrogen vehicles and supporting infrastructure including hydrogen production from renewable energy sources. Another round of investment is needed to keep this momentum going and to capitalize where success has grown much more than anticipated. The hydrogen transportation test bed serves as a focal point for the Center for Transportation Infrastructure and Safety - National University Transportation Center at Missouri University of Science and Technology, focusing on the overarching goals of collecting and evaluating the real-world performance and utility of hydrogen-powered vehicles and benchmarking issues related to the safety, operation, and maintenance of hydrogen-powered vehicles with other alternative fuel-powered vehicles. NUTC funds, along with specific project matches, have allowed Missouri S&T to accomplish Phase I. Tackling Phase II requires complementary capabilities for these three program areas and the Commons: EcoCAR Garage, Hydrogen Fueling Station, Renewable Energy Transit Depot, and the E3 Commons as a whole.

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Final Report

Missouri S&T Hydrogen Transportation Test Bed

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1. Background

The National University Transportation Center at Missouri University of Science and Technology (Missouri S&T) sponsored this project entitled "Missouri S&T Hydrogen Transportation Test Bed" as an initiative of the *Transition-state fuel vehicle infrastructure leading to a hydrogen economy* focus by leveraging earlier investments from the Defense Logistics Agency (DLA) in sponsoring a project entitled "Hydrogen Infrastructure Technologies" via a contract with the Air Force Research Laboratory (AFRL) for $1,940,000 during the period October 2006 - April 2009 with a time extension through December 2009.

The "Missouri S&T Hydrogen Transportation Test Bed" project has now enhanced three hydrogen major facilities at Missouri S&T: the Hydrogen Fueling Station, the EcoCAR Garage, and the Renewable Energy Transit Depot. Missouri S&T Chancellor Carney calls it the "E^3=C" Challenge, i.e., "*Energy, the Environment, and Education equals Civilization*". Hence, the new hydrogen transportation test bed at Missouri S&T, coined "E^3 Commons", has been established to develop, demonstrate, and deploy hydrogen vehicles and supporting infrastructure including hydrogen production from renewable energy sources and serves as a focal point for the US DOT funded Center for Transportation Infrastructure and Safety - National University Transportation Center (NUTC) at Missouri S&T, focusing on the overarching goals of collecting and evaluating the real-world performance and utility of hydrogen-powered vehicles and benchmarking issues related to the safety, operation, and maintenance of hydrogen-powered vehicles with other alternative fuel-powered vehicles. A photograph of the Missouri S&T E-cubed Commons is given in Fig. 1 of the Appendix.

Table I shows a summary of an overall ten-year timeline envisioned and adopted for the demonstration and deployment of hydrogen transportation systems in the United States including Steam Methane Reforming (SMR) and Electrolysis of water for the onsite production of hydrogen to fuel both hydrogen Internal Combustion Engines (ICE) and hydrogen Fuel Cell Plug-in Hybrid Electric Vehicles (FC-PHEV). In Phase II, the EcoCAR: The Next Challenge is the leading technology demonstration project in North America for hydrogen FC-PHEVs.

Table I. Hydrogen Transportation Test Bed Timeline.

	2006-08	**2008-11**	**2011-16**
	Phase I: Development	**Phase II: Technology Demonstration**	**Phase III: Commercial Deployment**
Infrastructure	Analyze hydrogen generation options (SMR vs Electrolysis)	Evaluate hydrogen generation from multiple feedstock	Demonstrate viability of hydrogen infrastructure
Vehicles	Evaluate emerging pathways to hydrogen vehicles (ICE vs FC-PHEV)	Evaluate hydrogen powered vehicles under real-world conditions (EcoCAR)	Demonstrate commercial viability of hydrogen fuel cell vehicles
Research	Address safety issues, codes and standards, and performance and cost barriers		

The NUTC funds, along with specific project matches, have allowed Missouri S&T to accomplish Phase I and begin Phase II. However, tackling Phase II and Phase III will require complementary capabilities for these three program areas and the E-Cubed Commons.

2. Objectives

The Missouri S&T Hydrogen Transportation Test Bed has achieved the following:

- Collected and evaluated real-world data to help address safety and environmental issues, develop statistically validate codes and standards, formulate policies and regulations, and understand reliability and large-scale deployment of hydrogen technology under diverse operating conditions;
- Addressed the transition to a manufacturing environment, commercially ready, non-destructive testing technologies for hydrogen storage and transport systems;
- Tested, demonstrated, and validated hydrogen vehicles, hydrogen transportation infrastructure, and vehicle and infrastructure interfaces for complete system solutions;
- Gained public acceptance to the use of safe alternative energy sources to power the transport system that is independent of the fossil fuel supplies including hydrogen and electric drive vehicles;
- Integrated research and develop activities into a comprehensive undergraduate and graduate curriculum to educate the future workforce on hydrogen technologies and electric drive vehicles;
- Developed and implemented outreach programs at Missouri S&T including the US DOE/GM sponsored EcoCAR Competition and the Missouri S&T award winning National Hydrogen Association's Hydrogen Student Design Competition teams (Grand Prize Winning team in 2008 and 2010), in collaboration with other national programs, which has a special emphasis on safety training for operators, maintainers, code officials, and first emergency responders at the local and state levels.

3. National University Transportation Center

The Center for Transportation Infrastructure and Safety National University Transportation Center (NUTC) at the Missouri S&T under the "Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users," expanded the research and education activities to include alternative transportation fuels and other issues that are at the forefront of society and the national agenda. A holistic approach was taken to address not just the technology but also public perception, permitting, safety standards, and education and training. A key partner in this initiative was the National Association of State Fire Marshals (NASFM) that regards this as an "excellent candidate for the model approach to introducing hydrogen to communities." The tasks identified in five areas, viz., Infrastructure Development and Deployment, High-Pressure Composite Cylinders, Inspection and Monitoring, Statistically Validated Codes and Standards, and Safety, constitute a comprehensive research, development and demonstration program to address some of the challenges which were described in the U.S. Department of Transportation (DOT) Hydrogen Roadmap 2005 "Research, Development, Demonstration, & Deployment Roadmap for Hydrogen Vehicles & Infrastructure to Support a Transition to a Hydrogen Economy".

This initiative was built on previous studies on manufacturing of composites, non-destructive testing and evaluation, expanded the current theme of the NUTC at Missouri S&T. The preliminary activities were aimed at initiating the research related to the development of a rural hydrogen transportation test bed that will demonstrate, evaluate and promote hydrogen-technologies in a real-world environment, which included:

- On-site generation of hydrogen from ethanol
- Modeling of composite hydrogen storage cylinders using finite element analysis
- Non-destructive testing and evaluation (NDT&E)
- High voltage disconnect systems (HVDS)
- Statistically-validated codes and standards - stationary fuel cells
- Hydrogen safety of transportation vehicles
- Blast wave modeling

The Missouri S&T NUTC is charged with addressing national needs in the area of transportation infrastructure and safety topical areas:

- Advanced materials
- Transition-state fuel vehicle infrastructure
- Non-destructive evaluation (NDE) technologies and methods

Within the topical area of "Transition-state fuel vehicle infrastructure" which focuses on hydrogen as a transportation fuel, two critical targeted tasks are as follows:

- Development of safety codes, standards, and regulations
- Infrastructure development and deployment

The NUTC has supported proposals in the areas of advanced materials, transition-state fuel vehicle infrastructure, and NDE technologies and methods with the objective of advancing the state-of-the-art of transportation infrastructure and safety. One earlier example is the modeling of composite hydrogen storage cylinders as pressurized hydrogen storage cylinders are a critical component of hydrogen transportation systems (vehicle fuel systems, bulk commodity transport, portable storage, and stationary storage). These cylinders also have pressure/thermal relief devices (P/TRDs) that are activated in case of an emergency. Also recent studies illustrated the ongoing development of comprehensive finite element analysis tool for the modeling, simulation, and design optimization of composite hydrogen storage cylinders for safe installation and operation. By using of a neural network model, one can effectively predict the burst pressure of these composite hydrogen storage cylinders undergoing thermal loading. Missouri S&T researchers have applied their two-dimensional, shear deformable, composite shell model for static finite element analysis, thermo-mechanical analysis, dynamic analysis and failure analysis. The extension to three-dimensional analysis, for example, has accounted for hydrogen with fluid-structure interactions; three-dimensional failure analysis/life prediction due to thermo-mechanical dynamic loading; impact analysis; nonlinear analysis with geometric nonlinearity (large deformation) and material nonlinearity (plasticity for aluminum liner and visco-plasticity for polymer liner); and the design optimization using neural network models.

