UMTA-MA-06-0153-83-3
DOT-TSC-UMTA-83-13

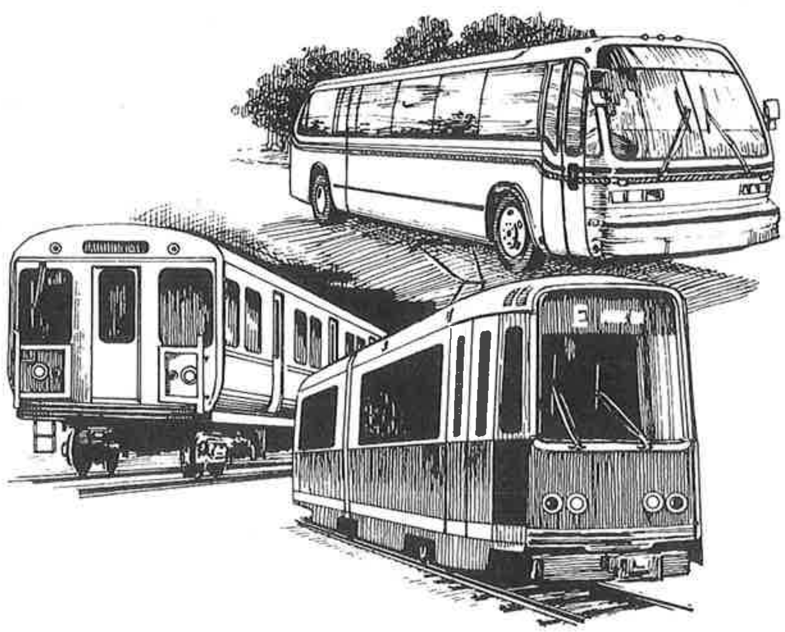
U.S. Department of Transportation

Urban Mass Transportation Administration

Study of Smoke Detection and Fire Extinguishment for Rail Transit Vehicles

IIT Research Institute
10 W. 35th Street
Chicago IL 60616

August 1983
Final Report



UMTA Technical Assistance Progra

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTA-MA-06-0153-83-3		

4. Title and Subtitle	5. Report Date
STUDY OF SMOKE DETECTION AND FIRE EXTINGUISHMENT FOR RAIL TRANSIT VEHICLES	AUGUST 1983
	6. Performing Organization Code TSC/DTS-77
7. Author's) K. Mniszewski, J. Campbell, T. Waterman, H. Wakeley	8. Performing Organization Report No. DOT-TSC-UMTA-83-13
9. Performing Organization Name and Address *IIT Research Institute 10 W. 35th Street Chicago, IL 60616	10. Work Unit No. (TRAIS) UM268/R2671 11. Contract or Grant No. DTRS-57-81-C-00124
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technical Assistance Washington DC 20590	13. Type of Report and Period Covered Final Report Nov. 1981-Nov. 1982 14. Sponsoring Agency Code URT-12

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, MA 02142

16. Abstract

This document presents the results of a study to determine the feasibility and cost effectiveness of the use of heat/smoke/fire sensors and automatic extinguishing systems in rail transit vehicles. Work presented includes: a survey of major rail transit systems to determine their fire experience, a survey of available hardware, determination of placement, review of cost effectiveness, and an outline of a testing program to validate conclusions of the study.

17. Key Words	18. Distribution Statement
Transportation Safety Fire Detectors Fire Extinguishers Fire Management Systems	DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	138	

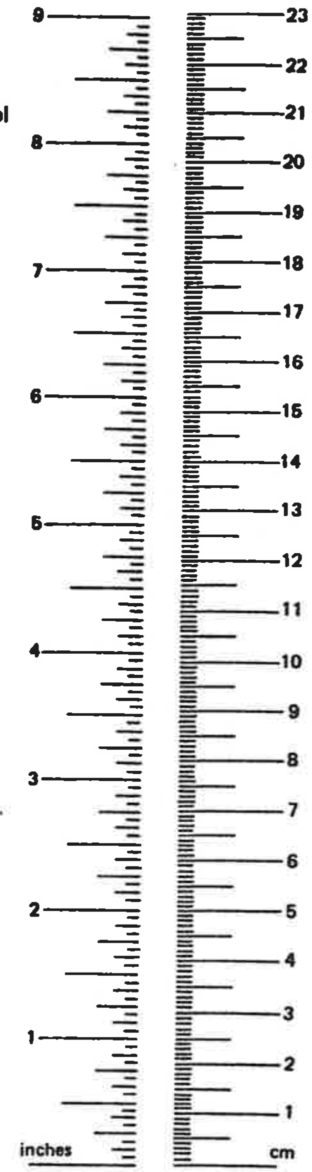
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

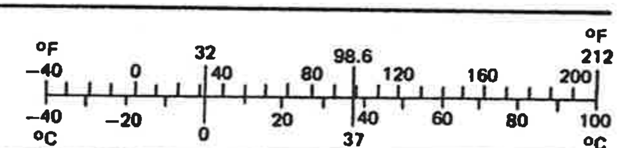


TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

LIST OF FIGURES

LIST OF FIGURES CONTINUED

LIST OF TABLES

1. INTRODUCTION

The objective of this study was to determine the feasibility of developing fire detection and suppression systems suitable for use in rail transit vehicles, and a special subclass of unmanned vehicles including automated guideway transit (AGT) systems. Very important issues in the study were:

1. an assessment of the need for fire responsive systems,
2. an imperative requirement for a negligible detector false alarm rate, and
3. a need for a safe and cost-effective suppression system.

Criteria for adequate performance were defined on the basis of rail transit property historical data, an evaluation of potential fire sources, and known operational requirements.

Scenarios representing identified independent variables in fire evaluation were used as models for the application of fire detection/suppression systems. A survey of applicable detection/suppression technology and hardware was used as the basis for describing possible state of the art systems specifically designed to meet the strict requirements of rail transit vehicle operations.

A variety of special problems addressed during the study included factors such as salt spray, de-icing fluids, trash accumulation, enclosure requirements, climate, operator behavior, and property operating policies.

A survey of properties and fire problems revealed a generally held view that very few fire fatalities occur in spite of frequent fire incidents. The possibility of catastrophic fire in which a large number of fatalities would occur persists, as evidenced by subway and tunnel fire incidents described in this report.

Trends to deferred maintenance, unmanned transit vehicles, and new materials and construction methods are increasing the possibility of catastrophic fire. There is little evidence that present approaches to managing fire would be effective under conditions less favorable to survival. A search for a mode effective fire response system is therefore a necessary step in maintaining or improving the safety of rail transit vehicle users and operators.

The feasibility study identified microprocessor controlled systems as exceptionally good prospects for reliable fire detection. The microprocessor, by using analog information for the time-series analysis of data from multiple mode detector heads, in conjunction with a fire signature algorithm, can provide fire identification with a reliability improvement that is orders of magnitude better than present systems. For suppression, Halon based systems offer significant potential for development. Some specialized applications might be able to utilize a suppression/refrigerant system which would entail minimal capital expenditure, or possibly a water spray system which possesses the advantage of being readily fabricated and installed by property maintenance personnel with existing hardware.

Preliminary criteria and designs for prototype systems are described with an outline of the testing program required for development.

2. RAIL TRANSIT VEHICLE SYSTEMS FIRE EXPERIENCE SURVEY

A survey of seven major rail transit vehicle systems in the United States and Canada was conducted to collect information on the relative occurence of fires, where and how fires occur, whether detection and extinguishing systems were installed and used, and the results of these fire incidents.

The transit systems surveyed were:

1. Washington Metropolitan Area Transit Authority (WMATA)
2. Port Authority Trans Hudson Corporation (PATH)
3. New York City Transit Authority (NYCTA)
4. Bay Area Rapid Transit District (BART)
5. Toronto Transit Commission (TTC)
6. Chicago Transit Authority (CTA)
7. West Virginia University Automated Guideway Transit System at Morgantown, WV

The amount of data obtained from each transit system varied considerably because of variations in keeping and interpreting records. None of these systems, or any other United States or Canadian rail transit vehicle system that we are aware of, has any automatic fire detection or fixed fire extinguishing systems onboard their cars. Overall, the fire experience has been comparatively good although there have been a number of incidents which represented a serious potential threat to both life and property.

2.1 WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY

WMATA is one of the newer United States rail rapid transit systems having begun subway operations in 1976. The complete system includes both underground and aboveground guideways. During rush hours, WMATA runs eight-car trains with an average passenger load of 225 per car. Evacuation drills have been conducted and have shown that it is possible to evacuate a complete train in the subway in less than 1 hour. The WMATA cars are of aluminum construction with major load bearing structural elements of steel. The car floor is a plywood-aluminum sandwich; carpeting is installed on the top and fiberglass on the bottom which is covered with a third aluminum skin. Headliners and sideliners are polyvinyl chloride and acrylic. Seats have neoprene cushions covered with PVC coated fabric. The floor construction has been estimated to have the equivalent of a 15 minute fire resistance if tested under ASTM E-119. There are no floor penetrations from the undercar and the passenger compartment except for some wire and cabling.

The cars are powered by 175 hp dc traction motors on each axle. The car equipment includes the motor control center in a metal enclosure with a fiberglass cover, the dynamic braking grid, a 5 gal. hydraulic reservoir and pumping unit which serves two cars, and electrical cables. Air conditioning units are installed in the concealed ceiling space and heat is supplied by baseboard strip heaters. None of the undercar cable is PVC insulated although the insulation is combustible.

The cars must operate in pairs; propulsion and control systems are not completely duplicated in each car. Trains normally operate in an automatic control mode with speeds up to 75 mph. The crew consists of both an operator and a conductor and the trains can be operated manually. About 90 percent of braking is dynamic; secondary braking is friction which is hydraulically actuated. A manual parking brake is also provided. The dynamic braking grid is located underneath the car and exposed to ambient cooling air. Normal operating temperatures above the grid are approximately 800°F.

WMATA has had no interior or undercar fires since they began operation. There have been two serious grid overheating incidents which produced significant smoke and melted the aluminum and fiberglass under the car. Some charing of the plywood floor also occurred. If any flaming combustion did occur, it did not propagate beyond the local area of damage. One of these incidents occurred underground but all occupants were evacuated at a station. The fire department hose stream application of water to hot grids did cause some damage as a result of cold shock. The total loss on one of these overheated grid incidents was $25,000 and on the other between $10,000 and $12,000. There have been some additional brake grid incidents with minimal consequent damage. Traction motor burnouts have also occurred, which have produced small amounts of smoke but no fires. Brake shoe hangups have also occurred that produced some smoke which was quickly detected visually. The brake shoes are located outboard of the wheel so any smoke that is produced is readily visible to passengers or the conductor. Smoke from minor electrical overheating or brake hangup is not considered a fire by WMATA and the fire department is not called.

Some of the overheated grid incidents were caused by welding of contacts in the motor control center which caused the car to go into dynamic braking when the rest of the train was under traction. The estimated time between the electrical malfunction and detection was about 5 minutes. The first detection is usually by the train operator who feels a sluggish operating condition. This may be the result of the dynamic braking being on, a brake shoe hangup, or propulsion motor control center problems. Each car has its own circuit breaker so the operator can electrically disconnect it from the system. WMATA has now installed a circuit breaker system which is intended to open if the dynamic braking for a car goes on when the rest of the train is under power.

WMATA does not believe they have any need for any interior or undercar automatic fire detection; human detection systems have worked quite well in all incidents. They are considering installation of heat detectors above the dynamic braking grids to provide early warning of malfunction and overheating.

2.2 PORT AUTHORITY TRANS HUDSON SYSTEM

The Port Authority of New York and New Jersey operates the PATH rail transit vehicle system which includes both underground and aboveground guideway. The system uses two types of cars, one of which is about 24 years old and currently being phased out. This type, which is referred to as the K car, is of steel construction with fiberglass and steel interiors. The seats have neoprene cushions with vinyl covering. The newer type of car, referred to as the PA car, is of aluminum frame and skin construction. The interior is essentially fiberglass and the seats have latex foam cushions and a fire resistive covering. These cellular foam seat cushions are being replaced with a formed fiberglass insert which has a low flamespread and low smoke emission. This replacement is expected to be completed by June 1982.

The floor construction on the PA car is plywood in an aluminum pan; the top is surfaced with rubber tiles and the bottom with a sprayed-on fire retardant urethane insulation.

The PATH system operates on 650 volts dc power. All undercarriage equipment is enclosed in metal compartments and the wiring and cable is in conduit. The resistance grid is enclosed in a cage that physically shields it from the track. A wayside grease with a flashpoint of 370°F is used to reduce friction and noise on curves. This grease does accumulate on the undercarriage but has created no fire problem.

The PATH system had not had any major fire incident up to time of the survey. In the past, arcing on older style current collectors which were fastened by a wood block had ignited the wood. However, fire did not propagate from the wood block. This wood block has been replaced with a new material and the problem eliminated. Traction motors have burned out producing some smoke but no fire propagation. One PATH car did have a battery fire but it was confined within the metal battery compartment.

PATH did not feel that they had any serious fire problems in the car interiors now that the new seats are being installed. All of the materials have been tested and are believed resistant to ignition sources of the level likely to be encountered by the car. Since there has not been a major loss due to an undercarriage fire, PATH does not believe that any detection or suppression is necessary in that location. Enclosing the equipment in metal compartments has been very effective in confining the few fires that have occurred to the point of origin.

Since the PATH survey was completed, a PA car fire involving 400 commuter passengers did occur in the Hudson River tunnel. The New York Times, 17 March 1982, reported that an electrical fire in the undercarriage of the train's middle car brought the train to a halt about 1000 feet west of the first stop in Manhattan at Christopher Street and about one car length from an emergency kiosk exit. Power to the system was turned off and 30 pieces of fire quipment sent to the emergency exit kiosk on West Street south of Morton Street. Firefighters entered the tunnel through the kiosk after passengers were evacuated. The fire was declared under control 2 hours after it started. The train was backed through the tunnel to the New Jersey side for repairs. Eighty four passengers were treated for smoke inhalation and released, and 19 admitted to the hospital for observation. No serious injuries were reported. Uptown service was disrupted for 6 1/2 hours. Newspaper accounts of the fire are presented in Appendix C.

An informal description of the fire indicated that initiation began in undercar cables and progressed to within an enclosed motor controller box. The fire penetrated the floor of the car but did not burn within the car. Aluminum exterior structure was melted. The electrical equipment was valued at $80,000 with an additional $240,000 to the car shell and components. A complicating factor in smoke involvement was a lack of tunnel ventilation.

2.3 NEW YORK CITY TRANSIT AUTHORITY

The NYCTA operates the largest rail transit vehicle system in the country; it has approximately 6400 cars which run over 232 miles of guideway both underground and above ground. The majority of the guideway is underground.

Cars are of steel construction with fiberglass end caps on the front and rear. The floor is plywood with a stainless steel top covered by a vinyl asbestos tile. Four inches of fiberglass insulation covered by stainless steel is installed on the bottom of the plywood floor. The interior sidewall and headliners are of polycarbonate plastic. The seats are molded fiberglass on metal frame without any cushions. An electric closet and chase are located at the front and rear of each car to bring cables and wire up from the underside to circuit breakers within the closet and also to supply power to equipment in the ceiling space above the headliner.

The traction motors operate on 600 volts dc. All electrical cables under the cars are in conduit. The motor control centers are in metal enclosures. Many of these have a fiberglass top which is combustible. One car in each paired car set has batteries located in a steel compartment with a plastic top.

NYCTA has had interior car fires typically caused by spilling of fire accelerant on the seats and floor. Fire damage has been localized to the area of the spill and has not propagated beyond. In addition, there have been a number of fires of electrical origin in the closet/chase located at each end of the car. These fires have spread in the chase and some have burned through the fiberglass ends caps without any further spread. There were three major fires which originated in the electrical closets while the cars were stored in the yards; one of these caused approximately $100,000 loss.

Most undercar fires have started in the motor control center although there have been some which originated at current collectors and resistance grids. Occasionally, wayside trash picked up and collected on the grid ignites. These fires are relatively minor. In one incident, an overheated grid is believed to have caused the ignition of a wayside station. These grids can run "white" hot, if overheated, without causing any damage to the grid itself. A study by the National Transportation Safety Board [1], indicated that there were 66 heavy burnups NYCTA undercar equipment in 1979 and 1980; 51 of these involved motor control centers. The National Transportation Safety Board also conducted detailed investigations of eight serious fires which occurred in a 13 month period. These fires injured 53 people and did over $500,000 in property damage. Two of these eight fires penetrated the car floor. NYCTA indicates that on the average the car floor is penetrated about twice a year by undercar fires. Another serious cause of fires is grounding of current collectors against the car frame.

Although NYCTA has had a number of fires which originated inside the cars, they do not feel any fire detection system is necessary. They do believe that a fire detection system would be of considerable value for protecting the electrical closet/chases located at each end of the car and the undercar equipment. Automatic fire suppression would also be desirable to protect specific locations such as the electrical closets and motor control centers, both of which have been involved in serious fire losses.

2.4 BAY AREA RAPID TRANSIT DISTRICT

BART was the first of the modern United States rail transit vehicle systems; it operates over 75 miles of track about one-fourth of which is underground, including the long tube underneath San Francisco Bay. The car interior sidewalls and headliners are constructed of a fiberglass reinforced polyester resin. The lower sidewall serves as a plenum for heated and cooled air. The seats are neoprene cushioned which recently replaced foam polyurethane cushion seats because of adverse fire experience. The floor is covered with carpeting which includes a sound deadening pad.

The floor construction is a polyurethane foam core sandwiched between aluminum sheets. The traction motors operate on 1000 volts dc. All operating and environmental control equipment is located underneath the car. Most wires and cables are run exposed, attached to the underfloor car beam.

BART has had a number of serious fires which did heavy damage or destroyed the interior of cars. The worst incident was the January 1979 fire which occurred underneath the San Francisco Bay; an Oakland fire department lieutenant was killed and 40 other firefighters and passengers injured.

---

[1] "Safety Effectiveness Evaluation of Rail Rapid Transit Safety" (Report No. NTSB-SEE-81-1, Jan. 22, 1981). National Transportation Safety Board, Bureau of Accident Investigation, Washington, DC 20594

Prior to that, serious fires had been recorded in 1974 and 1976. In 1974, a locked brake initiated an underfloor fire which penetrated into the passenger compartment. The car was totally involved on arrival of the fire department. The 1976 fire was of incendiary origin and did heavy damage inside the car. Another major fire occurred in December 1979 which also did very severe damage to the car interior. Intermittent arcing from an unknown cause ignited the evaporator box for the heating, ventilating, air conditioning system which is located underneath the car. Fire spread through the sidewall skirt into the car. Flames then spread through the air ducts and penetrated the sidewall and floor of the car.

Most other incidents are categorized as "smokers" since no actual flaming was observed. There were 66 such incidents recorded for 1980, 37 of these being from overheated brakes. The most common causes of interior car fire/smoke incidents were carelessly discarded smoking materials and arson. There were several incidents of carelessly discarded cigarettes entering the return air filter.

In the 1979 to 1981 period, 12 incendiary fires were reported on the BART system. One BART fire incident illustrated a possible disadvantage of the use of multipurpose dry chemical extinguishers on fires near hot brake grids. Wayside debris had apparently become lodged in a brake grid and ignited; it was extinguished by the train crew using the onboard multipurpose dry chemical extinguisher. The residual hard and sticky coating left by this agent partially shorted the grid. Steam cleaning failed to remove the material and the grid had to be removed from the car.

As a result of the adverse fire experience, particularly in 1979, BART had an extensive study performed to investgate the feasibility of fire detection and suppression systems on the new "C" cars. The conclusion was that the false alarm and failure rate of any detection system would be intolerable.

2.5 TORONTO TRANSIT COMMISSION

The TTC rail transit vehicle system which opened in 1954 operates over 27 miles of track, most of which is underground. The transit cars are of aluminum tube and frame construction mounted on a steel structural subframe. Sidewalls and headliners are ureaformaldehyde laminate. Seat cushions are neoprene, which replaced the original foam rubber cushions after some adverse fire experience. The floor is sheet steel with a plywood deck covered with a rubber flooring material. Traction motors are powered by 600 volt dc power which also drives a motor alternator supplying 520 volt, 400 Hz power for fluorescent lighting. Heat for the cars is provided by air blown over the dynamic brake resistors and ducted into the car through diffusers which penetrate the car floor. Cooling is supplied by axle driven roof mounted fans.

The TTC has had two major fires which destroyed a total of 11 cars. The first, in 1964, originated in the undercarriage. A decision to move the car away from the station and delayed fire department notification contributed to the loss of all cars of the eight-car train even though the initial fire development was relatively slow.

An incendiary fire in 1976 destroyed three cars, damaged three others, and resulted in a total property loss of 2½ million dollars. Foam rubber seat cushions which were used at that time were identified as contributing to the very rapid fire development and the dense smoke that was produced. Fortunately, in the 1964 fire, all passengers were evacuated early before the train was moved away from the station. The 1976 fire occurred shortly before 2 a.m., so the train had very few passengers; all escaped, although heat and heavy smoke made it difficult.