4. EcoCAR Garage

The U.S. Department of Energy and General Motors, as well as other industry leaders, are funding the three-year premier collegiate advanced vehicle technology competition, the "EcoCAR: The NeXt Challenge" (2008-2011). Missouri S&T has already received in excess of $4 million of EcoCAR support, including both cash and in-kind. Competition sponsors include General Motors Corporation, U.S. Department of Energy, Government of Canada (Transport Canada and Natural Resources Canada), California Air Resources Board, A123 Systems, Inc., dSPACE, Inc., National Instruments, The MathWorks, Freescale Semiconductor, AVL

Powertrain Engineering, Inc., National Science Foundation, Woodward Mototron Control Solutions, Vector CANtech, Sensors, Inc., Robert Bosch, LLC, Snap-On, Inc., Magna International/Magna Powertrain, Renewable Fuels Association, Siemens PLM Software, Electric Power Research Institute, Delphi Foundation, EcoMotors, Women in the Winner's Circle Foundation, igus, and CarSim by Mechanical Stimulation. The Missouri S&T EcoCAR team has re-engineering a pre-production vehicle into hydrogen FC PHEV with the donations of a PEM fuel cell, hydrogen storage system, electric traction system, three years of financial support for the Missouri S&T team. In addition, Missouri S&T team received from The MathWorks licenses for all product produced by the company; from National Instruments a hardware in loop (HIL) simulation hardware and software; from Siemens NX 6 software licenses; from Woodward Mototron financial support for hardware; from A123 Systems five custom lithium-ion battery packs and from Bosch financial support for additional hardware. All of these companies are providing three years of technical support and training to the Missouri S&T team.

The EcoCAR Competition has challenged the Missouri S&T engineering students to re-engineer a light-duty vehicle, minimizing energy consumption, emissions, and greenhouse gases while maintaining the vehicle's utility, safety, and performance**.** Before Missouri S&T submitted their EcoCAR proposal in Jan 2008, they faced an uphill challenge in this latest Advanced Vehicle Technology Competition (AVTC). Missouri S&T was a newcomer to the US DOE funded AVTC, noting that U.S. DOE had already sponsored 45 AVTCs since beginning in 1987. The EcoCAR Challenge was Missouri S&T's first entry in the AVTC series. Missouri S&T was selected in May 2008 as one of only 17 universities in North America (14 USA and three Canada). And in February 2009, Missouri S&T was selected by GM & DOE as the *only* team in U.S.A. to receive hydrogen fuel cells, the cutting-edge powertrain technology for the EcoCAR Challenge. As one of the surviving 16 teams, Missouri S&T is now entering into Year Three of the EcoCAR Competition.

The NUTC grant funded the installation of the following safety items at the Missouri S&T EcoCAR Garage:

> [1] a hydrogen gas leak detection system (catalytic beads) connected to a full safety system of sensors, alarms, monitors, and security cams, and
> [2] an automatic fire suppression system.

The Appendix provides more details in the following figures: Fig. 2 on the Mainline Fire Suppression System Installed at EcoCAR Garage; Fig. 3 on the Fire Suppression System Data; and Fig. 4 on the Fire Sprinkler Piping Plan for Missouri S&T EcoCAR Garage.

5. Renewable Energy Transit Depot

The U.S. Department of Transportation, Federal Transit Administration (FTA) project entitled "Research on Alternative Sources of Energy to Power Transit Vehicles" was funded for $1,667,837 with a period of performance from April 1, 2008 through Aug 31, 2010. [Project No: MO-26-7010-00]. The goals of this FTA project are aligned with the FTA's strategic research goals to protect the environment and promote energy independence. The scope of work includes the following two tasks:

1. Implementation of an electric vehicle and plug-in hybrid electric vehicle demonstration project

2. Expansion of the Missouri S&T "Show Me the Road to Hydrogen" project which provides a rural transportation test bed for hydrogen-fueled commuter bus service.

Missouri S&T Renewable Energy Transit Depot, which is a new "green-building" fabricated from four recycled shipping containers. The overall design emphasizes state-of-the-art strategies for sustainable site development, water savings, energy efficiency, material and resource selection, and indoor environmental quality. This transit depot will be a multifunctional building acting as the terminus of the hydrogen and electric bus service, home of the Missouri S&T EcoCAR team offices and laboratory space, a small vertical wind turbine and flexible solar photovoltaic (PV) system. The solar PV and wind turbine system will demonstrate an attractive and cost effective renewable energy technology option for onsite hydrogen production. Furthermore, by integrating on-site solar and wind energy into the hydrogen transportation test bed, this site demonstrates that hydrogen is not just a clean-fuel, but that it can be produced through renewable, energy-efficient means. The Federal Transit Administration project funded:

[1] the erection of the four recycled shipping containers
[2] installation of the solar PV panels, wind turbine and the hydrogen electrolyzer.

The NUTC grant funded the installation of the following items at the Missouri S&T Renewable Energy Transit Depot:

[1] the foundation, electricity, water, natural gas and sewage connections for Missouri S&T Renewable Energy Transit Depot
[2] research instruments and equipment in the laboratories at the Missouri S&T Renewable Energy Transit Depot to enhance the design, analysis, simulation and modeling capabilities in support of the hydrogen fuel cell plug-in hybrid electric vehicle development.

The Appendix provides more information in the following figures; i.e. Fig. 5 on the Exterior Elevations of Renewable Energy Transit Depot; Fig. 6 on the Renewable Energy Power System Drawing; Fig. 7 on the Renewable Energy Transit Depot Finish Details; Fig. 8 on the Renewable Energy Transit Depot Power Details; and Fig. 9 on the foundation for the Renewable Energy Transit Depot.

6. Hydrogen Fueling Station

The Defense Logistics Agency sponsored Missouri S&T initial hydrogen transportation test bed project entitled "Hydrogen Infrastructure Technologies" operated via a contract with the Air Force Research Laboratory with $1,940,000 for the period 10/06 – 4/09 with a time extension through 12/09. The deliverables included a hydrogen fueling station with on-site hydrogen generation via steam methane reforming; hydrogen transportation test bed; educational material; safety protocols for stationary fuel cells. Missouri S&T steam methane reforming unit underwent a safety re-design resulting in one year delay in commissioning of the Missouri S&T station. With the funds from NUTC, Missouri S&T Hydrogen Fueling Station transformed the temporary facilities to a permanent fueling station. Thus, a renewable energy powered onsite hydrogen production system using an electrolyzer has been installed for the generation of high purity hydrogen for fuel cells. The balance of plant includes the steel storage tanks for high pressure storage of hydrogen gas; a 350 bar hydrogen dispenser for both internal combustion engine and fuel cell vehicles; and a stationary polymer electrolyte membrane (PEM) fuel cell which provides emergency backup electric power to the E-cubed Commons. The Appendix provides additional details of the Hydrogen Fueling Station Site Plan Update in Fig. 10; the

Hydrogen Fueling Station Wiring Diagram in Fig. 11; and the Hydrogen Fueling Station Enclosure for Hydrogen Compressor in Fig. 12.