With the exceptions described, the TTC has had very few car fires of any significance, except for two electrically caused control panel fires while the cars were parked in the yards. The losses were $7500 and $25,000.

Traction motors and other electrical malfunctions were the most common source of smoke incidents, generally with no active flaming noted. It is estimated that TTC has approximately 20 to 30 such incidents a year. In addition, there have been a few arson attempts on cars which self-extinguished. The TTC believes that the installation of neoprene seat cushioning has paid for itself as a result of these arson failures. One potentially serious incident was averted when a motorist who had run out of gas was prevented from boarding a train while carrying a bucket of gasoline.

TTC does not believe automatic fire detection is necessary. Except for the one incendiary fire, they believe all fires were detected in time and that failure to follow procedures was responsible for the eight-car train loss. TTC will be looking at automatic detection and/or extinguishment on an extension which is being built. Operation of this extension will be similar to that for an automatic guideway transit system although a vehicle operator will be on board.

2.6 CHICAGO TRANSIT AUTHORITY

The CTA rail transit vehicles operate over about 90 miles of right-of-way of which only about 10 miles are underground. The cars have an austere interior finish compared to many modern transit systems. Sidewalls and headliners are plastic or metal; seats are steel frame with molded fiberglass inserts or vinyl covered very thin padding.

The cars are steel shell and frame construction and the floors are stainless steel clad wood. Traction power is 600 volts dc. The dynamic braking is supplemented by hydraulically actuated friction brakes.

The CTA has not had a serious car fire since they discontinued the use of wooden cars in the mid 1950s. A number of cars have been destroyed by fires which spread from the combustible elevated guideway, however.

Only 17 smoke/fire incidents occurred in 1981. A few of these resulted in passenger evacuations, all of which were implemented without difficulty. All evacuations occurred above grade. Common causes were electrical malfunctions such as grounded current collectors or collector cables and miscellaneous electrical faults. The CTA has not had any serious problem with attempts at incendiary fires inside their cars.

In one fire incident, which occurred during this project period and was observed by project personnel, the fire produced a considerable amount of flames, approximately 3 to 4 feet long underneath the car while it was moving along an elevated guideway. The flaming ceased after the train had stopped, although light smoke persisted until the train continued on, when it dissipated.

One fire of small significance occurred approximately 3 years ago. A train was operating in the subway when fire was detected. The train stopped with the head end car approximately 20 feet from the tunnel portal. All occupants were evacuated without difficulty. The fire did produce considerable smoke in the subway from a civilian viewpoint, although not sufficient to impede fire department operations. The fire did not penetrate the floor. In fact, the fire department had to cut a hole in the floor in order to complete their extinguishment.

Based on their fire experience, the CTA does not believe there is need for fire detection or suppression systems in their cars. None of the incidents in recent years produced self-propagating fires inside or underneath any vehicles. It is likely that many incidents, like the fire recently observed by project personnel, were self-extinguishing.

2.7 WEST VIRGINIA UNIVERSITY - MORGANTOWN PEOPLE MOVER

The West Virginia University - Morgantown People Mover is an automatic guideway transit system which serves the 19,000 students and 7500 employees of the University as well as local residents. This also serves as a National Transportation Research Laboratory for this new form of public transportation. The system operates over 8.7 miles of single-lane guideway with 73 automated guideway transit vehicles. Control is completely automatic; there are no operators aboard the vehicles. The cars ride on rubber tires over a concrete and steel elevated guideway. Each car has a capacity of eight seated and 12 standing passengers. The cars are of steel frame construction with fiberglass reinforced laminate shells that are bolted to the frame. Power to the cars is supplied at 570 volts ac three-phase through a third rail system. It is rectified onboard to 470 volts dc to drive the traction motors. The only fires that have occurred on the entire system have involved a cover over the third rail; the cover did not present either a smoke or fire problem. No attempts at incendiary fires have occurred. West Virginia University officials do not believe that there is any need for onboard fire detection or suppression in these automated transit vehicles.

2.8 ANALYSIS OF SURVEY RESULTS

The majority opinion of rail transit vehicle operators was that there was no need for any automatic fire detection and suppression system aboard their transit cars. Operators who felt that detection and/or suppression was desirable had recent adverse fire experience. Operators who had not experienced any serious fires or felt the cause had been corrected did not feel that there was any need for detection and/or suppression.

One rail transit vehicle operator did engage a consultant to study the feasibility of installing automatic fire detection and suppression on some new cars. The consultant's conclusion was that the false alarm or failure rate of either heat or smoke detection systems would be intolerable and would seriously disrupt transit operations. This conclusion may be correct for presently available fire detection systems. The possibility of onboard fire detection and/or suppression has been and is currently being considered in rapid transit systems under construction, although no built-in protection is to be installed in any new cars at this time.

The only transit fires which could be identified as presenting a serious threat to human life were those that occurred underground where smoke and fire were confined in a limited area. In those incidents in which a lethal environment was actually produced, the burning of either polyurethane or latex foam seat cushions was directly responsible for the lethality of the fire environment. However, some serious smoke conditions have been produced without involvement of any seating material.

A contributing factor to the seriousness of one fire was the rupture of a compressed air line underneath the car. Air from the line fanned a relatively small fire, causing it to develop and spread quite quickly. Another fire scenario involved an electrical fault occurring in the operator or control panel of a car, with the fire spreading to cables running through a chase or compartment behind this panel. In each scenario noted, the fire occurred when the train was parked in the yards, not during operation. However, it should not be assumed that such a fire could not happen in the car during normal train operation. Such a fire scenario would be particularly significant in some of the new cars which are constructed to have cooling air from cable chases routed into the passenger air supply plenum.

The quantitative value of the data obtained in this survey is questionable, both because of the various ways in which incidents are documented by transit systems and because some transit systems consider detailed incident data to be proprietary. A reliable incident 'frequency of occurrence' and 'cause' distribution could not be developed. Some transit systems consider smoke and fire incidents as merely an unusual occurrence unless significant flaming was observed or damage resulted. These data cannot be readily retrieved without a laborious manual search of unusual occurrence or other files. In addition, some transit systems do not consider minor smoke producing incidents to be a potential fire or unusual occurrence. This is technically correct. Many electrical faults and failures will produce smoke even though there is no possibility of fire developing. However, there are other electrical problems which will produce smoke and may devleop into fire depending on the manner in which failures occur.

This survey of transit experience and other published information was used to identify 18 common fire scenarios which are identified in Table 2-1. As would be expected, the majority of fire scenarios originated underneath the car and were of electrical origin. Considerable variation in fire experience exists among transit system operators and over time. Many incidents are the result of inadequate maintenance, deficient design or construction, or component wearout. Frequently, if a fire scenario causes a serious loss or threat of a serious loss, some corrective action is taken by the operator such as replacement or modification of seat cushions, or circuit breaker changes. This particular fire scenario threat is then considered corrected.

Survey information and other reports indicate that most electrical fires were preceded for at least several minutes by abnormal current or voltage conditions. This is typical for most electrical fires except those caused by a massive short which can develop with explosive violence. Even in transit car fires caused by grounded current collectors or shunts, the initial grounding contact may not be sufficiently substantial and continuous to cause a massive short.

Incendiary fires in transit cars with latex foam or polyurethane foam seats may develop beyond control in 2 minutes and to flashover in 5 minutes or less. Fortunately, incendiary fires typically only occur when trains are almost empty; this reduces the risk to passengers and facilitates evacuation. No propagating incendiary fires were reported with neoprene or fiberglass seats. However, if an arsonist uses a sufficiently potent ignition source, fire propagation can occur. The seats, sidewalls, and headliners are all combustible, but fire retardant.

2.9 SURVEY ADDENDUM

During the preparation of this report, two particular significant rail transit vehicle fires were reported in the press.

A fire in the Hamburg-Altona Germany subway, set in a passenger compartment by vandals, could have been extremely serious if the train had been emergency stopped between stations.

An undercar fire in a NY PATH train in the Hudson River tunnel exposed several hundred passengers to a very hazardous situation.

The press reports of the two incidents are presented in Appendix C.

Since preparation of this report, several undercar fires have occurred on CTA vehicles. Three of these fires occurred while the trains were in the vicinity of the 35th Street station. Photographs taken by project personnel are presented in Appendix C to illustrate present problems and suppression response.

TABLE 2-1. TYPICAL RAIL TRANSIT VEHICLE FIRE SCENARIOS

NO.	CAUSE & ORIGIN	MATERIAL FIRST IGNITED	FIRE DEVELOPMENT & SPREAD	REF.
1	Incendiary, inside passenger compartment	Paper, trash or carried-on flammable liquid	Seat cushions ignited, spread to sidewall and headliner; seat to seat spread and flashover then follow	1,2
2	Electrical fault in cable running in duct inside car	Insulation	Sidewall and nearby seats	6
3	High resistance fault in electrical heater connection	Plastic heating duct	Plastic heating duct	
4	Insulator breaks allowing electrical heating element to contact bottom of case	Plastic duct	Sidewall, headliner and seats	6
	Electrical fault and arcing at ceiling light assembly	Plastic enclosure and diffuser	Headliner around light	1
5	Trash blown into dynamic brake grid; reduces heat dissipation, causes temperature increase	Trash	None, although additional overheating and ignition of floor would be possible in some cars	3
6	Oily dirt accumulates on dynamic motor grid, reduces heat dissipation and causes temperature rise	Cable insulation	Wooden car underfloor	1
7	Electrical fault in Motor Control Center	Wire insulation	Plastic components air bays, underfloor penetrated and spread into car interior; ruptured air line fans underfloor fire and accelerates development	4,1
8	Break or failure in current collector causes arcing and electrical flashover	Wood or plastic current collector parts or shunt insulation	Insulation, rubber air bags, cables and truck side frame burned	4
9	Impact with damaged 3rd rail brackets breaks collector shoe - arcing undercar	Air suspension bags or electrical insulation	Floor penetrated; spread to car interior and from car to car	5
10	Inadequate lubrication causes overheating of motor	Residual lubrication and cable insulation	Wood underfloor burns through; seats, sidewall and headlines burned near penetration	1
11a	Defective logic circuit board causes brake application on one truck	Leaking brake fluid and wood insulation blocks on on collector shoes	Air bays, cable insulation plastic enclosures, and air ducts; penetrates floor, local seats & sidewall burned	1
11b	Defective logic circuit board causes brake application on one truck	Heat vaporizes aluminum underfloor cover and ignites polyurethane core	Penetrates floor and ignites seats, sidewall and headliner	1
12	Handbrake not faully released, friction overheats brakes	Drive shaft lubrication	Oily dirt around traction motor	1
13	High resistance fault heats interior of switchbox	Cable insulation inside switch box		1
14	High resistance fault at battery terminal causes excessive heating	Battery cable insulation	Battery case	1
15	Foreign metallic object lodges under car and shorts starting resistor	Aluminum underfloor sheet melted and polyurethane core ignited	Floor penetrated, seats, headliner and sidewalls ignited; undercar spread to cables, hydraulics & enclosures	1
16	Compressor motor overheats due to inadequate lubrication	Insulation and paint decompose; flaming not specified	Scorched rubber mat inside passenger compartment	1
17	Journal bearing overheats due to inadequate lubrication	Residual lubrication and waste	None	1
18	Electrical fault in operator panel/cable chase	Wire insulator	Wire and cables, switch, breakers and fiberglass car caps	

3. FIRE DETECTION

Fire detection is the weakest link of the detect-alarm-extinguish chain. Numerous reasons for this exist. First, historical real fire data on detector performance are poorly documented, a fact often due to poor identification of detector type, sensitivity setting, and area coverage. Until recently, the majority of non thermal slow response detectors were of low reliability and were often incorrectly installed and improperly introduced into the detect-alarm-extinguish chain.

In addition, while suppression agents and techniques usually lend themselves to laboratory quantification, detectors and detection systems are difficult to fully evaluate since there is not a readily specified description of the required performance. Fire detector design often requires a tradeoff between success in detecting fires and minimizing false alarms. Thus, a more sensitive detector may not be a better detector in the end use.

Difficulty in characterizing detector parameters is evidenced by the differing treatments accorded to detection and suppression systems by nuclear, insurance, and regulatory agencies.

Detection system requirements consist largely of reference to standards and test procedures. The referenced items provide little quantitative information for use in evaluating the suitability of generic detector types. Guidance is limited to offering a means of relative ranking for detectors of a given type. Test procedures are not correlated between detector types, thus making the selection of a detector type difficult.

In contrast, specific codes and standards for suppression system selection, design, and installation are recommended for specific applications.

3.1 HEAT DETECTORS

Until recently, most fire detectors were "heat" detectors. These operate at a selected sensor temperature (fixed temperature detectors) or rate of change in temperature (rate of temperature rise detectors). Fixed temperature detectors employ either eutectic metals (which melt to open a circuit or release a spring) or a variety of temperature sensing techniques such as:

1. bimetallic strips (bend or "snap"),
2. thermocouples or thermistors (voltage/current),

3. expanding liquids or gases (pressure), or

4. synthetic fibers (melt or stretch).

Certain of these devices return to their original condition (self-restoring action) upon cooling. Others are "one shot" devices that must be replaced after actuation.

While often thought of as "spot" detectors (monitor conditions at one point in space), heat detectors are also available as "line" detectors. As their name implies, line detectors can monitor an increase in temperature anywhere along their length. Common line detectors are:

1. pneumatic (tubing filled with expanding liquid or gas),
2. capacitive (heat causes reversible change in capacitance between parallel conductors), and
3. "twin wire" (heat causes irreversible change in resistance, inductance or capacitance)

Rate of rise detectors also employ various sensing techniques. One method is to contain gas in a closed chamber with a prescribed leak. Rapid heating causes a pressure rise since the gas expansion rate exceeds the design leak rate. The differential expansion due to unequal heating rates of two similar elements having different configurations or insulation can also be used to indicate an excessive "rate of rise" by closing a set of contacts.

Rate compensation detectors are designed to actuate either at a prescribed temperature, or sooner if the upward rate of temperature rise is rapid. This can be achieved by differential expansion of two elements, where the elements are of materials with different coefficients of expansion. Heated very slowly so that temperature rise is quite uniform on both elements, contact closure at the desired temperature occurs due to the difference in expansion coefficients. When temperatures rise rapidly, insulation or configuration can influence more rapid heating of the element having the higher expansion coefficient, causing contact closure at a lower net temperature of the hot gases.

The role of heat detectors in a protection system is best suited to suppression actuation. They do not perform well as early warning devices for most applications.

3.2 SMOKE DETECTORS

3.2.1 Projected Beam Detectors

The term "smoke detector" is applied to all detectors sensing the presence of fine particles (smoke) in the air to indicate the presence of fire. The oldest of these is the projected beam detector.

The projected beam detector senses smoke by a reduction in signal from a photoelectric cell. The changes are caused by smoke obscuring a collimated light beam (see Figure 3-1). This obstruction is a combination of absorption and scattering. While not a popular residential smoke detector, the projected beam smoke detector has commercial/industrial applications and serves as a reference tool in smoke detector tests and various other aspects of fire research.

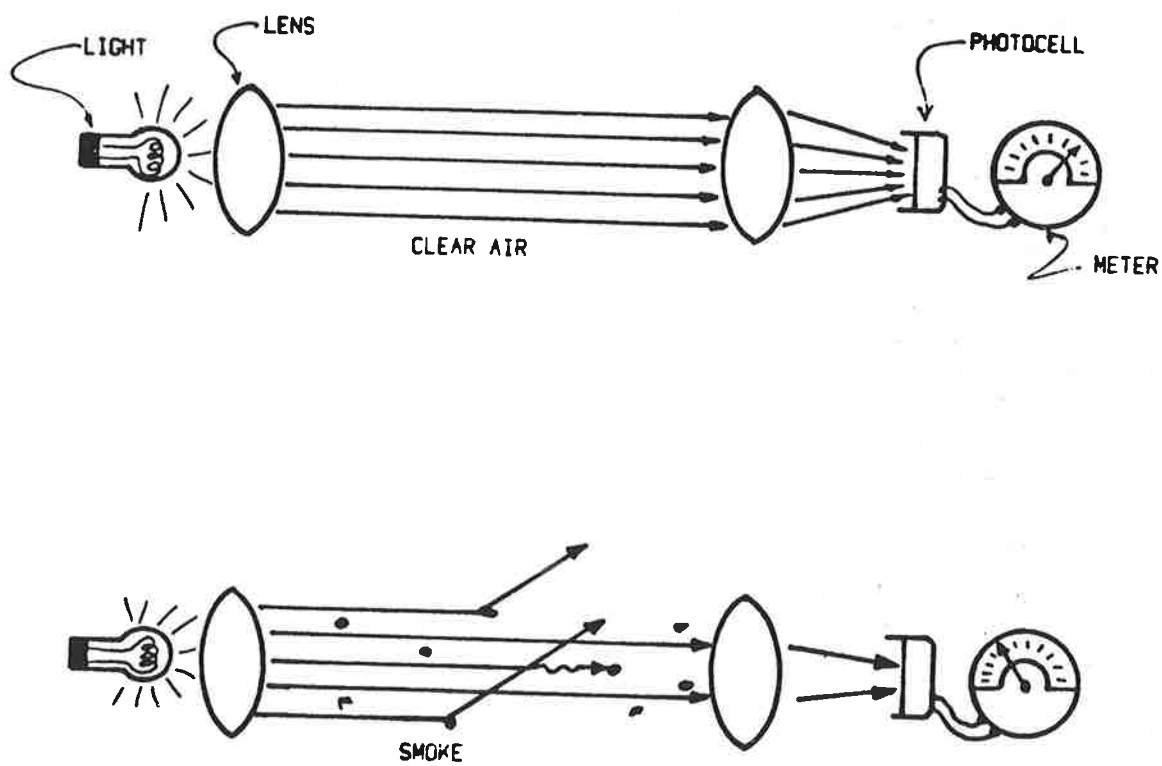


FIGURE 3-1 PROJECTED BEAM PHOTOELECTRIC SMOKE DETECTOR

Projected beam detectors are available that employ visible, infrared or ultraviolet "light beams". They offer the advantage of "line of sight" rather than "spot" detection. This is often a particular advantage since fewer detectors may be required for a given "area of coverage". The light source and photocell can be placed in protected locations of the area under surveillance offering some design advantages over detectors whose sensing hardware must be accessible to the smoke "flow". In addition to a discrete alarm signal, a proportional (analog) signal from the photocell may be monitored to assist in determining maintenance schedules to reduce false alarms due to service related causes (dirt on lenses and photocell aging).

A variant of the projected beam detector is the "photoelectric"detector. It differs from the projected beam smoke detector in that it measures the ability of smoke to scatter a collimated light beam. Early models generally placed the photocell at approximately right angles to a projected light beam in a small enclosure. These are called "side scattering photoelectrics" (see Figure 3-2). The enclosure entries formed a labyrinth to prevent stray outside light from reaching the photocell while permitting smoke to enter. More recently, a configuration has been developed in which the photocell is nearly in the path of the light beam, protected from line-of-sight by an intervening wall. This wall prevents scatter due to deposits on the lens from reaching the photocell. Light scattered at a slight angle by smoke just above this wall reaches the photocell causing a signal. This is the "forward scattering" photoelectric (see Figure 3.3). The response characteristics of the forward scattering photoelectric detector are comparatively insensitive to particle size providing more uniform response to a variety of smoke sources.

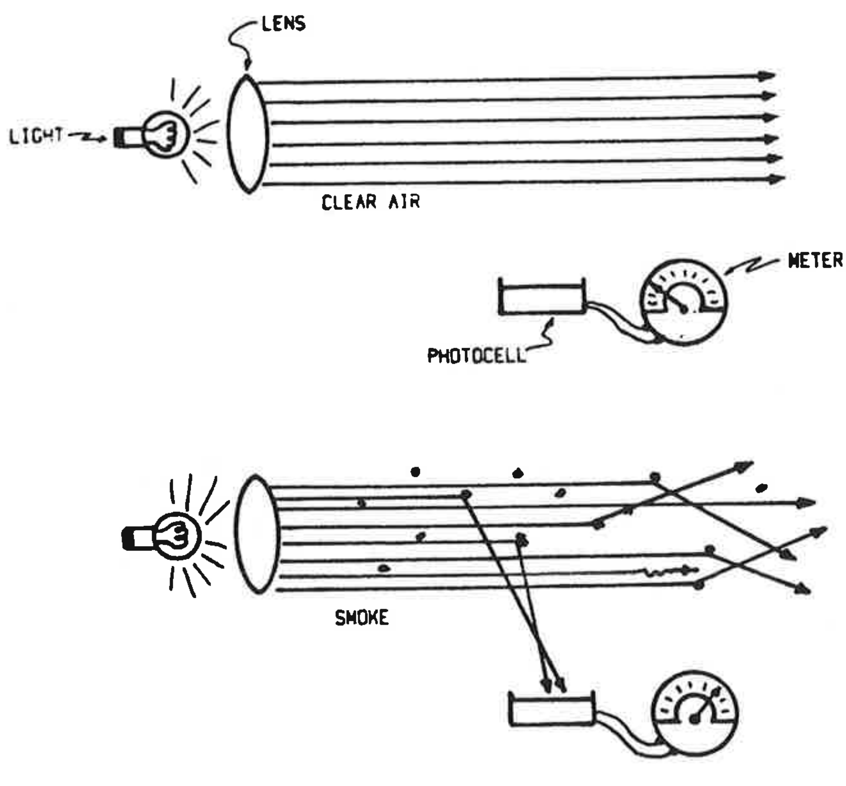


FIGURE 3-2 SIDE SCATTERING PHOTOELECTRIC SMOKE DETECTOR

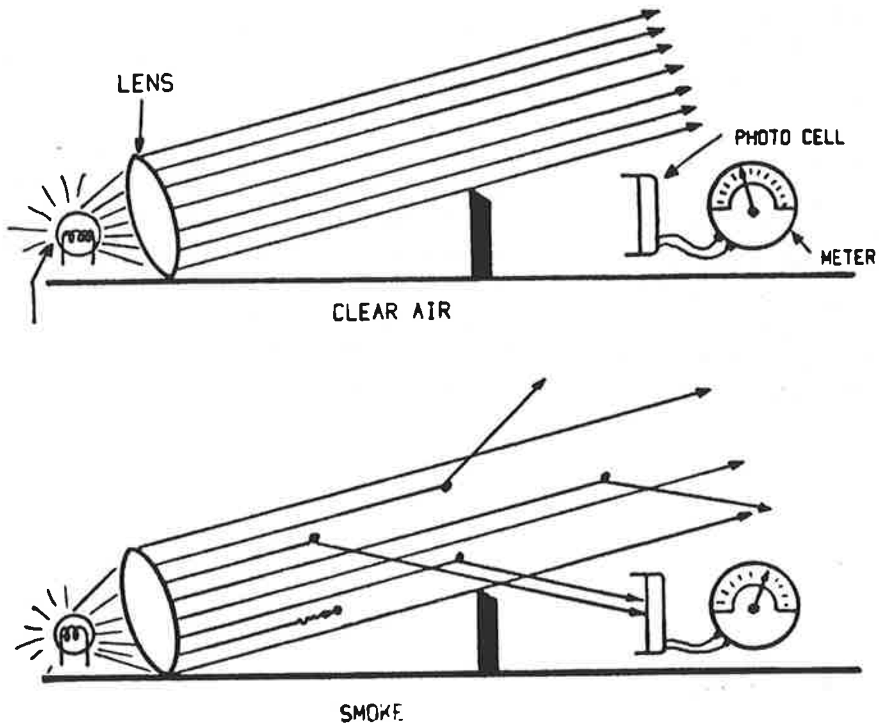


FIGURE 3-3 FORWARD SCATTERING PHOTOELECTRIC SMOKE DETECTOR

An important advance in photoelectric detectors was the substitution of pulsed light emitting diodes (LED) for incandescent light bulbs as the light source. Two obvious advantages were gained. First, by revising the electronics to monitor the magnitude of the pulse rather than total signal generated, stray light can be tolerated and the sensing chamber no longer requires elaborate labyrinths. This reduces the "time lag" for smoke outside the detector to pass into the sensing area. A second benefit is that the pulsed LED and the supporting electronics require very little power, which makes battery operation practical.

3.2.2 Ionization Detectors

A major portion of the residential market is held by "ionization detectors". These employ a radioactive source to ionize air between two electrodes causing a small current to flow. The presence of aerosols or smoke particulates reduces ion mobility, thus reducing current flow (see Figure 3-4). Most detectors employ radioactive sources releasing alpha particles to ionize the air; however, one unit uses a beta source. Ionization detectors respond best to the "invisible" combustion particles having nominal diameters in the 0.01 to 1 micrometer range.

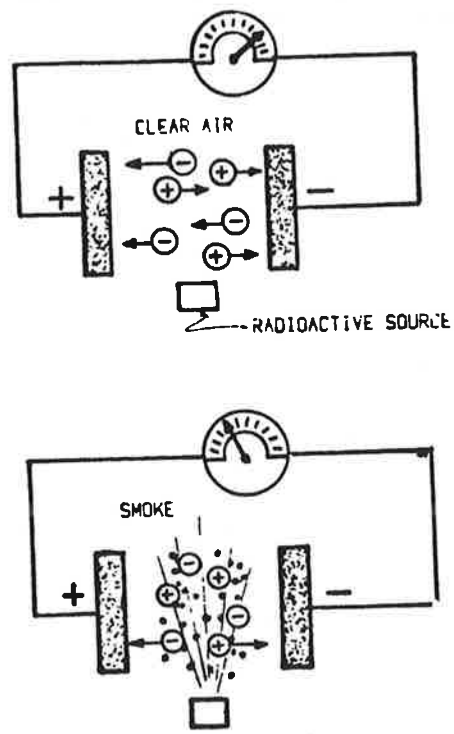


FIGURE 3-4 IONIZATION SMOKE DETECTOR

Ionization detectors are "spot" detectors and must be accessible to the "smoke flow" in the area. This presents an interface problem. Their use in return air ducts offers limited benefit since smoke laden air is significantly diluted at this point. These and other "spot" detectors may offer advantages as part of a remote sampling system to be discussed later.

Another problem exists in that ionization detectors may respond to electromagnetic radiation in the area. In some applications this problem has been solved by shielding the detector with a "top hat" of perforated foil. The shield produces some associated degradation in response time.

3.3 FLAME DETECTORS

Flame detectors can be designed to sense UV, visible light or IR radiation from flames or glowing embers. Flame detectors provide the fastest detection time for these stimuli but are insensitive to smoldering fires where surface glow is not present.

Flame detectors also have the highest false alarm rate of any detector in general application. This limits their use to special high hazard areas where their fast response is a necessity (barometric chambers and industrial processes). In this case, their false alarm propensity is tolerated and steps are taken to minimize false stimuli within their field of view. Where false stimuli cannot be eliminated, "flame flicker" detectors are sometimes used to discriminate between the flicker of natural fires and the more constant level of certain false stimuli (sunlight).

Flame detectors are line-of-sight devices and must "see" the fire. The cone of view typically ranges from 15 to 170 degrees. The devices are operated in fixed position or may be controlled to scan a larger area. A scanning narrow angle sensor can provide a sensitivity advantage over a wide angle sensor monitoring the same total view.

3.3.1 IR and UV Detectors

IR Detectors are sensitive to solar radiation. This can be a problem at many detector sites. Some man-made stimuli can be rejected by filtering and selection of a narrow band of IR energy for detector operation. Flame flicker techniques can also be employed which discriminate between differing UV signals in the range of 0.177 to 0.30 micrometers and retain insensitivity to both sunlight and artificial light. Wide viewing angles of 90 to 170 degrees are typical. In some models, self-checking of sensitivity loss due to dirt on the viewing lens, a faulty sensor, or failing electronics is provided. It is achieved through a contained UV source which emits a signal through the lens to the sensor where it must be properly detected. This action is sequential with normal monitoring.

3.4 REMOTE SAMPLING SYSTEMS

These systems employ a centralized smoke sampling device which sequentially examines samples of the atmosphere drawn from various protected locations through small plastic or metal tubes. They have many of the advantages of multiple spot detectors without requiring that complete sensing hardware sets be placed at each monitoring location. This is a possible advantage for some transit installations where vandalism, space, or accessibility for service cause problems.

Transport of samples through tubing may cause particle deposition, particularly of larger particles. For this reason, detectors employed in such systems tend to be those most sensitive to smaller particles. In fact, advantage has been taken of this, and the atmospheric sample is often preconditioned to remove all but very small particles prior to being passed through the sensing chamber and by this means false alarms are reduced.

Sensors employed in remote sampling systems have generally been of the following types:

a. Condensation Nuclei Type - the atmospheric sample is first humidified to 100 percent; then passed into a chamber where pressure can be suddenly reduced. Particles in the humidified sample act as nuclei for the condensation of water on a one droplet per particle basis. These droplets are large enough to permit photoelectric (light scattering type) detection.

b. Quartz Crystal Impactor Type - by passing the atmospheric sample through an impact separator, all but the smaller particles (<0.7 micron) are removed. These are then directed through a nozzle to impact on the face of a quartz crystal (50 percent of 0.3 to 0.7 micron particles are deposited). The added mass on the crystal changes its resonant frequency, the dependent variable.

c. Modified Ion Chamber - developed for use in the space shuttle, as was the quartz crystal type, this device employs the same impact separator used above, but substitutes an ionization chamber as the sensor. The particular sensor used is designed for high sensitivity to very small particles.

3.5 PERFORMANCE OVERVIEW

Specific fire detection techniques lend themselves to specific fire protection problems. The challenge is to select an optimum technique or combination of techniques. Obvious parameters for selection are sensitivity and cost. Certain detectors are found to be more sensitive to particular fire signatures than others. If the expected fire signature can be defined with confidence, an optimum detection technique can be more readily selected. Other factors play an important role. These are described by Grabowski [2] and repeated here in abbreviated form for reference.

Sensitivity - the response of the device or system to defined fire signatures, generally inherent in the design.

Reliability - often confused with the above, reliability is a measure of the ability of the device or system and each component to perform its intended function at any given time.

---

[2] Grabowski, G. J., "Fire Detection and Actuation Devices for Halon Extinguishing Systems" in "An Appraisal of Halogenated Fire Extinguishing Agents" Proceedings of a Symposium held April 11-12, 1972 at the National Academy of Sciences, Wash. D.C.

Maintainability - the need to clean, adjust, service, etc., to assure reliability during the intended working life of the device. The term "high maintainability" means little or no maintenance is required.

Stability - the ability to retain original sensitivity over time, neither increasing or decreasing.

Grabowski suggested the summary shown in Table 3-1 to be indicative of the performance of devices or systems available in 1972. Recent advances in photoelectric detectors should now cause them to be rated high in sensitivity rather than medium.

TABLE 3-1 DETECTOR EQUIPMENT PERFORMANCE SUMMARY

Detector	Sensitivity	Reliability	Maintainability	Stability
Fixed temperature	Low	High	High	High
Rate of rise	Medium	Medium	High	High
Rate compensated	Medium	High	High	High
Ionization	High	Medium	Medium	Medium
Photoelectric	Medium	Medium	Medium	Medium
Flame - UV	High	Medium	Medium	Medium
Flame - IR	Medium	Medium	Medium	Low

The descriptive categorizations presented above are somewhat interrelated for certain detectors. For example, many smoke detectors are capable of much higher sensitivity than that set by the manufacturer. The particular setting selected may be an attempt at avoiding a false response to contaminants with signatures similar to a fire. Stability may also be a problem requiring a sensitivity setting sufficiently low to preclude threshold shift into the "false alarm" region.

Various techniques are used to modify detector (or system) sensitivity and false alarm rejection. The most common means of rejecting false alarms is to require more than one detector or more than one type of detector to signal before certain actions are taken. Most recently, combined photoelectric-ionization detectors have been marketed for residential applications. These combine the advantages of the photoelectric detector's response to smoldering fires and the ionization detector's response to flaming fires in a single-station detector.

3.6 SUMMARY OF FIRE DETECTION DEVICES

Appendix A presents a tabular summary description of most common fire detection devices as well as other devices where performance as fire detectors is required. Included are devices or systems which are under development. A description of each device is given and common applications and unique characteristics of each are noted. References are cited identifying sources of further information and are listed immediately following the tabular material.

4. MICROPROCESSOR AIDED FIRE DETECTORS

At the present time, most prevailing fire detector concepts embody the use of two level, fire/no-fire signaling systems. The detector head commonly is capable of producing an analog signal based on temperature, particulate density, ion concentration, or light or acoustic spectral properties. This information is usually interpreted and converted to a fire/no-fire signal at the detector head by simple threshold sensing circuitry. Some fixed time series adjustment may be hardwired in the circuit.

The inflexibility of such a system, requiring threshold values defined for a broad range of environments, produces a high proportion of "false alarms" and/or "failure to detect" conditions. Apart from this form of error, there are differences in detection capability based upon sensor characteristics. The reliability and sensitivity problems associated with generic detector sensing methods are discussed in detail in Section 3.

The cause of false alarms or failure to detect can be generally attributed to three principal areas. These are:

1. environmental variation,
2. hardware malfunction, and
3. communications faults.

The environmental false alarm problem is largely based on the inability of existing detector heads and circuitry to reliably discriminate changes in variables associated with fire signal (fire signature) from background values. Present systems primarily rely upon either instantaneous, or a time weighted single measure of the detector variable. If the value exceeds a threshold, predetermined and preset by the manufacturer or installer, an alarm output is generated. Rate of buildup or variations in buildup pattern are not generally employed as part of the fire sensing algorithm. Similarly, concurrence of response, between detector heads or between successive samples, is not generally used to improve reliability.

Hardware malfunctions contribute substantially to both failure-to-detect and false alarm rate. These are usually mechanical failures which affect the electrical characteristics of the alarm circuit. Connections and terminations are common failure sites, with corrosion and poor contact being typical failure modes. Failure mode is markedly affected by severity of environment, aging of the properties of alarm system materials, and production of installation variability.

A third significant source of false alarms is in the communications network between detector heads and the central control or operators panel. Induced electrical noise, line interruptions, and power surges are typical sources of transients that can simulate fire indications. An important problem area is undetected installation errors. These are common with typical installations, even when inspection is required, and occur regularly when systems are expanded or modified. Failure to connect additional detectors and/or incorrect wiring in a supervised or monitored system are frequent examples. Wiring errors, where only two instead of four wires are added are deliberately used as labor or cost saving devices by some installers. A related communications problem is the lack of correct and specific identification of fire detector address. Zone systems permit only identification of the general location of detector activity, usually not providing information about the type of detector responding, or the response of adjacent detectors. More specific knowledge about the detector site can be used to confirm alarm status and furnish information about fire source and extent which may be useful in determining proper response.

A microprocessor system can be employed to reduce false alarm and failure to detect frequency in each of the three described areas by:

1. applying specific fire/no-fire signature criteria based upon the known environment and immediate history, to detector head output;
2. providing continuous system integrity testing, and
3. using transmission methods that reject error signals or commands, and provide discrete addresses for each source of data.

The general approach envisioned is to use the greatly increased logic and memory capabilities of microprocessors and to develop and incorporate such possible features as:

1. analog information from detector heads as a source of quantitative system input,
2. analog/digital conversion of data for economical and reliable initial installations, transmission, and maintainability.
3. association of a discrete address with each file of data to improve quality and usefulness of data
4. interpretive electrical/mechanical integrity checks to determine condition and wear-out or failure rates,
5. multiplexed transmission of data and commands for economical operation and ease of software changes,
6. option of dedicated or carrier transmission lines, providing cost-effectiveness options,
7. microprocessor logic system for data collection, interpretation, and control, to provide higher level decision making capabilities than available with present systems,
8. memory storage for data and software programs, improving the confidence in decisions or outcomes,
9. modifiable algorithms comparing time-series data with functions known to differentiate fire and no-fire conditions on the basis

of fire signature parameters, to provide higher reliability of prediction.

10. alarms or commands issued with a "degree of confidence that fire exists" or a false alarm probability rating for improving human confidence in system predictions, and

11. prompting functions nominating various responses on the basis of type and severity of fire, and the possible consequences or risk depending upon environmental, fire signature, and risk factors as an aid to operator decision making.

Microprocessors and analog/digital converters are presently available which can provide expanded capabilities in positive fire detection and communications at low cost. A microprocessor can perform more complex logical operations on larger data bases than is possible with existing electromechanical systems of comparable cost. Over time, new programs can be added or substituted to accommodate changed conditions, new hazards, altered levels of knowledge, or technological improvements.

The principal functions of the microprocessor are to make available:

1. extensive computer-logic capabilities, and
2. memory capacity for holding programs, algorithms and data bases.

As indicated in the preceding list of potential capabilities, microprocessor systems can perform the function of current systems, but with higher levels of sophistication. The results should yield correspondingly greater precision of fire identification and location. With the capabilities available, it is then possible to prepare updated or tailored software programs which match criteria for detection to environmental changes and which can provide greater amounts of information to the operator for use in responding to the problem.

A microprocessor-based detector system would typically consist of the detector heads, a local control with memory and microprocessor, a central control with similar capabilities used for monitoring each local control system and dispatching commands, and the communications links between these units.

Communications links may utilize microwaves, line-carrier, ultrasonic, radio, infrared, dedicated wire or fiber optic lines as transmission media. Data may be transmitted continuously or multiplexed, depending upon a number of cost, convenience, and reliability factors. With multiplexed systems, analog/digital conversion at the detector head is required with attendant considerations. A number of interrogation methods are available to multiplex operations which can yield economical and reliable data transmission. The design criteria for selecting the best interrogation system for a rail transit vehicle system require considerably more attention and should be addressed as a separate issue.

The basic units of a rail transit vehicle fire-detection system will consist of the detector heads and the local control. The assignment of various functions to the unit will depend to some extent upon the configuration of the system and the criteria for system performance.

Detector heads typically yield an analog electrical signal as a function of specified environmental parameters. Multiple heads at a location yield separate signals which may be processed locally or transmitted to the local control for processing. Processing of the signal at the head may include:

1. production of an analog signal,
2. conversion to a digital equivalent,
3. storage in memory at the head for multiplexed transmission,
4. storage at the head for use in computation of time-series data
5. continuous transmission of analog data via direct line,
6. storage and logical operations performed at a multiple detector head, as well as some other functions such as time weighted averaging or simple signal conditioning.

A system consisting of several multiple detector heads and a local control unit is representative of a design applicable to a rail transit train. Communications with a central control unit can be provided by existing operator controlled systems or via alternatives peculiar to the systems in use (carrier or radio).

Each detector head continuously monitors the assigned environment and the data are stored in a data base. This data base is used initially to develop an algorithm which incorporates the distributional shape and properties of the test parameter under conditions of varying background and under the fire conditions which provide a commonly defined "fire signature".

The use of a microprocessor for storing the algorithm allows convenient and economical revision or exchange through changes to the program software or stored program, which will be inevitable with changes in system and hardware configuration. Several alternatives are available for software update varying in cost, complexity and applicability. These include:

1. Read only memory (ROM) replacement in which a ROM device is physically replaced with a device containing a different program (special processing can be used to rewrite these devices after removal from the system),
2. Remote downloading of data for parameter driven software, in which a generalized software program uses sets of preselected data points as the threshold for alarm, new threshold values can be transmitted from a central unit,
3. Remote downloading of interpretive code, in which a program is stored as BASIC, PASCAL or other high level code and changes are incorporated as desired by transmission of new interpretive code, and

4. Remote downloading and cross compilation of object code, in which a machine language program is generated by a compiler.

The options described represent a progressive increase in sophistication. The choice of an updating method depends upon both the need for program changes (frequency and extent), the amount of hardware involved in each system, and the requirements for data acquisition and analysis. Required sampling rates and response time are variables to be considered in the selection.

A brassboard prototype system might use an object code program which could be readily managed by a computer programmer, while a series of units for field testing could be more reliably managed by downloading interpretive code.

When put into general use, parameter changes are still likely to be required on a regular basis as a function of environmental and hardware change. These changes are likely to be most readily executed by either entering the selected values for parameters or manually exchanging ROM for reprogrammed units. The last approach is less elegant from the point of view of program design, but offers a degree of simplicity which can be translated into improved system reliability and flexibility. A ROM can make best use of available memory, a feature which must be traded off against the need to replace the ROM each time a program change is desired. The availability of devices for rapidly erasing and reprogramming ROM make this a task which, once designed, can be executed readily by field technicians or maintenance personnel.

The microprocessor-based system described above does not represent any particularly new or innovative concepts, but rather makes use of improved data handling and transmission facilities to perform functions more effectively. As outlined, detector heads may have individual analog/digital converters, which can be combined with local time series processing of data, a discrete address for each detector, and self-checking routines; or a single converter and microprocessor can perform these functions by addressing detectors through multiplexing.

A definitive analysis of the advantages of alternative approaches is dependent upon characteristics of the environment and the criteria for system performance. As an example, systems with widely varying environments and fire signatures may be economically improved by using a central microprocessor with dynamic memory allocation based upon detector need, while detector head based memory capabilities may provide greater overall system reliability and maintainability.

With any system, there are ultimately three criteria which must be met for reliable fire detection. These are the ability to:

1. generate authentic data,
2. accurately transmit data, and
3. perform integrity checks to assure the physical performance of the system.

As outlined, each of these criteria can potentially be met by applying microprocessors to tasks presently performed by various electro-mechanical, or conventional electrical devices.