7. Energy Trends in the U.S.A.

In the U.S., it should be noted that DOT has authorities, regulatory responsibilities and expertise for vehicle safety and fuel economy, and for pipeline and hazardous material safety, including the safety of hydrogen fueled vehicles and hydrogen storage in vehicles, as well as the safe transportation and distribution of hydrogen. While the U.S. Department of Energy (DOE) is the federal government agency responsible for light-duty vehicles in U.S., it is the DOT which is responsible for heavy-duty vehicle research and provides capital funds to support, and to maintain the safety of the Nation's transportation infrastructure including the development of the hydrogen distribution and delivery system. Because DOT has primary responsibility for pipeline safety and transportation of hazardous materials, it must also coordinate the concurrent development of the infrastructure to support the pace of commercially available vehicles, and the pact of local production, storage and protection of energy using hydrogen.

The safety of the entire transportation system will be essential for the success of hydrogen as an emerging alternative transportation fuel. Accordingly, DOT has a vital role in developing, promulgating, and enforcing regulations in various aspects of transportation operations. In a small way, the rural hydrogen transportation test bed in Missouri will be addressing the issues and processes important for the transition to a hydrogen economy while maintaining the current high standard of safety, reliability, and public confidence in this rural transportation system. The project seeks to confirm the validity of the procedures and standards for the safe use and transport of hydrogen in transportation vehicles. Many believe that hydrogen safety codes and standards should be performance-based and systems-oriented and that the hydrogen safety codes and standards be designed to apply to general product applications as opposed to prescriptive, type-specific regulations for each application. Thus these new hydrogen codes and standards are being developed based on sound scientific knowledge of hydrogen effects on material properties and behavior. Finally, these new hydrogen codes and standards must address both the design and operation of transportation systems, subsystems, components, and consumer devices.

Public acceptance of hydrogen fueled vehicles will dictate fuel system integrity, vehicle safety, and crashworthiness performance equal or superior to the existing petroleum fuel currently in use. The challenges for developing safety codes, standards, and regulations for hydrogen fuel systems include the need for substantial research in understanding and anticipating the effects of hydrogen on various materials. The full-scale demonstration projects must be designed to research the complex systems operations, performance, reliability, and costs. Cross-cutting research is also required to examine the effects of hydrogen on conventional and composite materials (i.e., stainless steel alloys and carbon composites, respectively) including the effects of temperature, pressure ranges, and fluctuations. In addition, the effects of atmospheric and vehicle environmental stressors such as humidity, temperature, airborne and waterborne contaminants (acids, salt compounds, etc.), dirt, vibration, and shock on material integrity need to be fully understood before the standards for hydrogen use and transport can be promulgated. Inspection technologies must also be developed to detect and maintain the integrity of hydrogen fuel and commodity transport systems. The standards and regulations actions will rely on data collected from a diverse set of research and demonstration projects, including those conducted or funded by DOE, Environmental Protection Agency (EPA), Department of Defense (DOD), and DOT in U.S. as well as others international sources. Although basic knowledge and early research and development on materials behavior can be shared across the modes and used for

many purposes, regulations should be specific to the application and will be developed independently by the appropriate operating organizations, in collaboration with relevant standards organizations.

9. Conclusions

The outcomes of the Missouri S&T Hydrogen Transportation Test Bed are summarized as follows:

Phase I: (2006-2008)

The Missouri S&T Hydrogen Transportation Test Bed initiative which was funded initially by the NUTC seed funds resulted in the Defense Logistics Agency sponsored "Hydrogen Infrastructure Technology" via an Air Force Research Laboratory contract for $1.94M. Later the U.S. Department of Transportation, Federal Transit Administration (FTA) funded the Missouri S&T project entitled "Research on Alternative Sources of Energy to Power Transit Vehicles" for $1,667,837 with a period of performance from April 1, 2008 through Aug 31, 2010.

The outcomes for Phase I included the following:

- Commuter Bus Service (non Hydrogen) for FLW Established (May 07)
- Temporary Hydrogen Air Products Refueler Utilized Prior to Installation of Fixed Hydrogen Fueling Station (May 07)
- Ford Hydrogen Internal Combustion Engine (ICE) Buses Utilized on Missouri S&T Campus for Evaluation Purposes (June 07)
- Air Products Mobile Hydrogen Refueler Operational at Missouri S&T (June 07)
- First Responder Training Completed (July 07)
- Ford Hydrogen Internal Combustion Engine Bus Service at Missouri S&T Operational (July 07)
- Missouri S&T - Air Products Contract Negotiations for Fixed Hydrogen Fueling Station Unsuccessful (Oct 07)
- Missouri S&T Signed Contract with Gas Technology Institute (GTI) for Fixed Hydrogen Fueling Station-Steam Methane Reforming (SMR) (Dec 07)
- Open GTI Hydrogen Fueling Station and Hosted 2008 Hydrogen Road Tour (Aug 08)
- Begin FLW Hydrogen Bus Commuter Service (Rolla-FLW) (Aug 08)
- Negotiated for Continued Operation Through 2009
- Install GTI SMR at Hydrogen Fueling Station (May 09)
- Resume FLW Hydrogen Bus Commuter Service (Rolla-FLW) (May 09)

Phase II: (2008-2011)

As one of the next alternative fuel initiatives at Missouri S&T in Phase II, the Federal Transit Administration funded the Alternative Energy Research Project 00021459 to expand the Hydrogen-Powered Rural Transit Test Bed by installing on-site hydrogen production via electrolysis powered by two renewable energy sources, i.e. solar photovoltaic panels and a small vertical axis wind turbine mounted on the renewable energy transit depot. The U.S. Department of Energy (DOE) and General Motors (GM), as well as by Natural Resources Canada and other industry leaders, established a new collegiate advanced vehicle technology competition (AVTC), the "EcoCAR: The NeXt Challenge." EcoCAR challenges engineering students from universities across North America to re-engineer a light-duty vehicle, minimizing energy consumption, emissions, and greenhouse gases while maintaining the vehicle's utility, safety, and performance. Missouri S&T was selected in May 2008 as one of the 17 universities in North America (14 USA and three Canada) selected to join the three-year EcoCAR Challenge (2008-2011). In February 2009 Missouri S&T was selected by GM & DOE as the only team in U.S.A. to receive hydrogen fuel cells, the cutting-edge powertrain technology, for the EcoCAR Challenge.

The outcomes for Phase II included the following:

- Re-commissioning of the 15 kg/day on-site mobile hydrogen unit via steam methane reformation at the E-cubed Commons (May 27, 2009)
- Re-establishment of the hydrogen shuttle bus service between Rolla and Ft Leonard Wood in Missouri (May 27, 2009)
- Design/build a green building fabricated from four recycled shipping containers (2010)
- Design/build/install an electrolyzer system including chiller and new compressor integrated into the GTI designed hydrogen fueling station (2010)
- Design/build/install the renewable energy components: solar photovoltaic panels and architectural wind turbines on the renewable energy transport depot. (2010)
- Commission the fully integrated hydrogen fueling station (2010).

Appendix

Fig. 1 - New dawn at the Missouri S&T E-cubed Commons

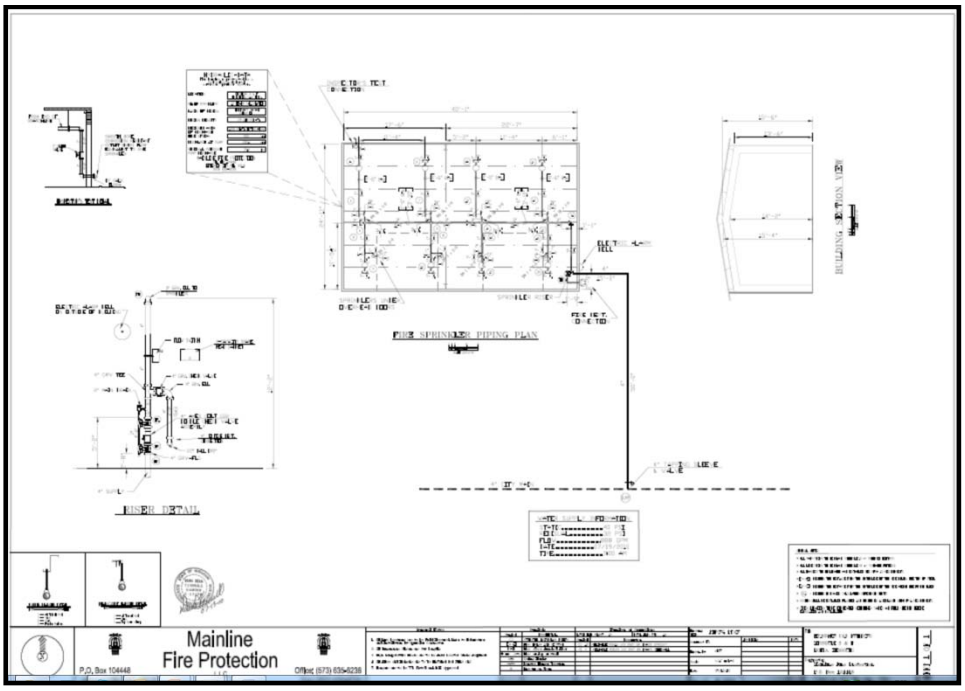

Fig. 2 – Mainline Fire Suppression System Installed at EcoCAR Garage

HYDRAULIC-DATA

This building is protected by a Hydraulically designed automatic sprinkler system.

LOCATION	MISSOURI S & T HYDROGEN CAR BLDG.
NO. OF SPRINKLERS	12 HEADS CALCULATED
BASIS OF DESIGN	ORDINARY HAZARD GROUP II
DESIGN DENSITY	.20 gpm/sq. ft.
DESIGNED AREA OF DISCHARGE	1,000 sq.ft. (Entire Area)
HOSE STREAM	250 gpm
DISCHARGE AT PUMP	235.4 gpm
RESIDUAL PRESSURE PUMP DISCHARGE	29.6 psi