5. FIRE DETECTION CONSIDERATIONS IN THE RAIL TRANSIT ENVIRONMENT

Current rail rapid transit vehicle fire protection is based on manned detection and manned suppression. No operating transit system we are aware of has either automatic fire detection or fixed fire suppression onboard its cars. Any automatic fire detection system used on rail transit cars would have to be very reliable and free from false alarms; false or unwanted alarms would completely disrupt any transit system operations. In addition, it is impractical (not cost effective) to provide any sort of fixed fire suppression system onboard rapid transit cars without a reliable detection system to actuate it. The problems associated with automatic detection include false or unwanted alarms, delayed alarms or failure to alarm, vandalism, environmental endurance or reliability, and maintainability.

The key to an adequate and reliable fire detection system would be the ability to reliably detect the fire while still avoiding false or unwanted alarms. As described previously, current fire detection systems are capable of sensing specific signatures that are characteristic of a fire. These include temperature, temperature rate of change, light obscuration, particulate concentration and flame radiation. Unfortunately, most of these signatures are not unique to fire but may be caused by normal operating or environmental conditions or an abnormal but non-fire-threatening situation. These false signatures include moisture, aerosols, smoking, dust, electrical transients, and normal equipment radiation or emissions. The false alarm record of detectors, even in the ideal environment of buildings, has been less than would be acceptable in transit vehicles. Even well maintained systems with high quality smoke detectors have a ratio of alarms to actual fires in the order of 15:1 to 25:1.

Although heat detectors are by themselves relatively free from false alarms in building environments, the total system has a false alarm rate that would be unacceptable in transit vehicles. In severe environments, such as aboard aircraft, heat detection systems have had serious false alarm problems in the past. It should also be noted that most heat detectors used aboard aircraft have been located in the engine nacelle where a very extreme thermal and vibration environment is encountered. This environment is similar, in rigor, to many transit vehicle detector sites.

Both heat and smoke detectors which are used aboard aircraft are used as an alerting device, not to actuate automatic fire extinguishing systems. Highly skilled crew members analyze this input together with other instrumentation and sensory input and then decide on what action to take.

Information obtained in the transit system surveys reported here as well as experience in previous investigations has led to the conclusion that the current state-of-the-art fire detection systems do not have the reliability required for rail rapid transit vehicles. A very high incidence of false alarms could be expected with some types of detectors which would seriously and unnecessarily disrupt transit operations. However, there may be some detectors and techniques which can be adapted for specific applications as are discussed in this section.

5.1 PASSENGER COMPARTMENT FIRE DETECTION

The results of the transit survey and system review of published information indicate that almost all fires originating within the passenger compartment were of incendiary origin. One exception was a fire caused by an electrical fault in a ceiling light fixture. Typically, incendiary fires occur late at night or early in the morning when the trains are almost empty. An arsonist is not likely to start a fire in view of many witnesses. An exception was the 8 April 1980 arson fire on the Hamburg-Altona German subway. This was a rare instance where fire setting was observed and subsequent rapid fire buildup was recorded by an amateur photographer at the scene. A more complete description of this fire is given in Appendix C.

Any automatic detection system for installation inside a passenger compartment should be designed to sense a fire that would occur in an almost empty car. Smoke detectors which sense either obscuration or particulates (photoelectric or ionization detectors) would provide the earliest warning of any fire inside a passenger compartment. A heat detection sensor would not respond until the fire had progressed to the flaming stage, but would be less susceptible to false or unwanted alarms than smoke detectors. However, since both life and property protection will require the sensing of both flaming and smoldering fires, a heat detection system is not preferred for monitoring the interior of a passenger compartment. A microprocessor controlled smoke particulate detection system appears feasible which can provide both early warning detection and freedom from false, unwanted and maliciously induced alarms.

The detectors under consideration for microprocessor operation are basically analog devices. A threshold value is selected which, when exceeded, produces a change of state or simple two-level (fire/normal) signal. Several alternatives to this form of signal processing exist if a microprocessor is located at the detector head. As examples:

1. two or more threshold values can be selected for system response,
2. the analog detector information can be converted to digital form and transmitted to a central unit for further processing,
3. data can be stored in memory at the microprocessor, for comparison with successive values over time,
4. data from all heads at that site can be compared for agreement about fire signature presence.

Combinations of the above processes can be developed if a sufficiently flexible set of microcomputer hardware and software is selected.

A local memory provides an opportunity for storing values in memory, with cyclical overwriting. The information can then be used at the local microprocessor for application of a pattern recognition or fire signature algorithm to the time-series data. Similar activity may occur separately or as a part of a single algorithm for all detector heads at a site.

In each case, communication with a central unit is required for further action to be taken. In place of a dedicated line for each input, a multiplexed system can access data from each local unit in sequence. Priority interrupts can be introduced for large systems.

The memory at each local unit should have a stored digital address which is transmitted with each access operation. The digital number provides identification and location of the detector head. The central unit therefore has a means of specifically identifying a fire alarm site, as opposed to the zone system concept, which is less precise. Information about fire spread, probable ignition source, potential hazard, and alternative response or extinguishment approaches can be obtained from a fully operational control center.

An example of microprocessor fire detection may be illustrative. Two dual head detectors, located some distance apart, monitor the interior of a transit car for fire. A single smoker or vandal would be unlikely to activate all heads simultaneously. Each detector would monitor both obscuration*(a photoelectric smoke detector head), and particulates*(an ionization smoke detector head). The individual heads would either actuate at two levels of signature intensity or provide an analog output through an A-D converter that could be compared with reference levels stored in either local or central memory. If compared with data in central memory, the digital output and detector address are transmitted when interrogated by the central unit. In either event, the time series data are tested for adequacy of fit to a fire signature by the pattern recognition algorithm. The algorithm can be altered as a function of experience with environmental and use factors. Methods of program change, as mentioned earlier, include:

1. ROM replacement,
2. remote downloading of data for parameter driven software,
3. remote downloading of interpretive code, or
4. remote downloading and cross compilation of object code,
   in order of increasing complexity and ultimate efficiency.

It is possible that the interior car fire monitor loop would not be operated in rush hours if it has been decided that the passengers would sense interior fire immediately and alert the train crew. This change to the overall algorithm could be part of the software. Similarly, a change in pattern recognition can compensate for the presence of crowd humidity, temperature, or air quality shifts during this period. For simplicity, it is assumed that the in-car detectors are inoperative during rush hour.

A concept level flow chart for the monitoring program is shown in Figure 5-1. During rush hour periods, as determined by program and a system clock, none of the detectors would be checked. If it is not rush hour, the reference level of detector sensitivity would be set low. The obscuration output is then read; if it is not over the reference level then the program moves to check the other detector.

---

* "Obscuration" and "particulates" are coined here as simple, if somewhat inaccurate, terms for use in the text and figures to follow.

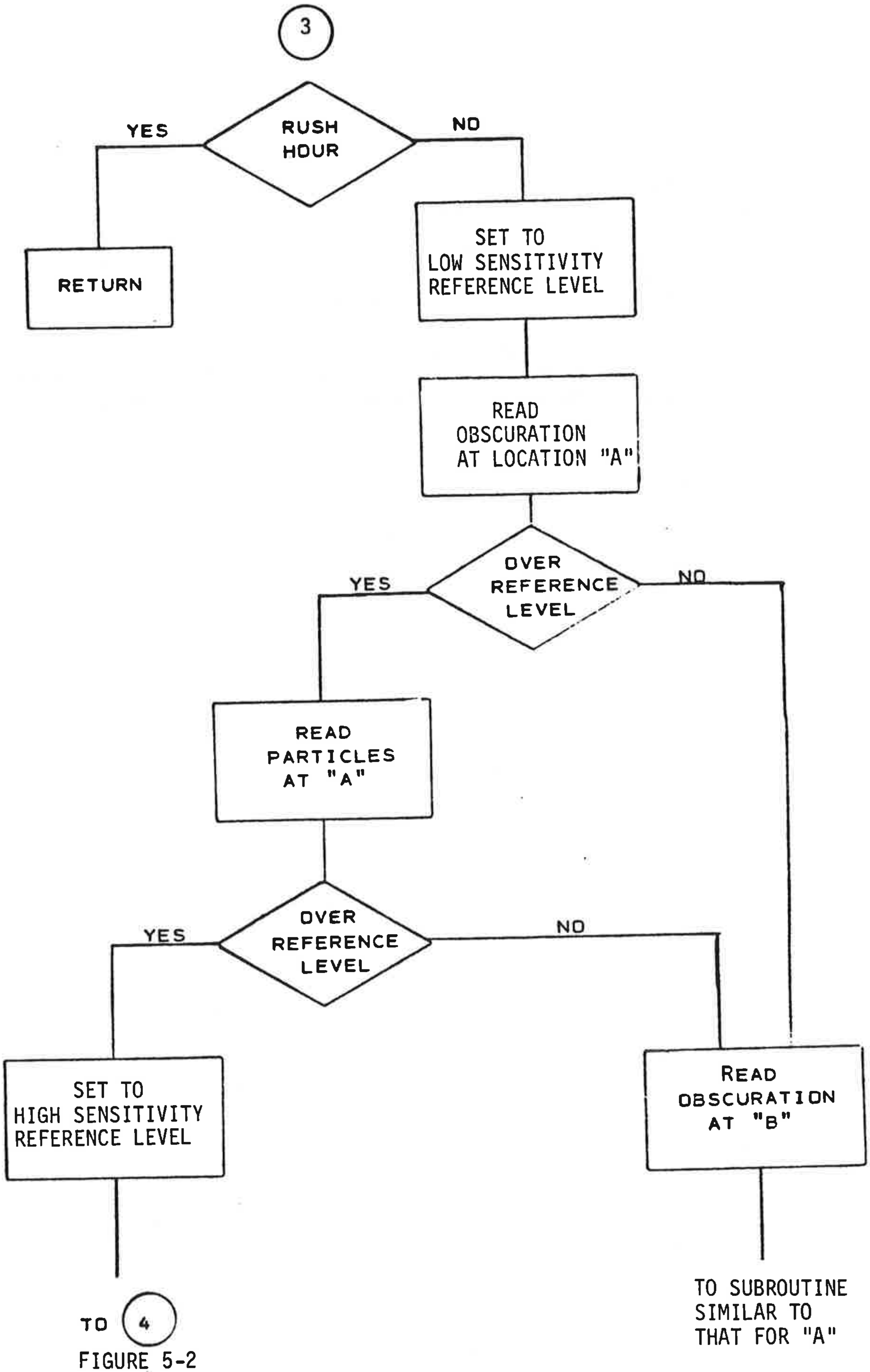


FIGURE 5-1. SMOKE DETECTOR LOGIC PROGRAM - 1

The obscuration and particulate sensing heads are first checked at low sensitivity. The outputs are effectively "and" gated and unless both exceed the reference levels, the program evaluation moves on. However, if the outputs of both heads exceed the reference level, the reference level is then set at a higher sensitivity and then the outputs of the second detector checked, Figure 5-2. The output of the two heads of the second detector are "or" gated so that if either the photoelectric or ionization detector head output is above the more sensitive reference level, an alerting process begins.

In the example, the motorman is in the control loop so if the train is crowded at a non-rush hour as a result of a special event or service delays, he can abort the alarm. It would also be possible to remove the motorman from the control loop and sense the load factor indirectly by monitoring weight.

5.2 UNDERCAR FIRE DETECTION

In the transit survey, fires that originated underneath rapid transit vehicles were all of electrical origin and should have been either preceded or accompanied by abnormal electrical current flows or voltage levels. The use of smoke detectors would be feasible only to cover specific equipment enclosures. The smoke detectors could not be practically installed within the enclosure, so sample air would have to be drawn from the enclosure for analysis by a detector. Some state-of-the-art detection systems do operate on this principle; however, these are very sophisticated, expensive and not judged suitable for rail rapid transit vehicle installation. New and potentially simpler smoke detectors are presently under development which pump samples of air from specific locations for analysis to detect fire. At present, performance data for those systems are insufficient to judge their value.

Protecting the undercar by the installation of heat detectors is possible; however, the flow of heat will vary considerably depending on the car and wind velocity. In addition, the undercarriage would be expected to have wide variations in heat level as a result of both normal and abnormal operations. The most feasible heat detection system appears to be through monitoring the temperature at each individual electrical component with continuous wire sensing detectors in order to sense dangerous levels. This would be both an operational/maintenance and a fire detection sensing system. Since electrical current and voltage abnormalities are anticipated under prefire and fire situations, monitoring these potential abnormalities instead of, or in conjunction with, monitoring temperature can serve both operational and fire safety purposes.

A simple example of such an application is illustrated in Figure 5-3 which is a simple logic diagram of a microprocessor program used in identifying possible grounding of a current collector or shunt against the car. A sensor would be installed to measure the voltage between the current collector and the frame. In normal operation it should be approximately the same as the traction power voltage. As long as this voltage is at or above

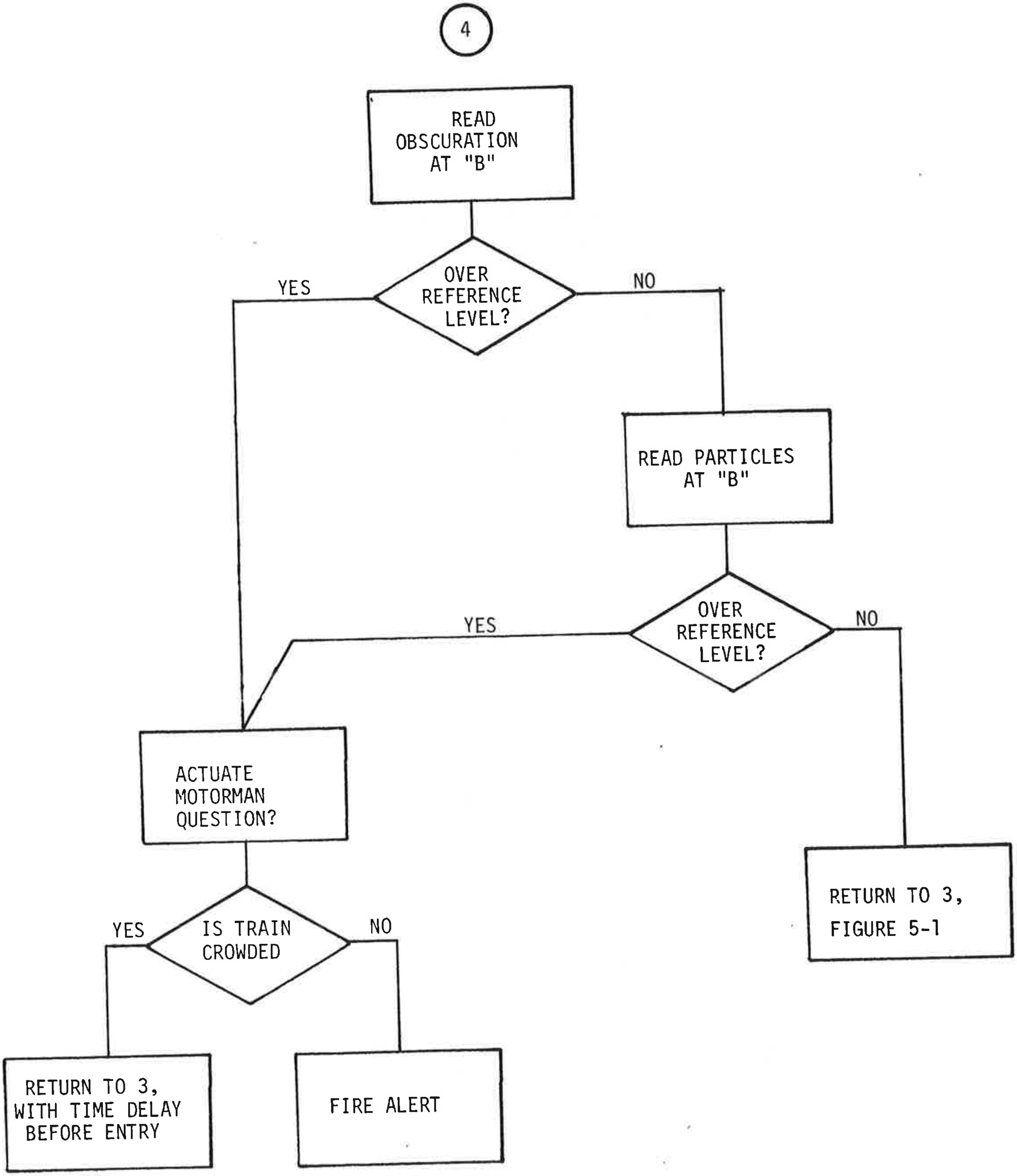
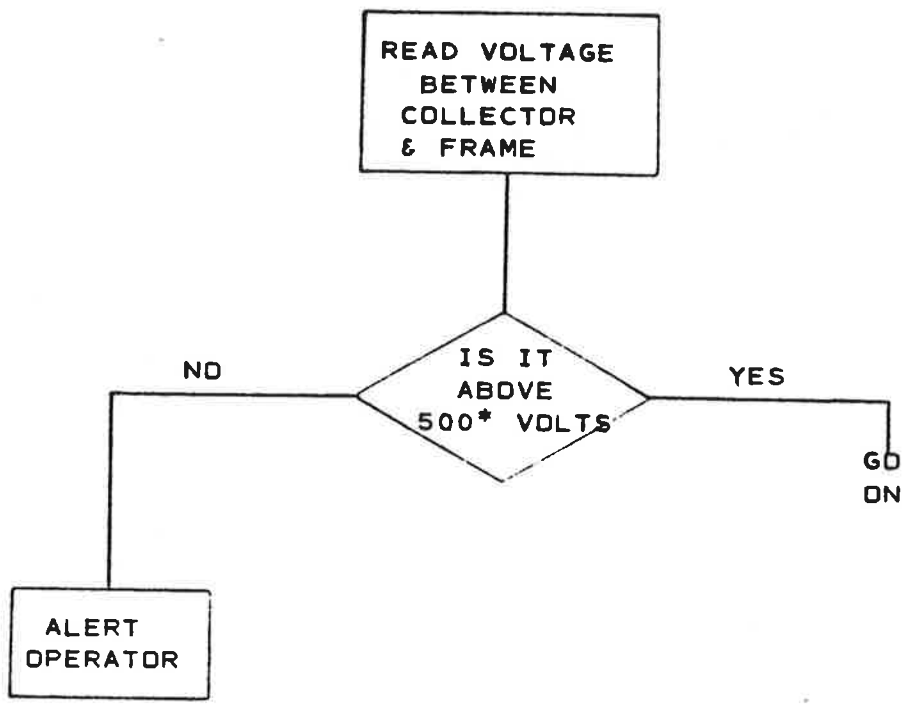


FIGURE 5-2 SMOKE DETECTOR LOGIC PROGRAM - 2



* VALUE FOR ILLUSTRATIVE PURPOSES ONLY

FIGURE 5-3 DETECTION OF CURRENT COLLECTOR FAULT TO GROUND a certain reference level, which would depend on the traction voltage and allowable variation, normal system operation is assumed. However, whenever the voltage falls below that value, as would occur during the complete or intermittent ground of the current collection device, an alarm is sounded and the operator alerted.

Another such example is presented for the logic involved in determining whether dynamic braking is energized on one car while another car is in traction, which can cause resistor grid overheating. Figure 5-4 is a logic diagram flow chart describing a microprocessor program for accomplishing this task. The objective of the program is to determine if each car is in dynamic braking or not, continuing on to check the next car. Whenever the status of dynamic braking is changed for one car, conditions are then reevaluated for the previous car. If one car remains in dynamic braking while another remains in traction, the operator is alerted and the motor circuit breaker is tripped.

In addition to the above cause of overheated resistance grids, there are other situations that also produce an overheated resistance grid, as presented in the Fault Tree Analysis of Figure 5-5. The temperature of the grid itself is not the important parameter. The grid is noncombustible and can run red or even white hot although the normal maximum temperature is estimated at 800°F. Grid temperature or temperature above the grid is important because of ignition of adjacent combustibles, not because of damage to the grid.

As illustrated in Figure 5-5, a high ambient temperature, oily dirt or debris on the grid, or a stationary car (braked to a stop) will result in poor heat transfer from the grid. Poor heat transfer and normal braking on the train will result in inadequate heat loss, causing a high grid temperature. Added to this, the heat caused by heavy dynamic braking of the car itself can cause a power overload of the grid resulting in an elevated temperature. A fire on the dynamic braking grid would also cause an elevated temperature.

Conditions yielding a high temperature at the resistance grid or a fire in or on the equipment or the underside of the car will cause high temperature on the underside of the car. This is simply stated in Figure 5-6, which relies on Figure 5-5 for detail on conditions yielding high resistance grid temperature.

A microprocessor code logic flow diagram for evaluating excess temperature at the resistance grid is partially presented in Figures 5-7. Examples of supporting subroutines are presented in Figures 5-8 and 5-9.