MAINLINE FIRE PROTECTION
P.O. BOX 104448
JEFFERSON CITY, MO. 65110
(573) 635-6238

Fig. 3 – Fire Suppression System Data

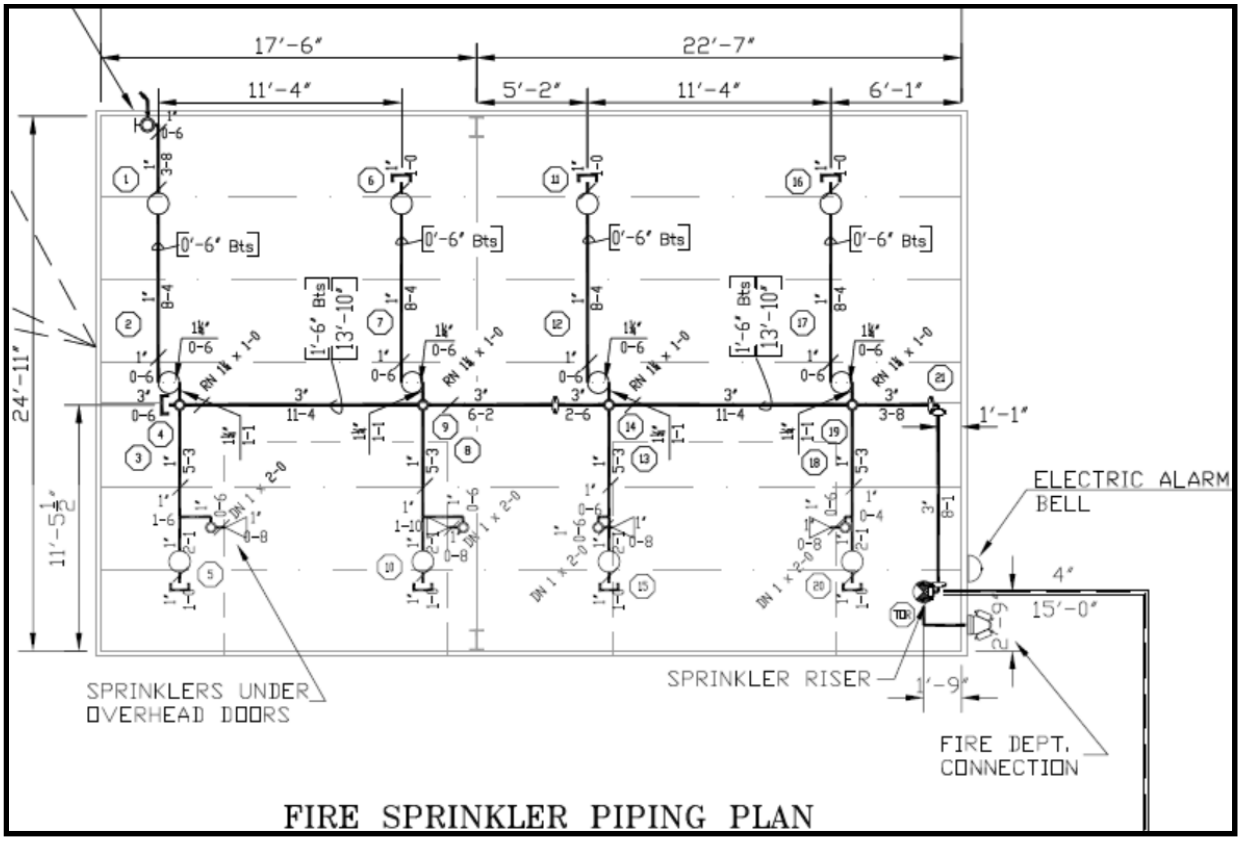

Fig. 4 – Fire Sprinkler Piping Plan for Missouri S&T EcoCAR Garage

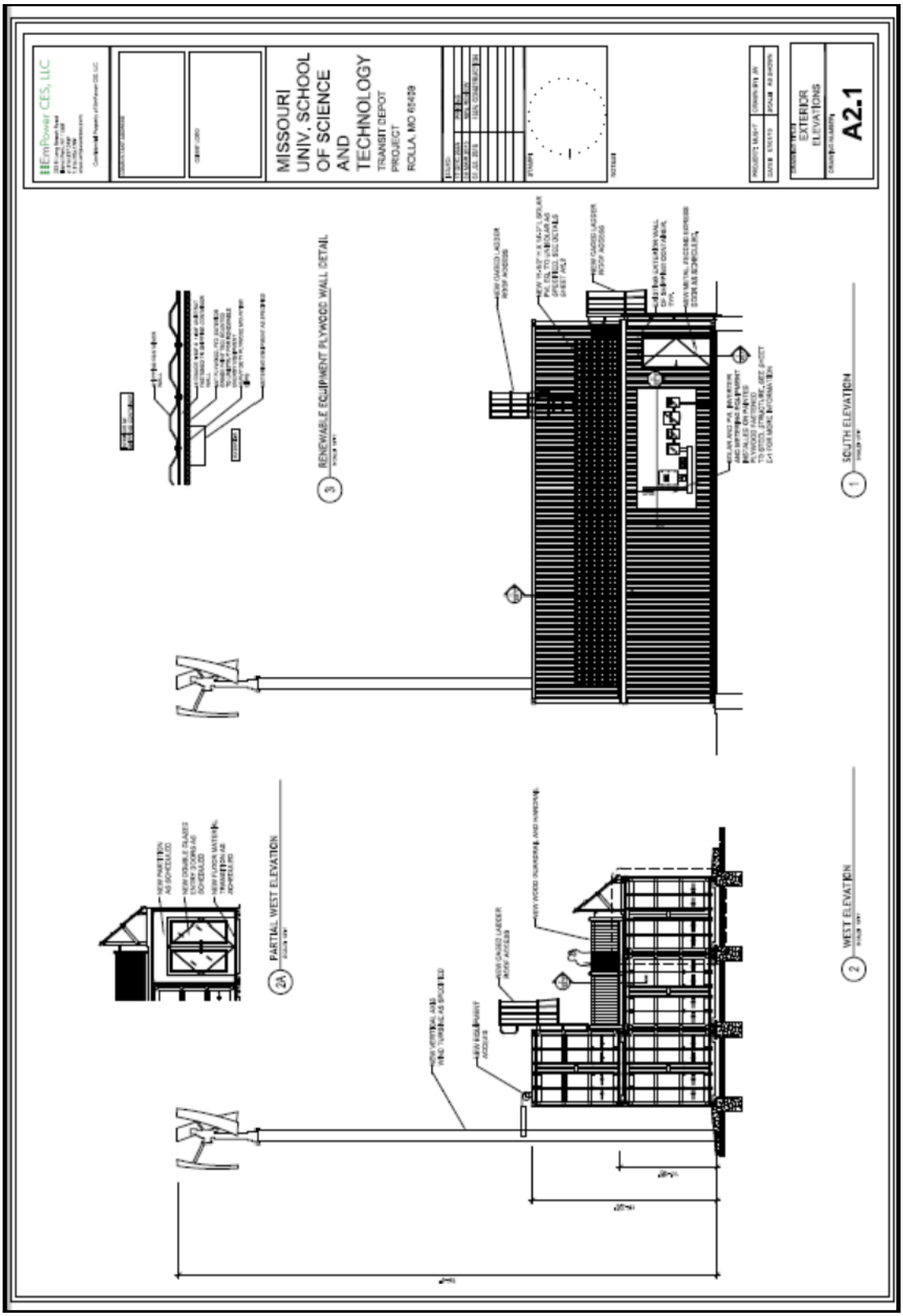