The temperature on the underside of the car is read into the program as shown in Figure 5-7. The microprocessor compares this temperature with a temperature stored in memory (T3), which is considered indicative of an under-car fire. If the temperature exceeds T3, a fire alarm is sounded and, perhaps, on-board suppression is initiated. If the under-car temperature is less than T3, the microprocessor then reads a temperature on the dynamic braking grid. If this temperature exceeds a critical value (also assumed to be T3 for this example) the microprocessor will ask if an adjacent car is in the braking mode. If not, the computer will send control functions to trip the breaker for the grid with excessive temperature and to alert the operator of this action. If

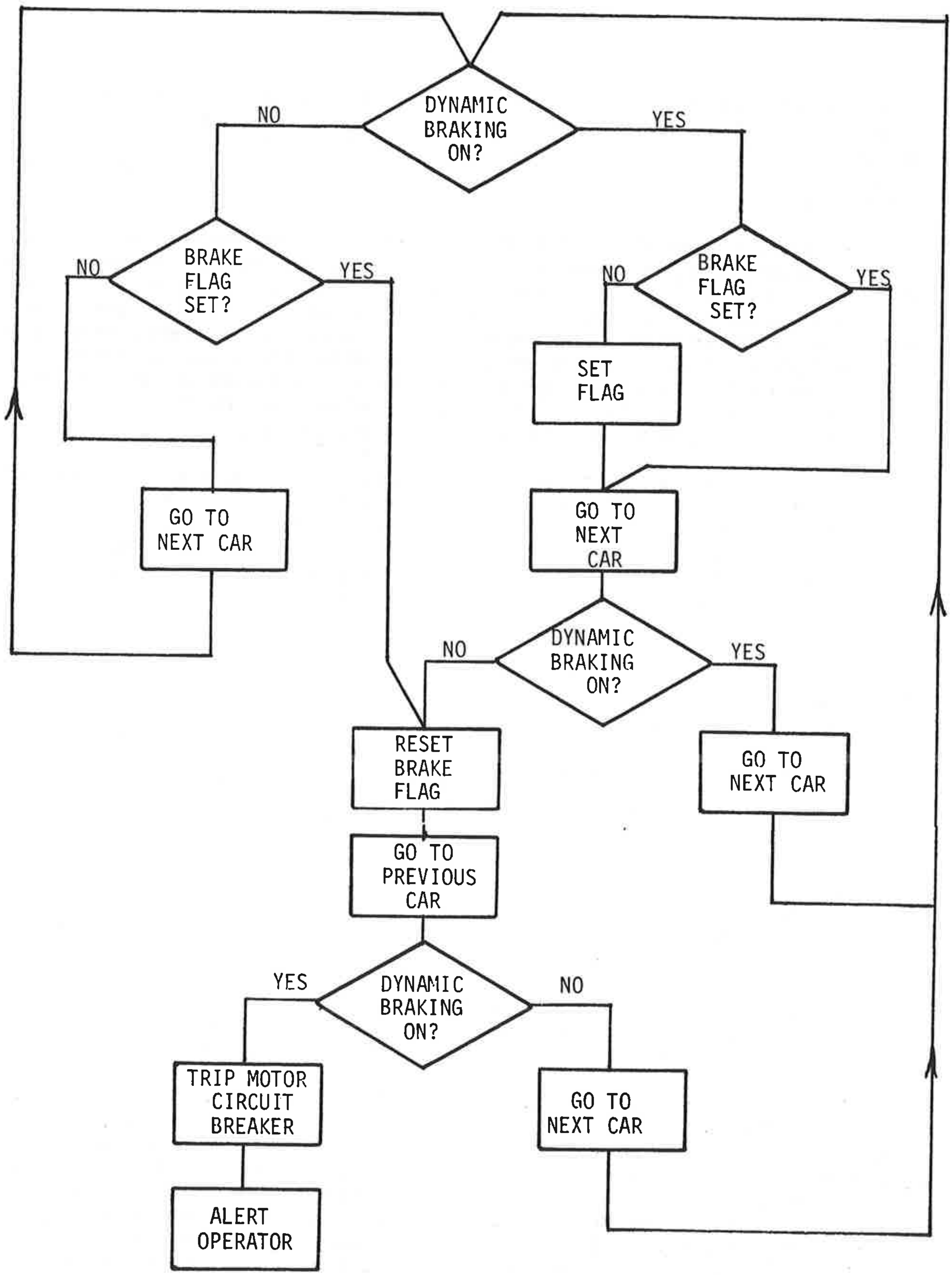


FIGURE 5-4 FLOW CHART - DETECTING DYNAMIC BRAKES ENERGIZED ON ONE CAR WHILE OTHERS ARE IN TRACTION

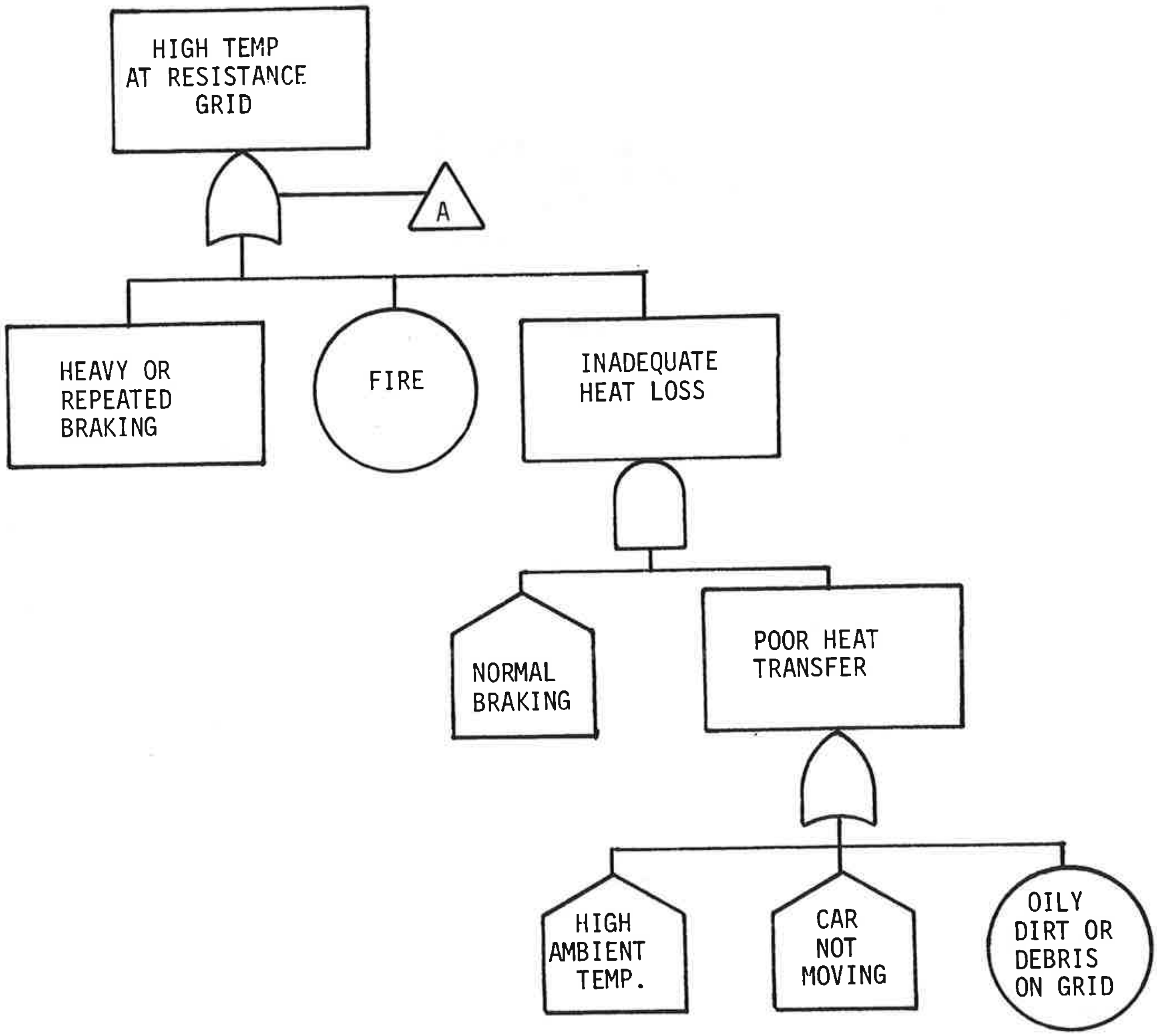


FIGURE 5-5 FAULT TREE ANALYSIS FOR HIGH TEMPERATURES AT RESISTANCE GRID

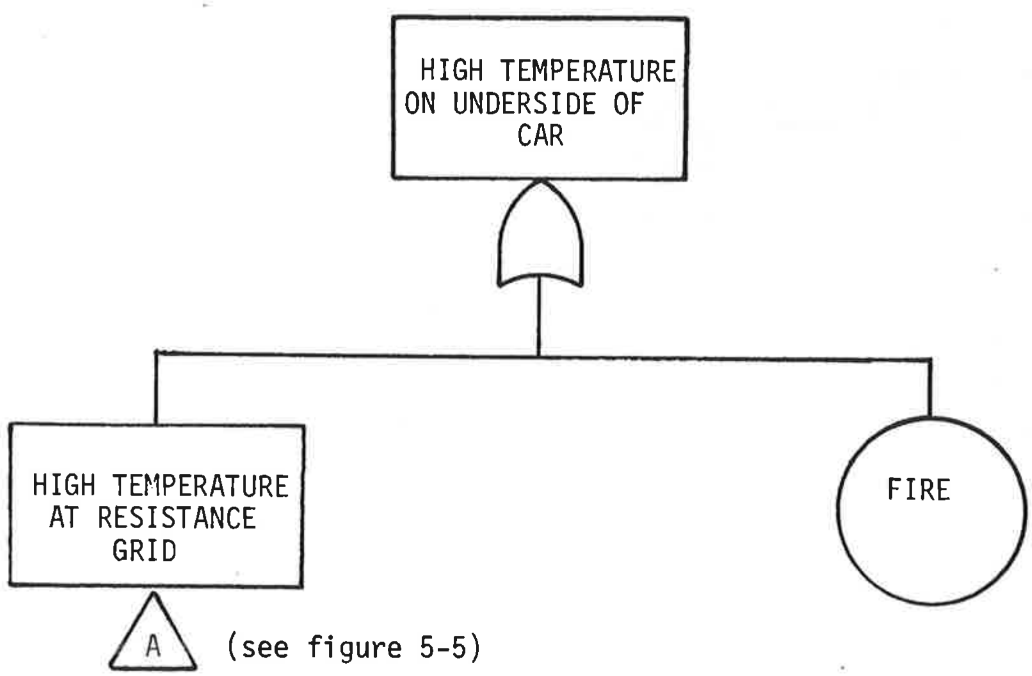


FIGURE 5-6 FAULT TREE ANALYSIS FOR HIGH TEMPERATURE ABOVE THE RESISTANCE GRID

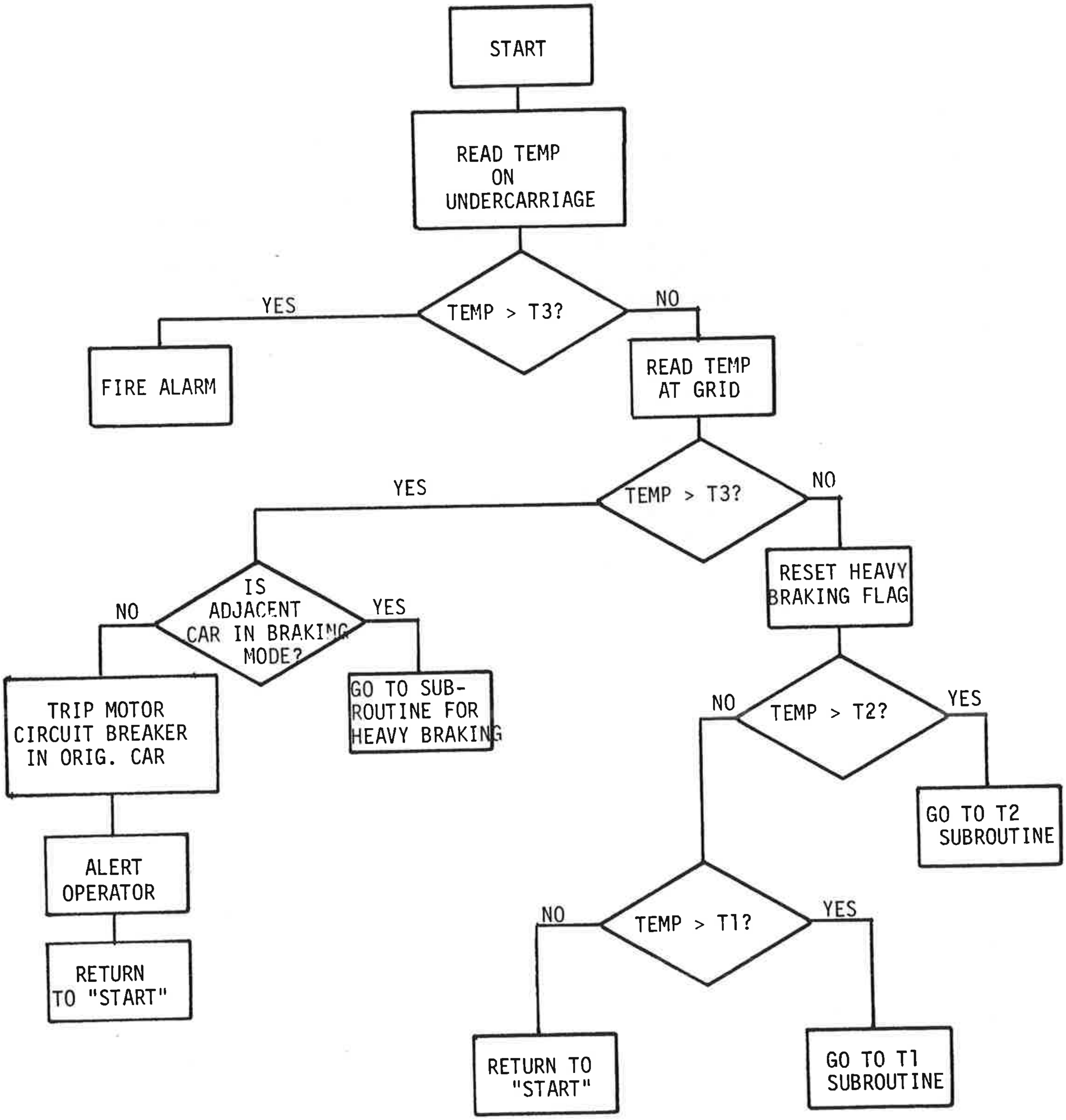


FIGURE 5-7 MICROPROCESSOR LOGIC DIAGRAM FOR EXCESSIVE TEMPERATURES ON GRID OR UNDERCARRIAGE

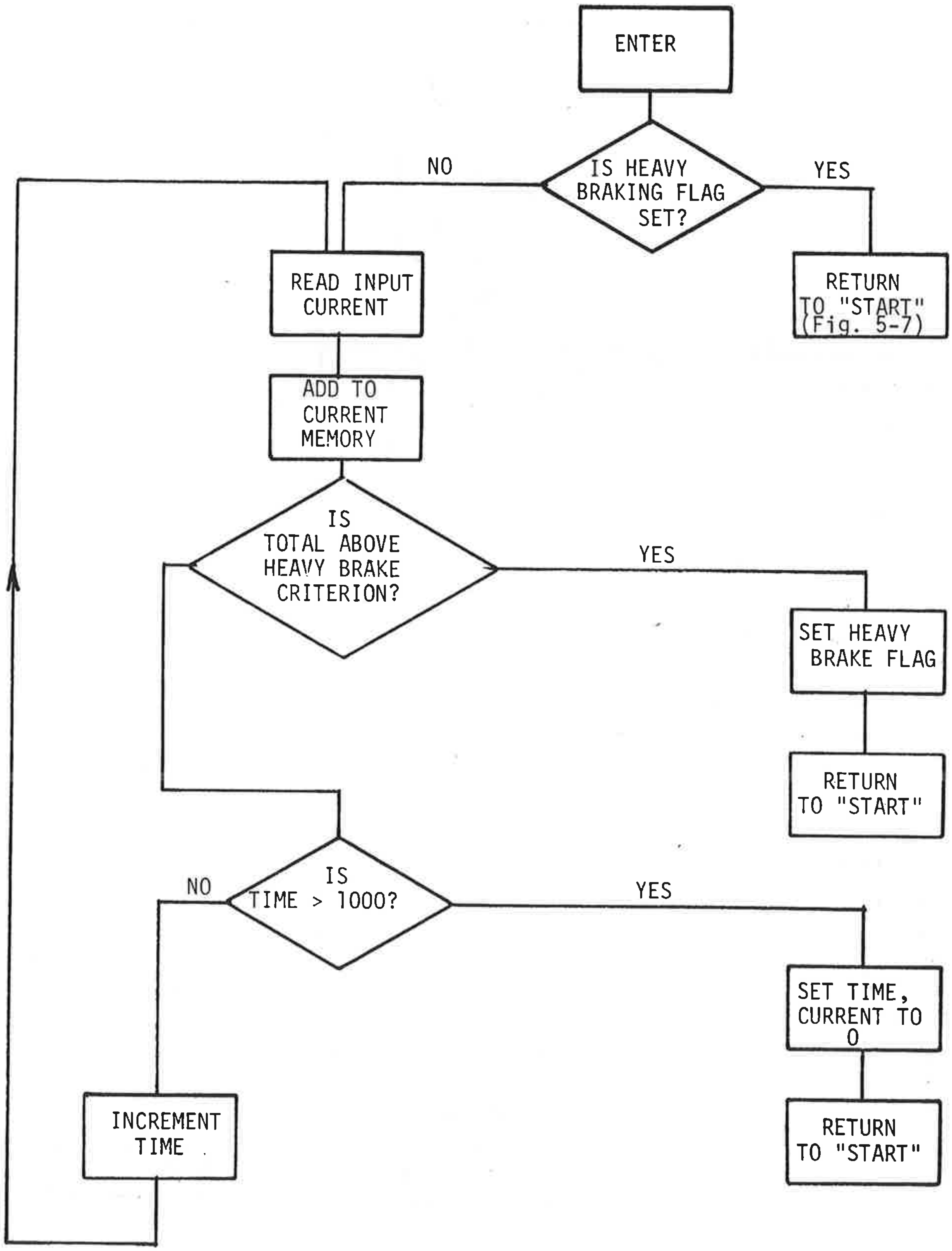


FIGURE 5-8 SAMPLE HEAVY BRAKING SUBROUTINE

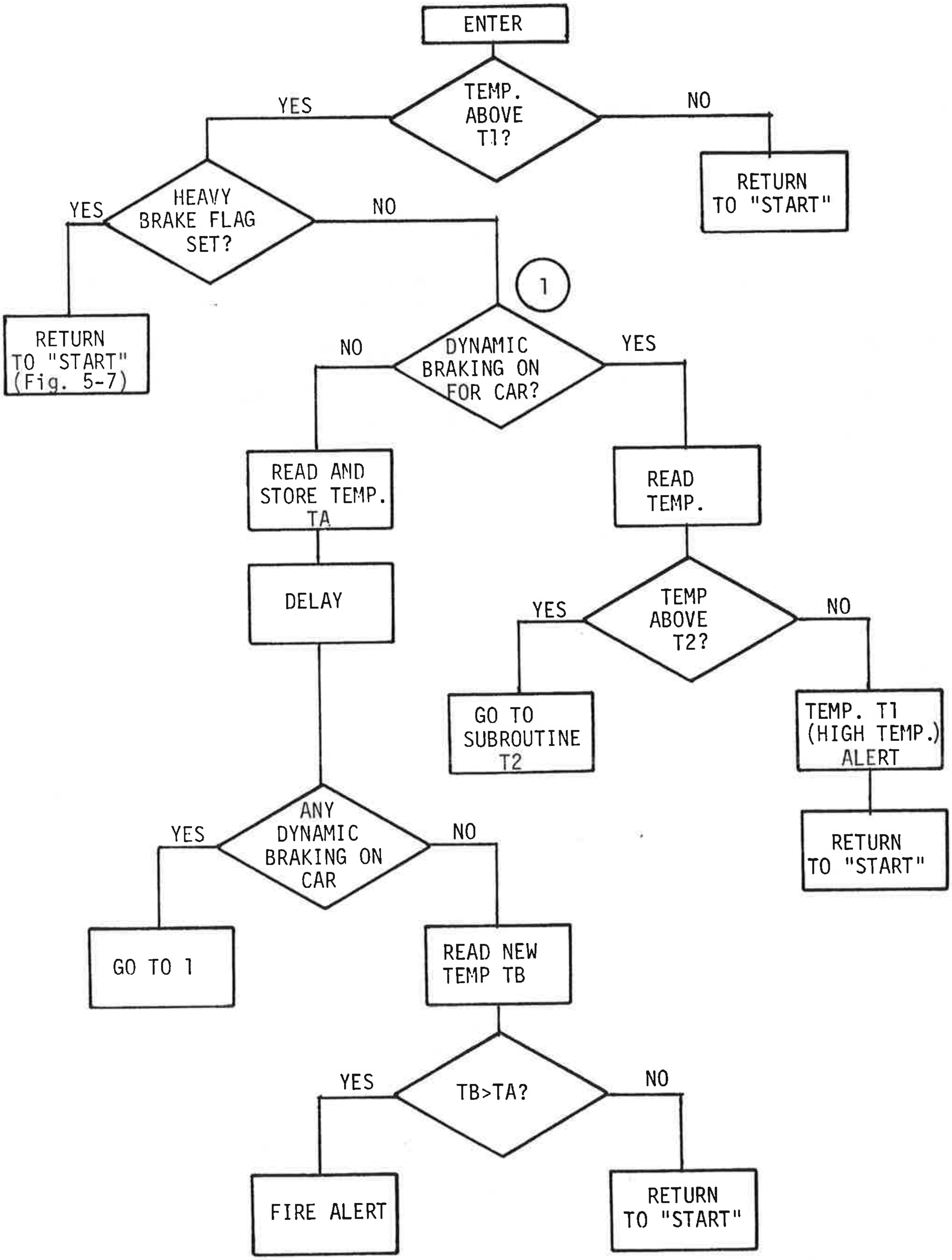


FIGURE 5-9 SAMPLE T1 SUBROUTINE

If the adjacent car is in the braking mode, the program will go to the subroutine for heavy braking.

If the grid temperature is under T3, the microprocessor resets the heavy braking flag, if set, and compares the grid temperature to the stored temperature T2. The T2 temperature is less than the T3 temperature but is still critical (fire warning condition). If the read temperature is above T2 but less than T3, the program would go to the subroutine for T2. If the temperature is less than T2 but higher than T1, an elevated temperature above normal but not necessarily critical, the program would go into subroutine T1. If the temperature is less than T1, the program is returned to the start.

A flow chart for one subroutine to be used in determining whether or not heavy dynamic braking is on, is presented in Figure 5-8. The microprocessor reads data from the motor center to determine if the car is in a heavy dynamic brake mode. If it is, the main program is returned. If the car is not in a heavy brake mode, the input current to the grid is stored and added to any current memory. If the total current is equal to or greater than the number assigned for the heavy brake mode, the heavy brake flag is set and the main program returned. If the total current is less than the heavy brake mode, the time increment is compared to some arbitrary number. If the time increment is over the number, both the time and current are assigned a value of zero and the main program returned. If the time is less than the number, an additional increment of time is added to the number and the program is returned to read another new current input level.

An example of a T1 subroutine is presented in Figure 5-9. The temperature T1 is an elevated temperature above the normal upper temperature T for the dynamic braking grid but may be caused by repeated hard braking. If the temperature is below T1, the main program is returned. For a recorded temperature at or above T1, the program will ask if the train is in the heavy brake mode. If it is, the main program is also returned. If not, the microprocessor will ask if dynamic braking is being applied for that car above T1. If dynamic braking is being applied, the temperature is recorded. The microprocessor compares this temperature with that of T2 and if greater than T2, the program will go to the subroutine for T2 (fire warning). If the temperature is less than T2, the microprocessor will print a high temperature alert for that car and then return to the main program.

If dynamic braking is not being applied on the car in question, the temperature TA, is recorded. After a preselected time delay, if dynamic braking is still not being applied, a new temperature, TB, is recorded. If TB is greater than TA, a fire alert is transmitted to the operator, since the grid temperature is rising without dynamic braking being applied. If TB is less than TA, the microcomputer returns to the main program.

A subroutine for T2 is not presented but is expected to closely resemble the T1 subroutine. Final design of the main program and all supporting subroutines should be specifically tailored to the configuration, operating features and operating conditions of rail cars upon which it is to be installed.

6. FIRE SUPPRESSION APPROACHES

6.1 FIRE MECHANISMS

Haessler [3] describes the primary methods of fire extinguishment as:

1. reduction of heat
2. reduction of air
3. inhibition of flame chain reactions

These can be restated, more descriptively, as:

1. intensive cooling of the reactants and the combustion zone,
2. isolation of the reactants from the combustion zone,
3. dilution of the reactants by a nonreactive material,
4. chemical retardation of the combustion reaction.

Cooling the fuel is most practical for those combustibles that do not generate flammable vapors at ambient temperatures. This method of suppression applies therefore to solid combustibles and to high flash point liquids. Liquids with flash points below normal ambient temperature usually cannot be effectively extinguished by cooling. Water is the most common coolant used for extinguishment.

Separating fuel from the oxidant, normally air, prevents continuation of the reaction. This separation must be maintained until the material has cooled below its ignition temperature and no ignition sources are left to reignite the material. Foam and light water on Class B fires, and multipurpose dry chemicals on Class A fires* act in this manner.

The combustion process actually consists of a repeating sequence of reactions involving free radicals, particularly OH, O, and hydrocarbon radicals. These reactions must continue for the fire to be self-sustaining. Certain chemicals such as metallic salts and hydrocarbon halides inhibit these reactions and thereby extinguish a flame.

The agents most commonly used for fire suppression include water, protein foams, fluorochemical surfactants, dry chemicals, CO_2, and halogenated hydrocarbons.

---

[3] Haessler, W. M., "The Extinguishment of Fire", Revised Edition, NFPA No. FSP-40, National Fire Protection Association, Boston, MA, 1974.

* Class A fires - fires in ordinary solid combustibles; Class B fires - burning liquids and gases; Class C fires - fires in proximity of, or involving electrical equipment.

The fire suppression agent is the basic resource required to negate a fire threat. The equipment and manning required to deliver an agent are all interrelated. In general, it can be considered that the characteristics of the agent will dictate the equipment and the equipment will dictate the required manning. The principal dependent variables of fire suppression are:

1. fire control* and/or extinguishing* time
2. quantity of agent required for control
3. quantity of agent required for extinguishment
4. permanence of suppression
5. damage caused by the agent.

Fire control time is defined as the time at which the fire is sufficiently reduced in intensity that it does not present an immediate direct hazard to occupants or facilities.

Fire suppression may be accomplished by the local application of an agent directly on the base of the fire. This technique is most often employed with liquid or solid agents. Gaseous agents may be applied locally, but also permit "total flooding" of confined spaces in order to attack the fire wherever it may be within the space.

The significant functional parameters of locally applied fire suppression are the fire extinguishing agent and the agent application rate. These parameters, when related to the variable of fire configuration, can define fire control time, agent required to control, and total agent required to extinguish.

The typical relation between fire control (or extinguishment) time and agent application rate is presented in Figure 6-1. At low application rates the time required increases rapidly and approaches infinity below a limiting or critical application rate. This is the minimum rate at which the fire can be suppressed. Increasing the application rate above the critical value decreases the fire control time, although at higher application rates increasing the rate only results in a small decrease in time. The total agent requirements as a function of application rate are typically related as indicated in Figure 6-2. The point below which the agent requirements approach infinity corresponds to the critical application rate. The minimum agent requirements occur at a rate slightly above the critical rate. Increasing application rate above the minimum rate results in a gradual increase in total agent requirements.

The significant functional parameters of total flooding fire suppression are: agent concentration in the confined space (rate of delivery of agent influences fire size by affecting the time at which maximum agent concentration is achieved), and "soak time" or required period for retaining a desired agent concentration. Short "soak times" may not permit sufficient cooling so that the fire may rekindle once fresh air is readmitted.

---

*Fire "suppression" implies fire "control". That is, the fire may not be "out" (extinguished), but it no longer poses an immediate threat.

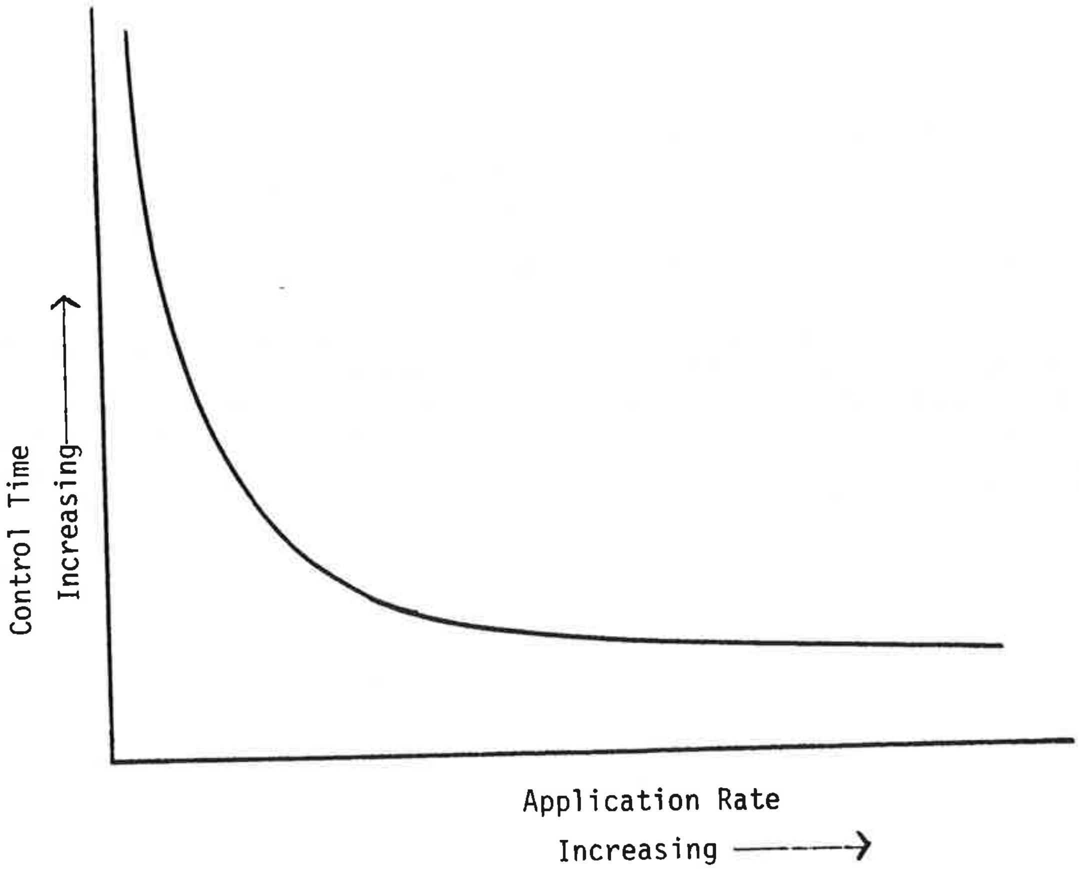


FIGURE 6-1 TYPICAL CONTROL TIME-APPLICATION RATE RELATION

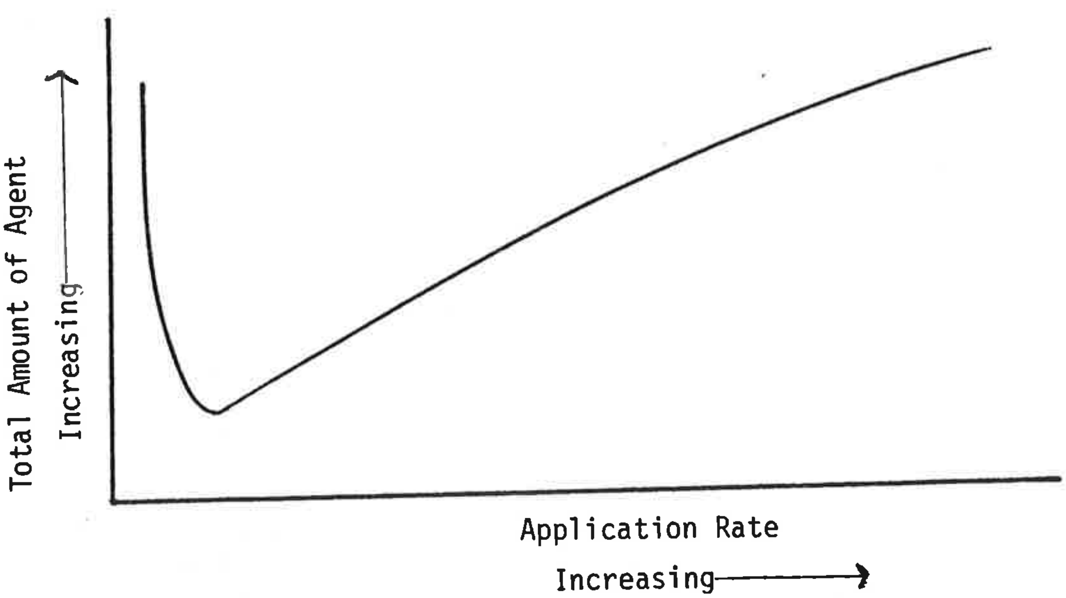


FIGURE 6-2 TYPICAL AGENT-APPLICATION RATE RELATION

The deep-seated fire is a circumstance which affects soak time requirements. The occurrence of deep-seated fires is peculiar to certain solid fuels. Liquids and many solid fuels burn by first vaporizing the constituents which then react with oxygen in the vapor phase above the fuel. Some solids burn without vaporization with a solid-gas reaction occurring on the solid surface. Glowing charcoal is an example of such a reaction. Agents which suppress fire by inhibiting the vapor phase reaction may not affect the solid-gas reaction.

Where the solid-gas reaction occurs on an exposed surface, suppression by cooling may bring surface combustion to a halt. However, in the case of a porous solid or other configuration where heat is somewhat confined, the solid-gas reaction may provide sufficient heat to sustain combustion for long periods. A "deep-seated" fire is the result. There is no line of demarcation between the two types of fires. National Fire Protection Association (NFPA) standards describe a surface fire as one in which glowing embers can be completely extinguished by 5 percent Halon 1301 with a soaking time of 10 minutes. Flames are readily extinguished in less than 30 seconds.

Although some tests have been made to demonstrate that plastics do not produce deep-seated fires, these results are not generally considered valid. Foam polymers when heated have been known to continue heating spontaneously to ignition; such a fire would definitely be deep-seated. Glowing combustion, a characteristic of a deep-seated fire, has been observed in polymeric cable insulation fire tests at Sandia Laboratories. In a transit vehicle similar heating could occur as a result of a high resistance electrical fault to ground.

Polymeric foams installed inside structures have fueled numerous rapidly spreading fires which have overpowered ordinary automatic sprinkler systems. The report of the May 1979 fire in an anechoic chamber at Hughes Aircraft indicates that such a fire is possible with non-fire retarded anechoic foam. Factory Mutual tests do not exclude the possibility of such fire development in fire retardant foam installations as well.

Users and suppliers of the fire retardant foams and materials often state that they cannot be ignited by ignition sources such as a cutting torch. This is not always a reliable index. An important factor to consider is the relation between thermal flux applied to a combustible and the heat release rate from the combustible. With cellulose materials, heat release rate is approximately a linear function of the applied thermal flux. However, with polymeric materials, the linear approximation generally exists up to a particular level of applied thermal flux; beyond this level there can be an exponential increase in the heat release rate with further increases in applied thermal flux. This phenomenon has been the cause of the major discrepancy noted between some fire test evaluations of foam polymers and actual fires.

The Factory Mutual corner tests show that with a high intensity ignition source a rapidly developing fire is possible even with fire retardant foam. If their crib represents a reasonable equivalent of a fire that might expose polymeric walls and ceiling, a rapidly developing fire will be possible in rail transit cars so equipped. The rapid buildup of fire in the Hamburg-Altona subway fire described in Appendix C may support this proposition.

6.2 FIRE EXTINGUISHMENT METHODS/AGENTS

Two basic extinguishing methods are suitable for managing rail transit vehicle fires. The methods are by total flooding of the space or by surface application of agent. Seven different agents are considered to have some utility for the problem at hand. Some agents are suitable for application by only one method while other agents may be applied by either surface or flooding methods under specified conditions.

An evaluation of the utility and effectiveness of method/agent combinations was performed. The combinations selected for further examination are listed below.

- Total Flooding System
  - Carbon Dioxide
  - High Expansion Foam
  - Halon 1301
- Surface Application Systems
  - Waterspray
  - Dry Chemical
- Surface Application or Total Flooding Systems
  - Halon 1211
  - Freon 12 or Freon 22

All of these, except the Freon based systems, are currently providing state-of-the-art protection for one or more of the following: structures, boats and ships, aircraft, racing cars, or mobile machinery, e.g., mining equipment.

No fire extinguishing systems were installed in any operational rail transit vehicles. The suitability of each of the above systems was evaluated for effectiveness, safety, endurance in the rail transit operating and storage environment, reliability and maintainability, cost and weight as appropriate.

6.2.1 Carbon Dioxide

One of the oldest fire extinguishing agents for use on flammable liquid fires and fires involving energized electrical equipment is carbon dioxide, CO_2. The fire extinguishing action of CO_2 is principally that of blanketing the fuel and displacing the air, although it does slightly inhibit the free radical chain reaction necessary to sustain combustion. Carbon dioxide does not leave a permanent blanket over the fire and if a residual ignition source remains after application of the CO_2, the fire will restart as soon as the CO_2 is dissipated.

The advantages of CO_2 are: it leaves no residue, it is low in cost; it does not react with most materials; it is a nonconductor of electricity, and it is self-pressurizing for discharge from storage tanks. Its disadvantages are that it does not leave a blanket over the fire and it can be dispersed readily. Also, the discharging gas-solid mixture is extremely cold and may cause thermal shock damage to apparatus.

Carbon dioxide systems are currently used in some structural and marine applications; it was once common for aircraft engine fire extinguishing systems. For aircraft use, carbon dioxide was long ago replaced, first by chlorobromomethane, which has now been replaced by Halon 1301. Carbon dioxide systems are very attractive in the protection of large occupied volumes in which fires may occur frequently, such as engine test cells. The agent cost of carbon dioxide is a small fraction of the cost of either Halon 1301 or Halon 1211.

Carbon dioxide is stored as a liquid (or vapor) under its own pressure at ambient temperature or in refrigerated storage containers at $0^{\circ}F$ and approximately 300 psi pressure. Refrigerated storage is not practical for systems of the size that would be used on rail transit vehicles. Because of its very high vapor pressure, over 800 psi at $70^{\circ}F$, carbon dioxide systems require very strong and heavy storage containers and distribution piping.

When discharged, a large portion of the liquid flashes to vapor and the rest is converted to solid carbon dioxide or dry ice at $-110^{\circ}F$. The effective range of the discharged stream in surface application systems is relatively short and when it is used in open areas it dissipates rapidly. The very cold vapor and solid dry ice may also cause damage through formation of particulates.

Turning to a gas, CO_2 mixes with and displaces air and therefore can cause adverse physiological effects on exposed personnel. Increase of the CO_2 concentration in inspired air stimulates respiration. As the concentration is further increased, it acts as a dilutant leading to anoxia. Short time exposure to slightly elevated CO_2 concentrations does not produce any irreversible damage. The lethal limit of CO_2 is very high at 65.8 percent with an associated anesthesia time of 1 minute. For short term exposures the maximum allowable concentration (MAC) is 5 percent. Under typical fire control conditions, a higher limit of about 10 percent is considered reasonable. Unfortunately, although it also does not produce any toxic decomposition products, the concentration of carbon dioxide required to suppress a fire inside a passenger compartment would also suffocate the passengers.

Fires in semiconfined areas require about 6 to 7 lb of CO_2 per lb of airflow to extinguish a severe fire. In confined areas a CO_2 concentration of 29.5 percent by volume is necessary to suppress or prevent ignition of n-heptane [4]. This corresponds to a concentration by weight of about 65 percent.

Experience and the inherent limitations of carbon dioxide indicate that it is not a practical agent for undercar surface application systems except possibly for spot protection. However, it could be used for total flooding systems although it would require confining undercar enclosures just as Halon 1301 and Halon 1211.

---

[4] The Halogenated Extinguishing Agents, NFPA Report Q48-8, National Fire Protection Association, Boston, Mass., 1954.

6.2.2 High Expansion Foam

High expansion foam is a very low-density assemblage of bubbles which are formed by air (or another gas) and a water-foaming agent solution. The foam is generated by blowing the air (or gas) through a stream which is wetted by a surface acting foaming agent. Expansion ratios (the volume of generated foam to the volume of water used to make the foam) range from 100:1 to 1500:1. High expansion foam was developed for extinguishing coal mine fires and also has been used and promoted for extinguishing structural fires in confined spaces. Currently, there is considerable interest in this foam for use on liquid natural gas spill fires.