Fig. 5 – Exterior Elevations of Renewable Energy Transit Depot

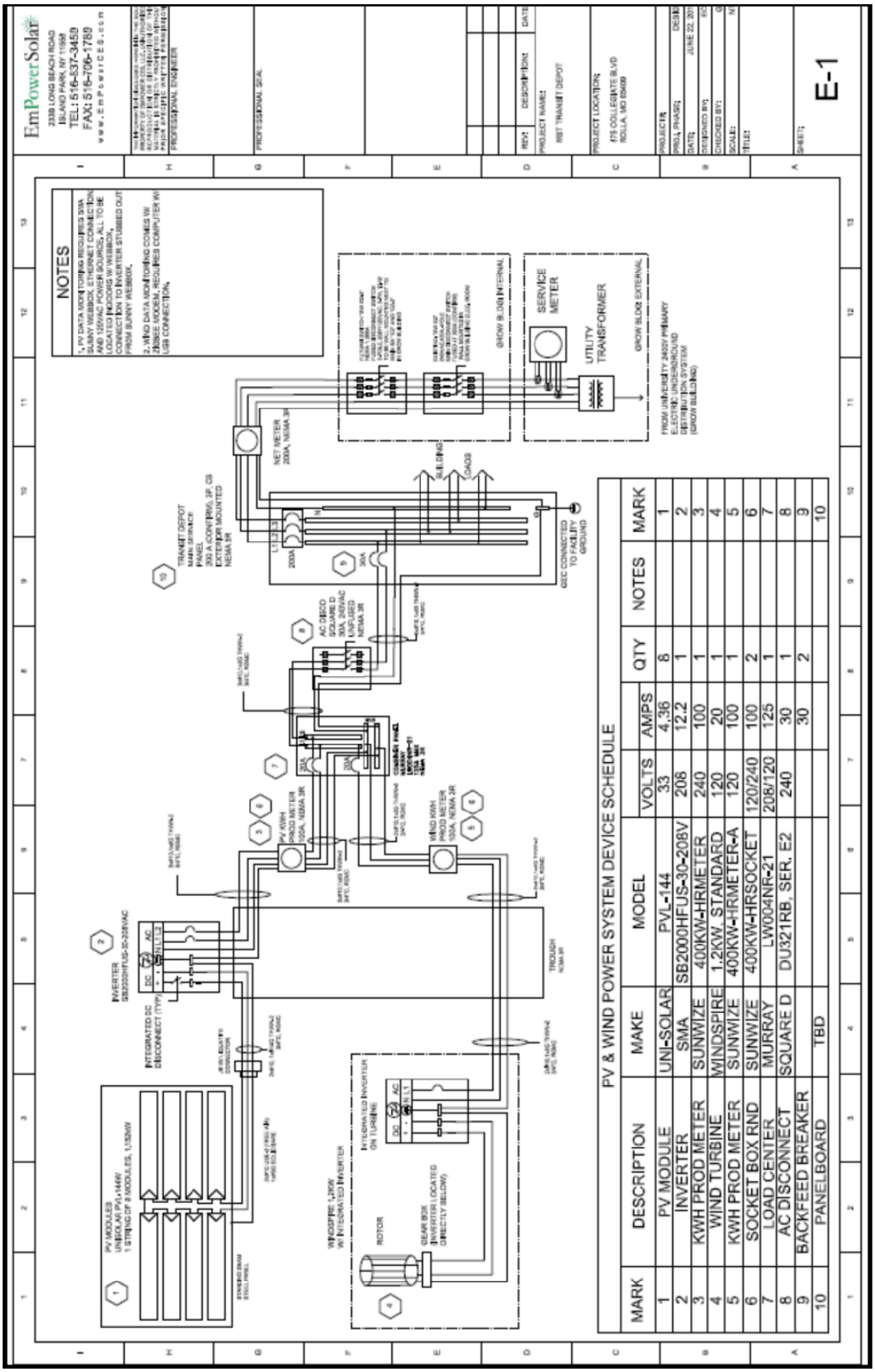

Fig. 6 – Renewable Energy Power System Drawing

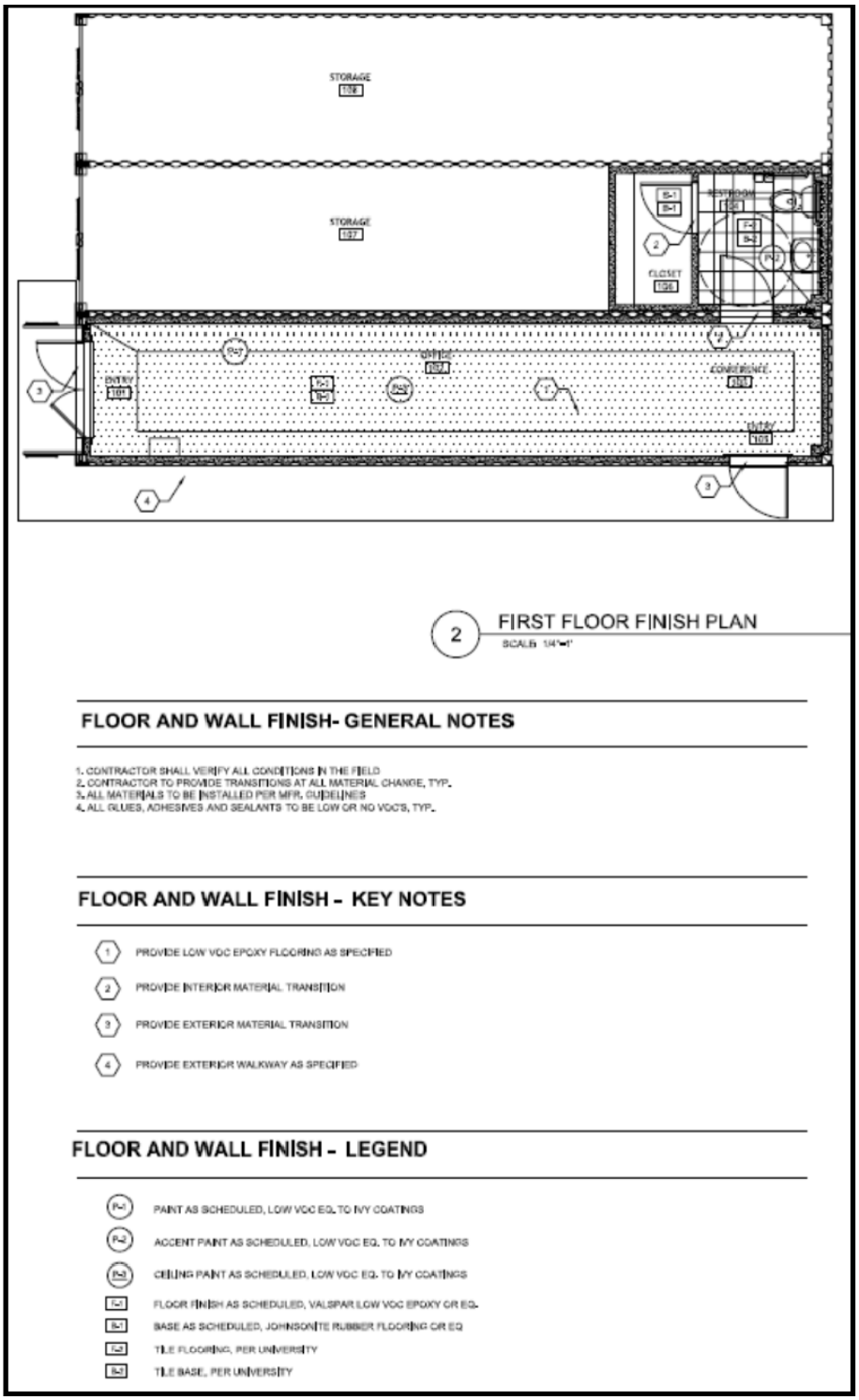

Fig. 7 – Renewable Energy Transit Depot Finish Details

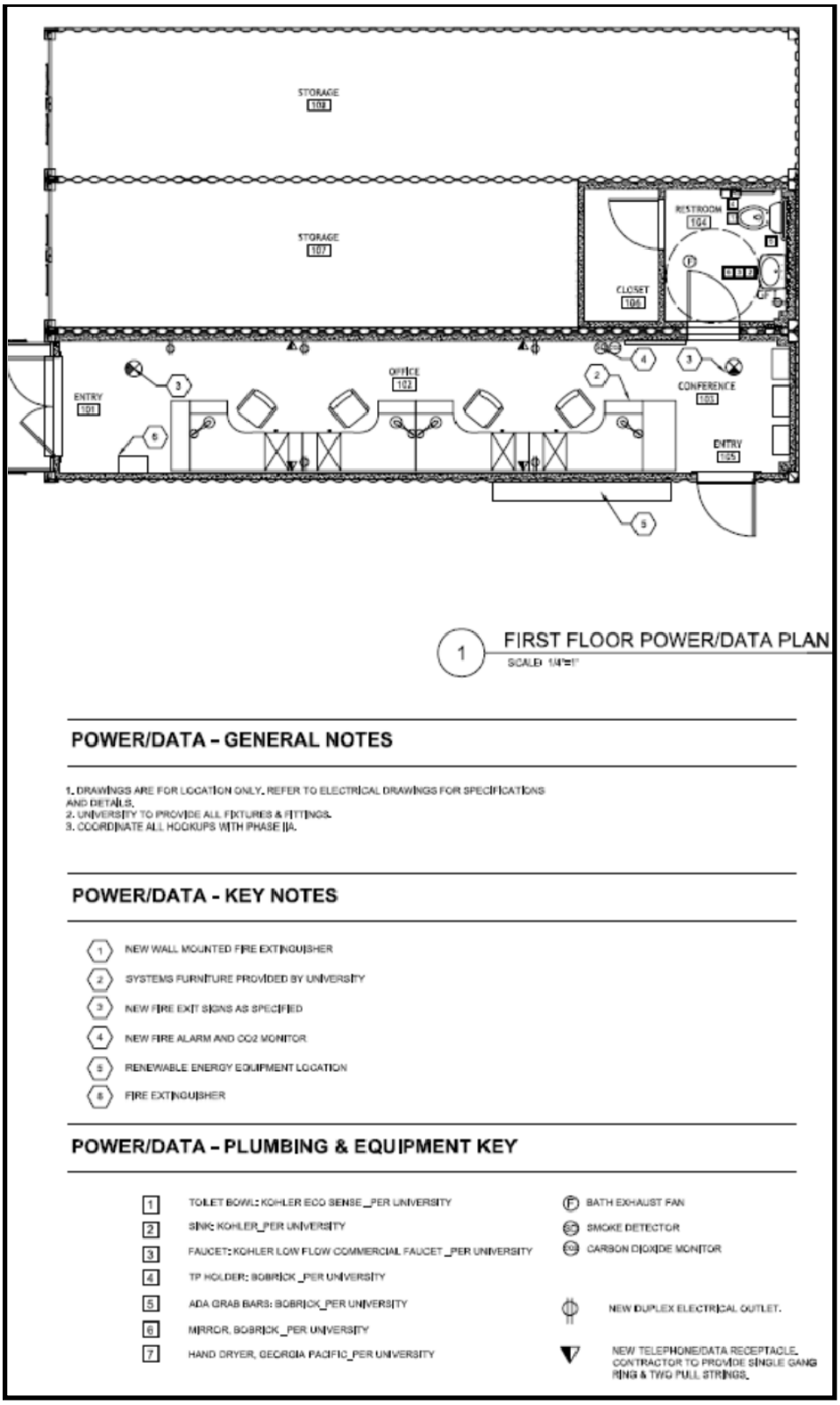

Fig. 8 – Renewable Energy Transit Depot Power Details

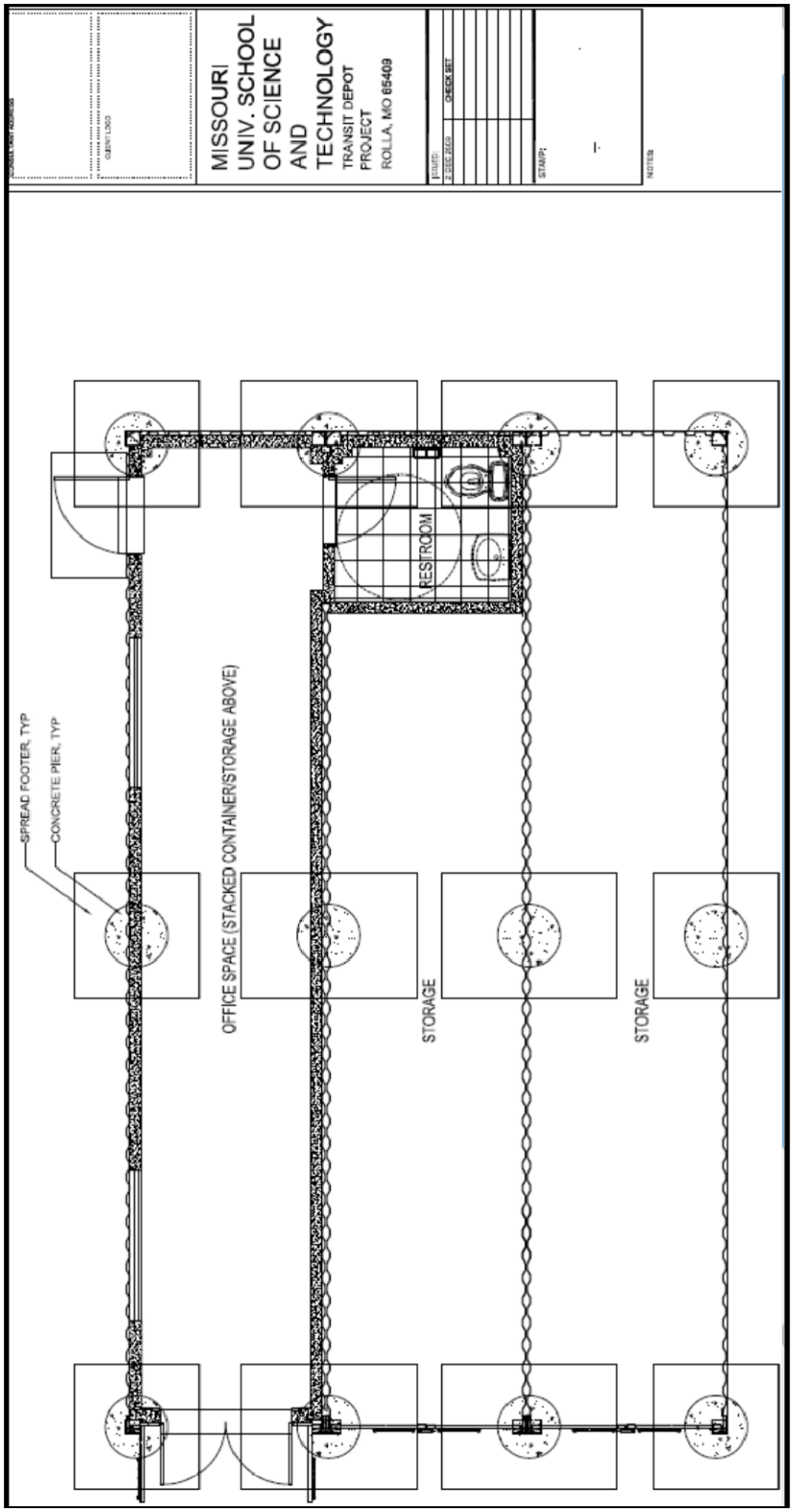

Fig. 9 – Renewable Energy Transit Depot Foundation

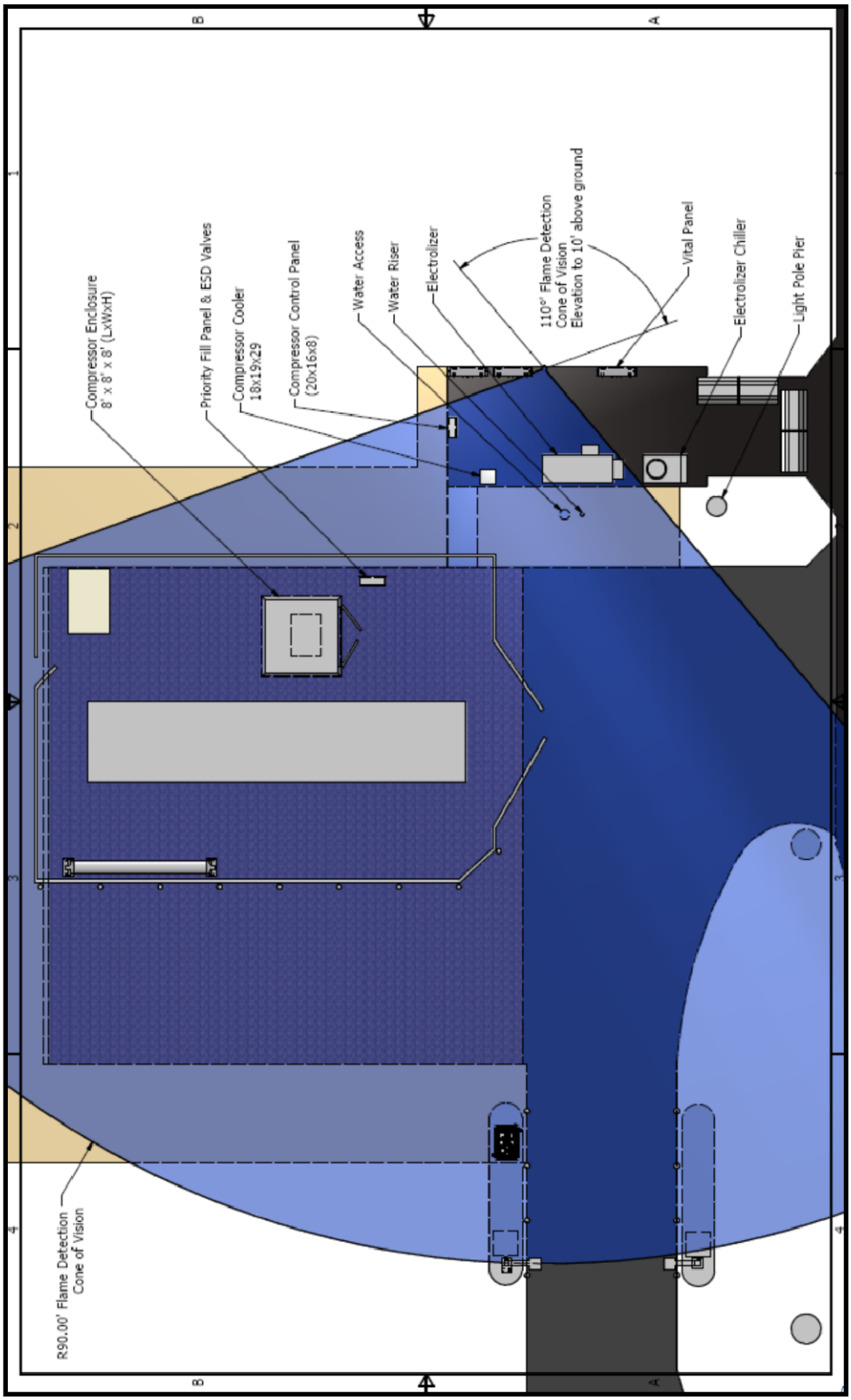