High expansion foam is used primarily in portable and mobile manual fire suppression. Some fixed installations have been used for the protection of warehouses and some areas aboard ship. High expansion foam is typically generated by air; however, it does not effectively expand if contaminated by many combustion products. Although nationally recognized standards consider high expansion foam electrically conductive, limited experimental data indicate that it is not a very good conductor. The U.S. Navy conducted tests in which they exposed a metal manikin to a 440 volt ac source when immersed in high expansion foam. The objective was to determine how close the voltage source could come to the manikin without inducing a flow of 10 milliamperes through the "body". The procedure was very conservative since the metal manikin had essentially no resistance to ground while even the moist human body would be expected to have a resistance of 1500 ohms. With foam made from fresh water and having an expansion ratio of 500:1, the current at an electrode-manikin separation of 1 inch, was 9 milliamperes. With another foaming agent, the current under similar conditions was 30 milliamperes. Some foaming solutions provide a better insulating foam than others. Higher expansion foams have a lower water content and therefore they should have a lower conductivity. The tests indicated that high expansion foams may be sufficiently poor conductors to permit their use on undercar fires involving energized electrical equipment; however, additional experimental work would be necessary to verify this result.

Due to its low water content, little water damage is attributed to the use of foam. However, this low water content, and the fact that the expansion gas is air, indicates that high expansion foam may not be effective against deep seated fires.* Although the foam may well subdue active flaming, its presence will hinder discovery and manual extinguishment of areas of deep seated fire character.

High expansion foams, like Halons or carbon dioxide, would have to be contained by an undercar enclosure. Unlike enclosures for Halons and carbon dioxide, the enclosure to retain high expansion foam does not have to be solid but could be a coarse screen. Such an enclosure permits free flow of cooling air to the electrical components and allows visual inspection of the undercar area.

---

* On at least one occasion, a liquid pool fire was sustained under a blanket of high expansion foam. This may be attributed to the particular foam density employed.

6.2.3 Halon 1301 Systems

Halon 1301 is very effective in suppressing flaming surface fires such as those involving flammable and combustible liquids and some solids. It can also be used on deep-seated fires; however, Halon 1301 provides very little cooling, so the suppression concentration must be maintained until the material cools naturally.

Since Halon 1301 neither cools nor blankets a fuel, it is most suitable for extinguishing surface fires in enclosed spaces which can be totally flooded. Since the agent is heavier than air, it s concentration will be greatest in the lowest levels of the space. The requirements for extinguishing surface fires with Halon 1301 flooding are presented in Table 6-1 [5].

TABLE 6-1 AGENT REQUIREMENTS FOR SURFACE FIRE EXTINGUISHMENT BY HALON 1301 FLOODING [5]

Combustible	Volume %	Weight %	Amount in 100 ft^3 Space lb
Acetone, n-heptane, ethanol	5.0	26.0	20
Propane	5.2	27.0	21
Ethylene	8.2	42.0	32

Halon 1301 is used in both total flooding and surface application fire suppression systems. Surface application of Halon 1301 is not considered practical for passenger compartment fires or for undercar fires. The total flooding protection is considerably more practical and efficient for interior passenger compartment use. Undercar rail transit vehicle fires are typically caused by electrical or friction overheating in which the adjacent combustibles are raised above their ignition temperature. Because of its high vapor pressure, Halon 1301, when discharged as a liquid, quickly vaporizes and provides very little cooling of the combustibles. In undercar application, the Halon would quickly suppress any surface fires; however, the agent would quickly dissipate and the hot combustibles could reignite.

Halon 1301 total flooding fire suppression systems are currently used in structural, aircraft, marine and vehicular fire protection. These systems are most commonly used to protect high value or critical equipment such as computers or control rooms, and spaces which have a serious fire problem such as engine compartments, engine rooms aboard ships, aircraft cargo compartments, and aircraft nacelles.

---

[5] "Standard on Halon 1301 Fire Extinguishing Systems, NFPA 12A-1980" National Fire Codes, National Fire Protection Association, Quincy, Mass., 1981.

Halon 1301 is but one of a family of vaporizing liquids which can be used as fire extinguishing agents. Carbon tetrachloride (CCL_4) was the first of this family to be used as a fire extinguisher; it was followed much later by methyl bromide (CH_3Br). These two agents are being phased out because of possible toxicity problems. Many other halogenated hydrocarbons have been investigated for fire extinguishment applications--the agents in current use or being considered are listed in Table 6-2.

TABLE 6-2 COMMON HALOGENATED HYDROCARBON FIRE EXTINGUISHING AGENTS

Name	Formula	Halon Number	Molecular Weight
Chlorobromomethane	CH_2BrCl	1011	129.4
Dibromodifluoromethane	CBr_2F_2	1202	209.8
Bromochlorodifluoromethane	$CBrClF_2$	1211	165.4
Dibromotetrafluoroethane	$C_2Br_2F_4$	2402	259.9
Bromotrifluoromethane	$CBrF_3$	1301	148.9

These agents extinguish fires by inhibiting the free radical reactions necessary to sustain combustion. They do not leave a vapor sealing blanket over the fuel nor do they significantly cool a fuel.

There are no theoretical relationships or adequate experimental data to compute the concentration of halogenated hydrocarbons needed to extinguish all fires by total flooding. In contrast to Table 6-1, tests conducted for the Boeing 747 transport [6] have shown that incipient cargo fires can be extinguished with the application of 4.84 lb of Halon 1301 per 100 ft^3 of volume ($\sim$1.3 percent by volume). However, once deep-seated fires are established, the required amount is much higher [7].

The toxicity of halogenated hydrocarbon extinguishants must be considered both from the parent compound and from products produced by thermal decomposition. At high temperatures, these agents break down, yielding carbonyl halides (phosgene type gases). For further detail, the reader is directed to the comprehensive review by Musick and Williams [8].

---

[6] "Fire Suppressive Systems Tested", Aviation Week and Space Technology, April 14, 1969.

[7] Ford, C. L., "Extinguishment of Surface and Deep Seated Fires With Halon 1301", in "An Appraisal of Halogenated Fire Extinguishing Agents", Proceedings of a Symposium held April 11-12, 1972 at National Academy of Sciences, Wash., D.C.

[8] Musick, J. K. and F. W. Williams, "The Use of Halons as Fire Suppressants, a Literature Review", NRL Report 8161, Naval Research Laboratory, October 5, 1977 (AD No. A050098).

In the extinguishment of fires in ventilated areas, no hazard is anticipated. The toxic products are quite noxious and the natural tendency is for one to move away. Even CCL_4 and CH_3Br, which are more toxic than Halons, did not create a direct hazard in actual fire extinguishment. Almost all injuries and fatalities from those agents are from exposure to the natural vapor--often because of misuse.

Some indication of the relative life hazard of Halon 1301, 1211, and Freon 12 (R-12) is provided in the Standard for Halogenated Fire Extinguishing Systems, Halon 1301 (NFPA No. 12A), 1977 edition [5]. The Standard presents an Underwriters Laboratories, Inc. classification of life hazard of various chemicals based upon the results of exposure of test animals. Materials are ranked by decreasing toxicity in six categories. Halon 1301 and Freon 12 (R-12) are classfied as "least toxic" or Group 6, which is defined as "Gases or vapors which in concentrations up to at least 20% by volume for duration of exposure of 2 hours do not appear to produce injury."

Halon 1211 (see Section 6.2.6) is assigned to Group 5 which is defined as being intermediate between Group 6 and 4. Group 4 is defined as containing those "Gases or vapors which in concentrations of the order of 2 to 2½ percent for duration of the order of 2 hours are lethal or produce serious injury".

Freon 22 (see Section 6.2.7) is not classified.

The NIOSH/OSHA Pocket Guide to Chemical Hazards addresses the issue of workplace exposure to these agents in terms of maximum exposure for given periods of time [9]. The Permissible Exposure Level (PEL) specifies maximum concentration for an 8 hour workday. A concentration represented as Immediately Dangerous to Life or Health (IDLH) is defined as that which can be tolerated for no more than 30 minutes without irreversible damage to health.

The Permissible Exposure Limit (PEL) value for Freon 12, Freon 22, Halon 1301 and Halon 1211 is 1000 ppm for an 8 hour time weighted average.

The Immediate Danger to Health Limit (IDLH) for Freon 12, Halon 1301 and Halon 1211 is 50,000 ppm. A Short Term Environmental Limit (STEL) of 1250 ppm Maximum Air Concentration (MAC) exposure for 15 minutes duration with 16 minutes between exposure is specified for Freon 22. None of the above data address the toxicity of the pyrolysis products of these agents.

Halon 1301 is typically stored in liquified form at ambient temperature and elevated pressure. Storage containers are typically superpressurized with nitrogen to 360 or 600 psig. The liquid is distributed from the storage containers through a valve to nozzles which disperse it into the protected

---

[5] op. cit.

[9] Machison, F. W., Stricoff, P. S., and Partridge, L. T., Jr., Eds., NIOSH/OSHA Pocket Guide to Chemical Hazards, DHEW(NIOSH) Publ. #78-210, GPO Stock No. 017-033-00342-4, Government Printing Office, Washington, D.C., 20402

volume. Opening the storage container valve initiates system operation; solenoid, pressurized gas, pyrotechnic and squib valve operators are used in Halon 1301 systems.

Halon 1301 is considered a relatively safe total flooding agent and national standards permit its discharge in occupied rooms as long as the resultant concentration does not exceed 7 percent. Concentrations as high as 10 percent are permitted in occupied rooms if they can be evacuated in one minute.. Such a short evacuation would not be possible on a crowded transit vehicle during a rush hour.

A two-step extinguishing program is sometimes appropriate in which Halon 1301 concentration is automatically raised to 7 percent. Subsequent manual or delayed automatic second discharge can be employed to maintain or to further increase concentration.

The toxic gases produced in extinguishing a fire will depend upon the size of the fire when the agent is discharged and how rapidly the fire is suppressed. A rapid discharge of Halon will quickly suppress the fire but will also produce extremely high compartment noise levels.

A passenger compartment Halon 1301 total flooding system would be intended to suppress a fire that originates within the passenger compartment itself. It could be expected to delay but not prevent the spread of an under-car fire into the passenger compartment. A fire that originates under the car and burns through the floor would induce hot gas and airflows that could dilute the Halon concentration within the passenger compartment. Once diluted, the fire could spread unimpeded. In addition, a fire penetrating the floor would also allow smoke and toxic gases to enter the passenger compartment and produce a lethal atmosphere before the interior seats and finish became involved in fire.

Such a system would also require that the passenger compartment ventilation system be shut down at the time the agent was discharged. If the ventilation were to remain operating, an excessively large amount of Halon 1301 would be required to produce and maintain agent concentration. A total flooding system for under car use would require partial enclosure of the undercarriage to minimize the loss of agent.

6.2.4 Waterspray Systems

The oldest and most basic of all fire extinguishing agents is water. It can be used to suppress any kind of fire, with the exception of highly reactive metals such as sodium. The principal advantages of water are its high latent and specific heats, its low cost, the ease with which it can be transferred and applied, and in general, its local availability. Its high freezing temperature and poor blanketing characteristics are two important disadvantages for many rail transit applications.

Spray application of water creates small droplets which increase the total surface area for heat transfer. This increases droplet vaporization in the flame, decreases flame intensity, and also distributes the water over the surface of the combustible. A spray is the most efficient way of applying water except when distance, air velocity, flame intensity, or materials would prevent the water from reaching the base of the fire.

The water droplets must have a size/velocity relationship such that most of the droplets reach the surface of the fire. Droplets below 100 to 150 microns in diameter will be largely dissipated in a fire before reaching the surface. Most of the droplets over 300 microns will reach the surface of the combustible. High-pressure water sprays, 600 to 800 psig, feature high velocity droplets of small diameter. Penetration of the flame is achieved by the high velocity and the small droplets then rapidly evaporate at the base of the fire.

High and low pressure sprays are used in flammable liquid fires where a large water supply is available and where a securing and blanketing agent is not. The use of spray in flammable liquid fire suppression is being supplanted somewhat by agents with blanketing action or quick knockdown characteristics.

Additives are often used with water to improve its advantages or negate its disadvantages. Wetting agents added to water decrease its viscosity and increase the rate at which the water penetrates porous materials. Additives are also used which increase the viscosity of water to decrease the rate at which it runs off surfaces and thereby increase the heat transfer from the surface to the water. Finally, foaming agents or surfactants and air are mixed with water to form blanketing foams.

Application of water in a straight stream permits it to penetrate the flame and reach a burning combustible immediately. This does not directly reduce the flame intensity and often puts an excessive amount of water on a local part of the combustible. If a straight stream hits a burning liquid it scatters the fuel, often spreading the fire. The straight-stream is most effective in fires involving solid combustibles where the flame or draft intensity is so great that small water droplets can neither reach the surface nor significantly reduce the flame intensity.

Waterspray fire suppression systems are presently suitable for suppressing passenger compartment and undercar fires only in climates where the water can be carried and stored in cars without a danger of freezing. It is likely that there will be strong opposition to using water underneath and inside a transit car because of concern over use of water around live electrical equipment. Attitudes and practices concerning the use of water on fires involving live electrical equipment vary widely. It is common in both industrial and utility facilities to install fire suppression waterspray systems to protect oil-filled electrical transformers of all voltages. In addition, many electric utilities routinely install automatic water sprinkler protection in areas of their generating stations containing live electrical equipment. However, there are many other electric utilities which will not install any water fire suppression systems around live electrical equipment. The Browns Ferry Nuclear Generating

Station fire nearly became a major national disaster instead of a minor incident because the electric utility would not permit the use of water on a cable fire. Currently, the Nuclear Regulatory Commission requires that all critical areas of nuclear powered generating stations be provided with fixed water fire suppression systems either as the primary protection means or as a backup to any Halon or carbon dioxide system the utility may want to install.

The objections to the use of water on fires involving live electrical equipment stem primarily from concern over potential electric shock and possible equipment damage from the water. This concern is so great that many people involved in fire suppression will not even use water on fires involving de-energized electrical equipment where there is no shock risk. Actually, tests have shown that fresh water is a relatively poor conductor of electricity and experience suggests it is not likely to be a problem at the operating voltages of rail transit vehicles. Tests using hand hoselines have shown that an operator can safely use a waterspray nozzle within 6 inches of a 15,000 volt conductor and a 1-1/8 inch solid stream nozzle can be safely used within 6 feet of a 1100 volt conductor. The conductivity of water in a fixed spray system can be further reduced by using demineralized water instead of fresh water. Water may actually be safer under many conditions than some agents commonly used to extinguish fires in live electrical equipment.

Carrying and storing water on transit cars in colder regions would require the use of a solution which can affect the conductivity of the water. Commonly using antifreeze salts would increase the conductivity significantly to the point where it probably would not be safe. Organic antifreezes such as glycol may be usable although the effect of these solutions on fire extinguishment and conductivity is unknown. Glycols are used as antifreeze agents in automatic sprinkler systems but the initial solution discharge is always followed by a plain water discharge. Glycols are combustible and would have some combustibility properties even in a water solution. However, other agents, including some of the halogenated extingusihing systems, are also combustible under certain circumstances.

6.2.5 Dry Chemical Fire Extinguishing Systems

Dry chemical is a collective term encompassing a family of salts which are used to extinguish fires. With one exception, these salts do not blanket or cool a combustible; their fire suppression is primarily of chainbreaking action which inhibits the free radical reactions necessary to sustain combustion. The salts are used in an anhydrous form composed of fine particles typically 10 to 75 microns in size. The first dry chemical agent introduced was $NaHCO_3$; other salts used currently include $KHCO_3$ (Purple K), $(NH_4)H_2PO_4$ (multipurpose), KCl (Super K), and NH_2 COOK (Monnex).

All of these agents are effective in controlling flammable liquid fires. The $(NH_4)H_2PO_4$ is the only one considered suitable for general extinguishment of solid combustible fires. It extinguishes fires in ordinary combustibles by a blanketing action which leaves a gas-sealing crust on the solid combustible. This crust prevents distillation of combustibles from the solid and prevents oxygen from reaching the combustible. This blanketing crust does not form on liquid combustibles. The other dry chemical agents will knock down a fire in solid combustibles; and, if only a surface fire is present, it may stay extinguished. However, if the combustible is heated to its ignition temperature, the fire will quickly rekindle.

A major advantage of dry chemical agents is their ability to rapidly reduce the intensity of a fire, commonly termed knockdown ability. Additional advantages, particularly important in portable extinguishers, are that dry chemicals can be applied from a greater distance and are less dependent on skillful application than some other agents. This is a general qualitative evaluation, and it is not possible to define the exact magnitude of the advantage, except for range.

A major disadvantage of dry chemical suppression is the "mess" remaining after use, with difficult, costly, and often unsuccessful cleanup.

Dry chemical extinguishing agents are nonconductors and are all suitable for use on fires involving energized electrical equipment. However, when combined with moisture, the resulting solution can be highly electrically conductive. A fire service publication recently alerted firefighters to a possible electrical shock hazard when dry chemical extinguishers are used to control fires in pole-mounted transformers during a rain storm. The magazine stated that the chemical solution running down the pole could provide a conductive electrical path injuring someone at the base of the pole.

Despite the ratings of nationally recognized testing laboratories, which approve multipurpose dry chemicals for fires in ordinary combustibles, a number of institutions have found them relatively ineffective on certain types of chair and mattress fires. Dry chemical extinguishing agents also have limited application to electrical fires in power systems because of the residual heat in the conductors or combustible material.

In the absence of any effective cooling action, the only agent that might be effective would be the multipurpose dry chemical which forms a coating on the surface. These coatings are usually very difficult to remove. Although dry chemical may be a very appropriate extinguishing agent for use in portable fire extinguishers aboard rail transit vehicles, we do not feel it is an advantageous agent to consider for any fixed fire suppression system in or under these cars.

6.2.6 Halon 1211 Surface Application or Total Flooding

Halon 1211 is very effective on surface fires involving ordinary combustibles and flammable or combustible liquids, and on some types of deep-seated fires. When used in a surface application system, Halon 1211 is discharged as a liquid. Because of its low vapor pressure, much of the liquid stream will reach the burning combustibles. Total flooding systems protecting spaces containing ordinary combustibles require in excess of 5 percent concentrations and may go as high as 10 percent. For surface application systems, the application density should be determined experimentally. Recent Federal Aviation Administration tests on extinguishing fires in airplane seats suggest a possible application of 0.2 to 0.3 lb/ft^2 directly on a fire in a passenger compartment.

Halon 1211 fire suppression systems, though not as common as Halon 1301 systems, are still extensively used to protect engine compartments of boats, structures and as portable fire extinguishers in aircraft passenger cabins. Portable extinguishers have been found highly effective in suppressing fully involved fires in polyurethane cushions in passenger seats.

Halon 1211 is stored as a liquid at ambient temperature and elevated pressure. It has a relatively low vapor pressure, about 23 psi at 70°F, so it is normally superpressurized to 360 or 600 psig with nitrogen to facilitate discharge. Halon 1211 systems are discharged by actuating a valve, similar to 1301 systems. Some Halon 1211 systems use a fusible link valve and nozzle similar to an automatic sprinkler head; this provides a simple, self-contained and heat-actuated system.

Halon 1211 is not as physiologically safe as 1301 (see Section 6.2.3). NFPA standards do not permit the use of total flooding Halon 1211 systems in normally occupied spaces. Total flooding systems can be used in normally unoccupied rooms; e.g. telephone equipment rooms, switchgear rooms and storage rooms. However, it must be possible for any chance occupants of that space to evacuate within 30 seconds. NFPA Standards do permit the use of surface application systems in occupied spaces providing the resultant average residual Halon 1211 concentration is less than 4 percent. These safety considerations preclude the use of a total flooding Halon 1211 system inside a passenger compartment and limit the size of any surface application system used therein.

The yield of toxic decomposition products for Halon 1211 will be greater than for Halon 1301 which further reduces its attractiveness in occupied spaces. Because of the low vapor pressure of Halon 1211, considerable amounts of liquid agent will reach the burning material; this increases the cooling effect and may permit continued operation of passenger car ventilation during surface applied agent discharge. Like Halon 1301, Halon 1211 should be discharged early and rapidly to minimize the production of toxic decomposition products. However, early and rapid discharge increases both the risk of inadvertent operation and the magnitude of the noise during discharge.

Halon 1211 is a very efficient estinguishing agent on surface fires and provides considerably better cooling than Halon 1301 in deep-seated fires and with hot combustibles. In fact, portable Halon 1211 extinguishers have a higher per pound rated effectiveness on fires in ordinary combustibles than portable water extinguishers. This is not due to the inherent cooling capacity of Halon 1211; water has a significantly higher cooling capacity. It is believed that this is due to a combination of improved heat transfer and the fact that Halon 1211 applicators may be of more efficient design than those employed with portable water extinguishers.

A Halon 1211 total flooding undercar protection system would require an enclosure of the undercarriage equipment to prevent agent dissipation. A surface application system could be designed without such an enclosure.