Fig. 10 – Hydrogen Fueling Station Site Plan Update

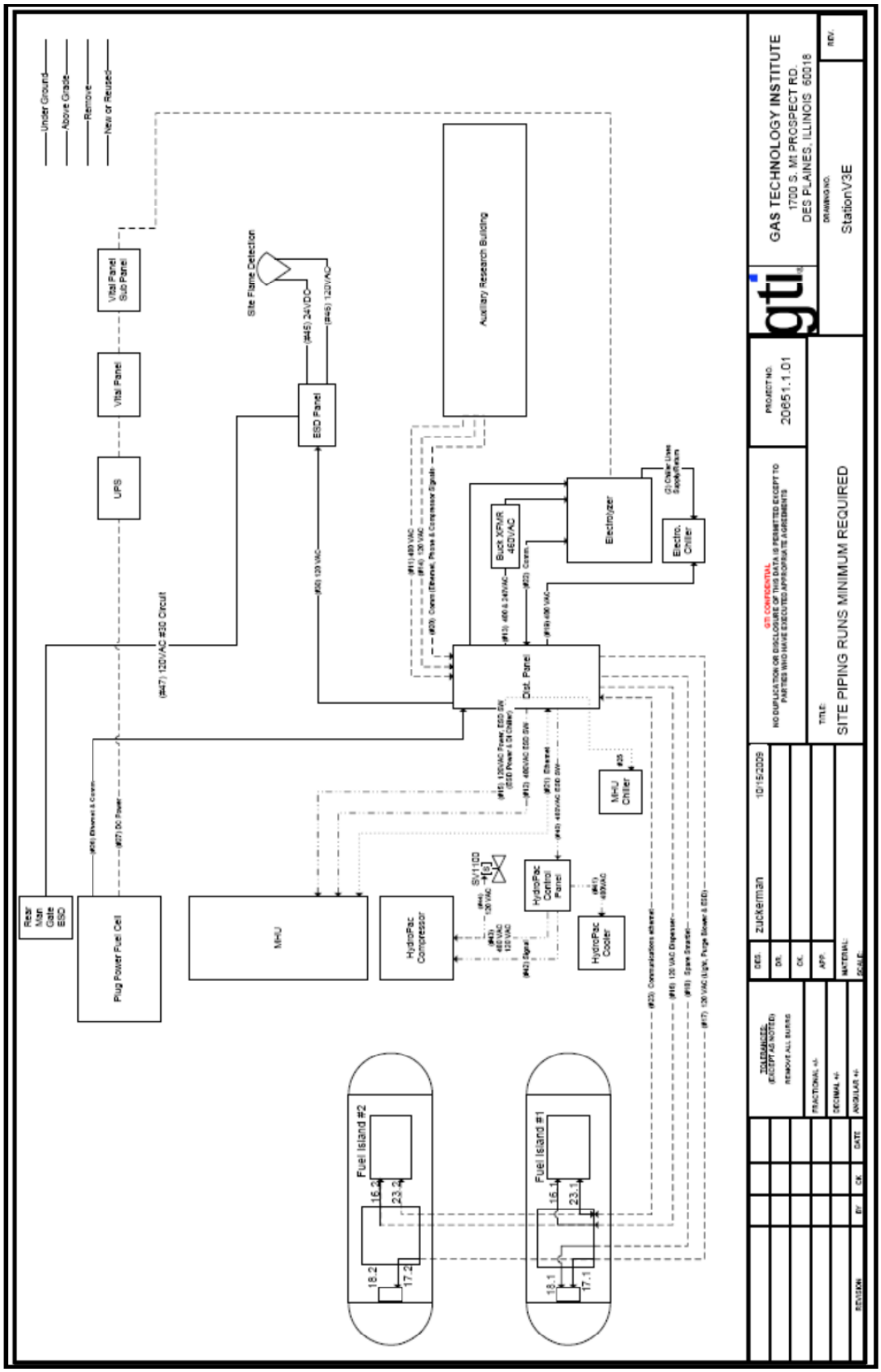

Fig. 11 – Hydrogen Fueling Station Wiring Diagram

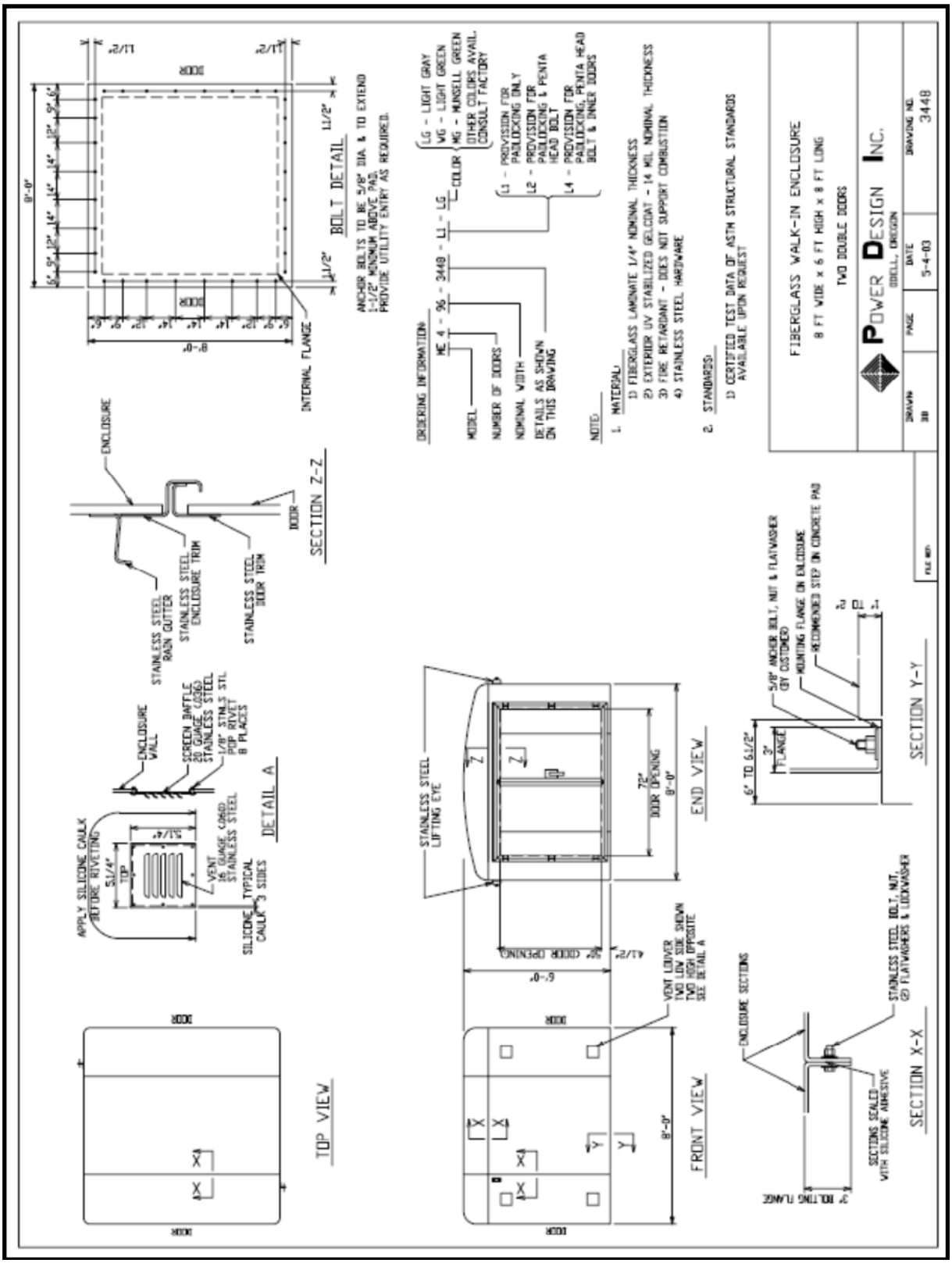

Fig. 12 – Hydrogen Fueling Station Enclosure for Hydrogen Compressor