6.2.7 Freon 22 or Freon 12 Surface Application or Total Flooding

Halon 1301 is an excellent low temperature refrigerant and was used as such until lower cost materials were developed. Common refrigerants presently used in air conditioning systems, Freon 22 and Freon 12, are also halogenated hydrocarbons belonging to the same general family as Halon 1301 and Halon 1211. Freon 12, CCl_2F_2, has the chemical nomenclature of dichlorodifluoromethane and Freon 22, $CHCl_2F$, of chlorodifluoromethane. Both of these agents are odorless, colorless and nonconductive gases; Freon 22 is about three times, and Freon 12 about four times, as dense as air. In early research and development work on fire suppression using halogenated hydrocarbons, both of these agents were known to be effective in extinguishing fires. The potential weight and cost benefit of using an agent already aboard a car for fire suppression may be attractive even though it may not be as efficient as other extinguishing agents. Both Freon 22 and Freon 12 can be discharged in a manner similar to Halon 1301 and 1211. Since Freon 12 has the lowest vapor pressure, it maintains a liquid stream longer than Freon 22. However, Freon 22 is the most commonly used refrigerant in larger air conditioning systems.

An effective Halon application rate is in the range of 1 lb/50 cu feet of space. Rail transit vehicle air conditioning systems presently contain approximately 28 to 32 lbs of refrigerant per car for a passenger compartment volume of 2800 cu feet (CTA cars). For enclosed underfloor fires there is probably more than enough capacity available for fire extinguishment.

Halon 1301 physical characteristics are such that it is usually used only in low temperature cascade refrigerating systems. A major redesign of existing rail transit vehicle cooling systems would be necessary to satisfactorily use it as an on-hand refrigerant/extinguishment. If Freon agents are retained, the significant question of the toxicity of the agent and pyrolysis products will have to be resolved.

6.2.8 Nitrogen

Nitrogen acts to suppress combustion by displacing oxygen, as does CO_2. Its principal disadvantage is that it must be stored as a compressed (rather than liquified) gas; thus, large high pressure storage tanks are required. For this reason, nitrogen has had limited application in fire suppression. Its use generally has been limited to small specialty applications. Nitrogen gas is added to Halon systems to hasten discharge.

6.2.9 Uncommon Suppression Agents

Numerous other possible fire suppression agents and combinations of agents were considered and rejected as candidates for rapid transit vehicle fire protection systems. These agents included: wetting agents, jelling or thickening materials, thixotropic materials, emulsifiers and Halon foams. All of these are water-based agent systems and none are believed suitable for storage below freezing temperature. In addition, the conductivity of these agents is not established and may pose potential shock or short hazards. These agents have all been considered for various fire protection applications and some are even currently used for special purposes. For example, wetting agents are very effective on fires in cotton bales and other materials where deep penetration of the coolant is required. There is no established advantage for the use of such agents on expected transit vehicle fires. Jelled or thickened agents which will adhere to some vertical and inclined surfaces are used in forest firefighting air drops and have seen some very limited use in structural firefighting. These agents have an ability to adhere to relatively cool surfaces such as would be encountered under a rail transit vehicle. These neither represent the state of the art nor appear to have any advantage in controlling fires in or under the transit vehicles. Thixotropic materials are water based agents which release the water when stressed. As fire suppression agents these are certainly not considered state of the art and, as with the previous agents, appear to have no particular advantage for rail transit vehicle application.

Emulsifiers mixed with water are used to reduce the fire hazard of spilled flammable liquids and have been promoted as a fire suppression agent. Their main function is reducing the fire hazard of spilled flammable liquids by forming a water-fuel emulsion with a very low vapor pressure. Any fire suppression or cooling properties that these materials possess do not appear to be beneficial for use in rail transit vehicles since spilled flammable liquids are not involved in most significant fires.

Halofoam was originally intended for suppressing flammable liquid fires and later considered for use in portable fire extinguishers aboard submarines. It is a relatively low expansion foam which would be expected to be more electrically conductive than high expansion foam. It has no significant advantages compared to the foams of higher expansion.

Appendix B presents a summary of fire suppression agents. Agents are categorized by their physical state at time of application (solid, liquid, gas) and identified by chemical composition. Their applicability to solid or liquid fuels and electrical fires is indicated under Fire Classification. Primary extinguishment mechanisms are also given along with general comments addressing advantages, disadvantages, and use requirements.

6.3 FIRE SUPPRESSION SYSTEMS

Fire protection equipment includes agent transfer and application systems for the purpose of preventing or suppressing hazardous fire situations. This equipment can be divided into three major classifications: fixed, portable, and mobile systems. Fixed systems are designed to provide protection at a specific site, usually against a well defined hazard. Portable equipment is that which is manually moved from its storage location to a hazard. This equipment provides protection over an area in which potentially hazardous situations may occur.

Mobile systems include vehicle and airborne systems which provide support at levels beyond that feasible for many fixed or portable systems. These will generally be a part of the support effort of nearby fire departments. Access to the fire site is a significant problem when considering the applicability of mobile systems to rail transit fires. They are not addressed further in this study.

6.3.1 Fixed Systems

These fire protection systems include prepositioned nozzles and hose reels connected to an extinguishing agent supply. Foam, water, CO_2, and dry chemical are all used in fixed systems. Those systems using water or foam-water are generally connected to water mains and a large if not unlimited supply of water is required to be available. Dry chemical and CO_2 are stored at the site in self-contained units.

Prepositioned nozzles provide spot coverage in areas where the hazard is well defined physically. The agent and application techniques most commonly used are outlined:

1. Automatic Spray Sprinklers - Conventional sprinkler heads with a spray pattern, automatically opened individually by heat.
2. Water Deluge Sprinkler - An array of normally open spray nozzles with a common water supply control valve; opening of the valve, manually or automatically, supplies water to all the sprinklers simultaneously.
3. CO_2 - Open nozzles supplied from storage through a manual or automatically actuated valve; CO_2 supply may be either high pressure cylinders or low pressure refrigerated storage.
4. Halon - Similar to Item 3.
5. Dry Chemical - Open nozzles supplied from container; agent is expelled by N_2 pressure supplied by high pressure cylinders.
6. Flash - Popup Water Spray Nozzle - Used to cover wider areas such as loading or service ramps; combination of water deluge system and lawn sprinkler system; manually operated; limited actual use.
7. High Expansion Foam - Fairly complex generating equipment dumps the foam directly into the space to be protected through short duct runs.

The advantages of prepositioned nozzle systems include rapid response, efficient agent distribution, independence of operator skill, and nonexposure of an operator to hazards. Even if the nozzle application does not reach the entire fire, it will generally contain the fire and limit fire damage, allowing time for other fire control operations. A custom designed system is most appropriate if limited amounts of agent are to be dispensed. Special application nozzles are required to direct the agent to all surfaces.

Hose reels attached to an agent source can supply prepositioned nozzles or be used as hand-held lines. These should be considered a "backup"; and should be restricted to water as the agent. Hoses should be small diameter (1 to 1½ inch), and the flow velocity (supply pressure) limited such that one person can handle each line. Lengths of 100 to 200 feet are common.

Unlike the fixed nozzle, hose stream effectiveness is very largely a function of the skill of the operator. In addition, the operator must have the protective clothing of a fireman. The need or desirability of such hose stations is only positively filled if well-trained operators are immediately available. Without trained operators, hose systems often impair fire suppression by delaying effective responses.

6.3.2 Portable Systems

Hand-carried and wheeled portable fire extinguishers are common around most transit properties. These are often referred to as first aid firefighting equipment, indicating that their purpose is to extinguish minor fires or contain medium size fires until professional assistance arrives. The most common extinguishers and their application are outlined below:

- CO_2 - high pressure cylinders from 5 to 75-lb capacity - suitable for small spill fires, very effective on incipient closed space fires if reach and access are possible.
- Dry Chemical - 5 to 30-lb hand carried and 150 to 350-lb wheeled containers of $NaHCO_3$, foam compatible $KHCO_3$, KCl, and ammonium phosphates. Useful on spill fires and small enclosed fires.

Data describing the utility of portable extinguishers are not available. Their effectiveness is strongly dependent on operator skill and their use may expose an operator to definite danger. Too often, personnel in areas protected by portable extinguishers have never read the instructions. Unless the personnel are trained in their use, most hand extinguishers are useless. For example, a 30-lb $KHCO_3$ hand portable is rated by Underwriter's Laboratories, Inc. at 80 B. This means a skilled operator can extinguish a naphtha pan fire of 200 square feet and assumes that an unskilled operator can extinguish a naphtha pan fire of 80 square feet. Portable extinguishers are of the most value in suppressing incipient fires in enclosed compartments such as a carburetor fire or small fuel leak.

There is definite doubt about the utility of the number of portable fire extinguishers common to many industrial installations and transit properties. Investigation is appropriate into what sizes and types are most useful.

7. DESIGNS FOR FIRE SUPPRESSION SYSTEMS

7.1 SUPPRESSION SYSTEM SELECTION

Rail transit vehicle fire suppression can be provided by total flooding, specific enclosure or compartment flooding, or direct surface application of an extinguishing agent. Any fire suppression system will be of limited value if an electrical fault is responsible for the fire threat and is not cleared or isolated. Continuing flow of fault current will heat up and vaporize insulation, nonmetallic enclosures, and other metallic and nonmetallic materials. These will keep generating smoke and, when the agent dissipates or application ceases, the hot materials may ignite or re-ignite. Any electrical fault should be cleared or isolated as soon as it is identified. It is very difficult to isolate some faults such as one involving a grounded current collector. If it is possible to isolate a fault from power quickly, the fire threat may dissipate naturally without any agent application. Fault isolation has the additional advantage that it can be done while the car is in motion. Most undercar suppression systems would not be effective until the train stopped. The airflow under the car would either dissipate the agent or deflect its application streams. Normally, it is very dangerous to stop a train involved in a fire between stations, particularly in a subway or on an elevated guideway. Passenger evacuation is difficult, slow, and dangerous and fire department access is often delayed and difficult. With a reliable fire suppression system, the risk of a stop between stations to control a fire is reduced, but some residual risk remains.

Some candidate fire suppression systems were excluded in the initial analysis. Reasons are summarized in Table 7-1, and briefly described below.

Gaseous total flooding suppression systems for complete undercar coverage would require a solid enclosure around the undercar perimeter. This is very undesirable because it would:

1. Prevent free flow of cooling air and confine the electrically generated heat,
2. Greatly hinder undercar inspections,
3. Make maintenance difficult and costly.
4. Act as a collector of wayside trash, and
5. Be subject to physical damage from wayside debris.

Such an enclosure would likely increase the risk of fire or overheat damage rather than improve fire safety. Any system requiring a solid enclosure is not recommended.

TABLE 7-1 REASONS FOR EXCLUDING SPECIFIC FIRE SUPPRESSION AGENT/SYSTEMS IN INITIAL SCREENING

FIRE SUPPRESSION AGENT/SYSTEM	UNDERCAR AREA	SYSTEM COVERAGE PASSENGER COMPARTMENT	EQUIPMENT & WIRE ENCLOSURES
HALON 1301 TOTAL FLOODING	Need for perimeter enclosure	-------------------	-----------------
SURFACE APPLICATION	Poor cooling and ease of gas dissipation	Relatively ineffective	Similar to total flooding in a small enclosure
HALON 1211 TOTAL FLOODING	Need for perimeter enclosure	Toxicity	-------------------
SURFACE APPLICATION	---------------	Relatively ineffective	Similar to total flooding in a small enclosure
HALON 121 (122) TOTAL FLOODING	Need for perimeter enclosure	Toxicity	-------------------
SURFACE APPLICATION	Uncertain effectiveness	Toxic problems & uncertain effectiveness	Similar to total flooding in a small enclosure
CARBON DIOXIDE TOTAL FLOODING	Need for perimeter enclosure	Toxicity	-------------------
WATERSPRAY	----------------	--------------	-------------------
DRY CHEMICAL	*************Possible damage or disruption to electrical equipment************		
HIGH EXPANSION FOAM	---------------	Psychophysiological effect on passengers	--------------------

Existing equipment enclosures such as those around motor control centers, batteries, and evaporators could be protected with a total flooding agent applied directly inside the compartment housing the hardware. Electrical fault isolation is still important; continued fault currents could heat up the vaporized material, and possibly build up pressure to blow out the enclosure. A pressure relief disk or valve might possibly be used to prevent such an excessive pressure buildup. Halon 1301, Halon 1211, or carbon dioxide would be satisfactory agents for this flooding application. The use of Freon refrigerant from the car air conditioning system is potentially interesting because most modern cars already have 40 to 50 lb of agent onboard. A few properties still have cars with smaller receiver capacity. The Freon agent could be taken from the air conditioning receiver, passed through an oil separator, and discharged from inside the enclosure being protected. Assuming that Freon agents are feasible extinguishing agents, the toxicity of the material and of pyrolysis products remains as a parameter limiting applicability to those situations which cannot result in hazardous human exposure.

Total undercar flooding using a high expansion foam appears more attractive in some respects than the use of gaseous agent if the foam can be made with low conductivity properties. Additional experimental work is needed to establish the conditions under which the low-conductivity foam can be made for safe application at all rail transit system voltages. Such a foam would have to be generated using a solution of low conductivity and freezing point. Combustion and pyrolysis products in the air used to generate foam will prevent proper foam expansion. Therefore, a pressurized gas supply for foam-making may be necessary. A coarse-screen undercar enclosure could be used to contain the foam. Such an enclosure would create some maintenance problems but not impede cooling airflow or visual undercar inspection. Although of apparent potential, further analysis here has excluded high-expansion foam because: (1) hardware has not been developed for generating high-expansion foam using a self-contained gas supply, and (2) data are unavailable on using water-antifreeze solutions in generating high-expansion foam.

7.2 DESIGN CONCEPTS

Conceptual designs have been generated for those agents/systems deemed suitable for protecting the entire undercar and/or passenger compartment. All the designs described herein are based on a representative transit car; an actual system would be custom designed for the particular car series to which it was applied. The dimensions of the representative car are based on those of some actual transit cars currently on order:

1. Length - 70 feet
2. Width - 10 feet
3. Clearance from top of rail to bottom floor - 33 inches
4. Net interior volume - 4600 cu feet (based on Dade County cars)
5. Net undercar volume - 1200 cu feet

The concepts illustrated in this section are presented for comparison purposes only and are not intended to be applicable to any actual series of transit cars. The routing of piping and locations of the agent's supply containers as well as the nozzle arrangement would all have to vary from one car series to another.

The design criteria for each major suppression system are itemized in Table 7-2. They have been based on structural fire protection practice and/or engineering judgment. However, the undercar area is a unique application and considerable experimental validation will be required for all such systems. The undercar water spray system application rate selected was 80 percent of the rate normally recommended to protect electrical equipment in and adjacent to buildings. It was assumed that the nozzles on the transit car would cover a smaller area than in structural applications. The Halon 1211 undercar suppression application rate is based on engineering judgement only. There is insufficient structural experience in similar applications to support design effort. The level of confidence in the application rate for the Halon 1211 is considerably less than for the waterspray system.

The duration of discharge for both waterspray and Halon 1211 undercar systems is based on engineering judgement only. A series of experiments will be necessary to determine if the total agent carried must be increased or can be decreased.

The interior waterspray and automatic sprinkler application densities are based on full-scale experimental fires in residential occupancies. The fire suppression requirements for furnishings in residential buildings are considered to closely approximate those required for the interior furnishings and finish of transit cars. The duration of discharge is considerably shorter than required by present automatic sprinkler standards in residential buildings; however, it is judged reasonable. This judgement is based on an engineering evaluation of performance observations of sprinkler and waterspray systems in actual experimental fires. The Halon 1301 total flooding system is designed according to standard structural criteria. All design criteria for interior suppression systems have been established with a relatively high degree of confidence.

The Halon 1211 and 1301 spot protection systems are based on standard structural fire suppression criteria. The criteria used for the Freon system are based on the extinguishing performance of other halogenated hydrocarbons with an adequate safety factor so the fire will be overpowered. Transit car air conditioning systems presently contain more refrigerant than is necessary to protect any specific enclosure aboard the car except the main passenger compartment.

The conceptual design of each candidate fire suppression system is presented in Figures 7-1 through 7-8. The piping and nozzle arrangements in all systems, particularly those for undercar protection, are shown to provide uniform area coverage. However, in an actual transit car, the nozzles and piping should be located so as to most effectively cover all possible fire sources. All interior systems feature aluminum tubing to distribute the agent to application nozzles. Although aluminum readily melts in a low-intensity fire, all the systems must be designed for rapid actuation and suppression not only to protect the tubing but primarily to protect the occupants. Undercar distribution manifolds are stainless steel tubing in order to endure the exterior corrosive, shock, vibration and thermal environments.

TABLE 7-2 FIRE SUPPRESSION SYSTEM DESIGN PARAMETERS

SUPPRESSION SYSTEM	COVERAGE	MINIMUM DESIGN APPLICATION DESITY	DURATION OF DISCHARGE
Open Head Water Spray	Undercar in 4 zones	1.2 gpm/sq ft	2 minutes with one zone actuated
	Passenger Compartment in 5 zones	0.8 gpm/sq ft	4 minutes with one zone actuated
Closed Head Water Spray (automatic sprinkler)	Passenger Compartment	0.8 gpm/sq ft	3 minutes minimum with 4 heads opened
Halon 1211 Surface Application	Undercar in 4 zones	.75 lb/sq ft	2 minutes with one zone operating
Halon 1301 Total Flooding	Passenger Compartment	6% by volume agent concentration	5 seconds

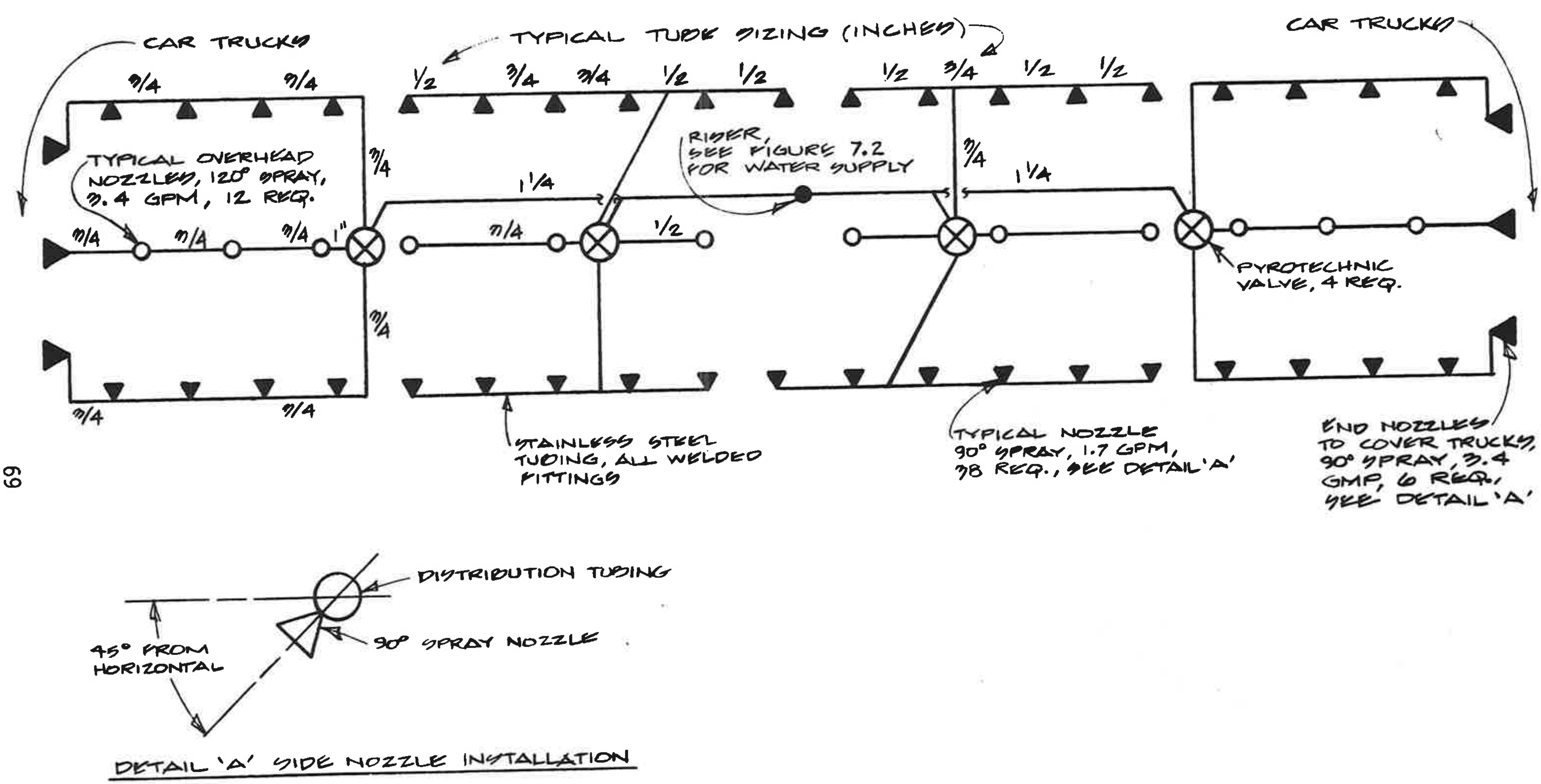


FIGURE 7.1 UNDERCAR WATER SPRAY SCHEMATIC

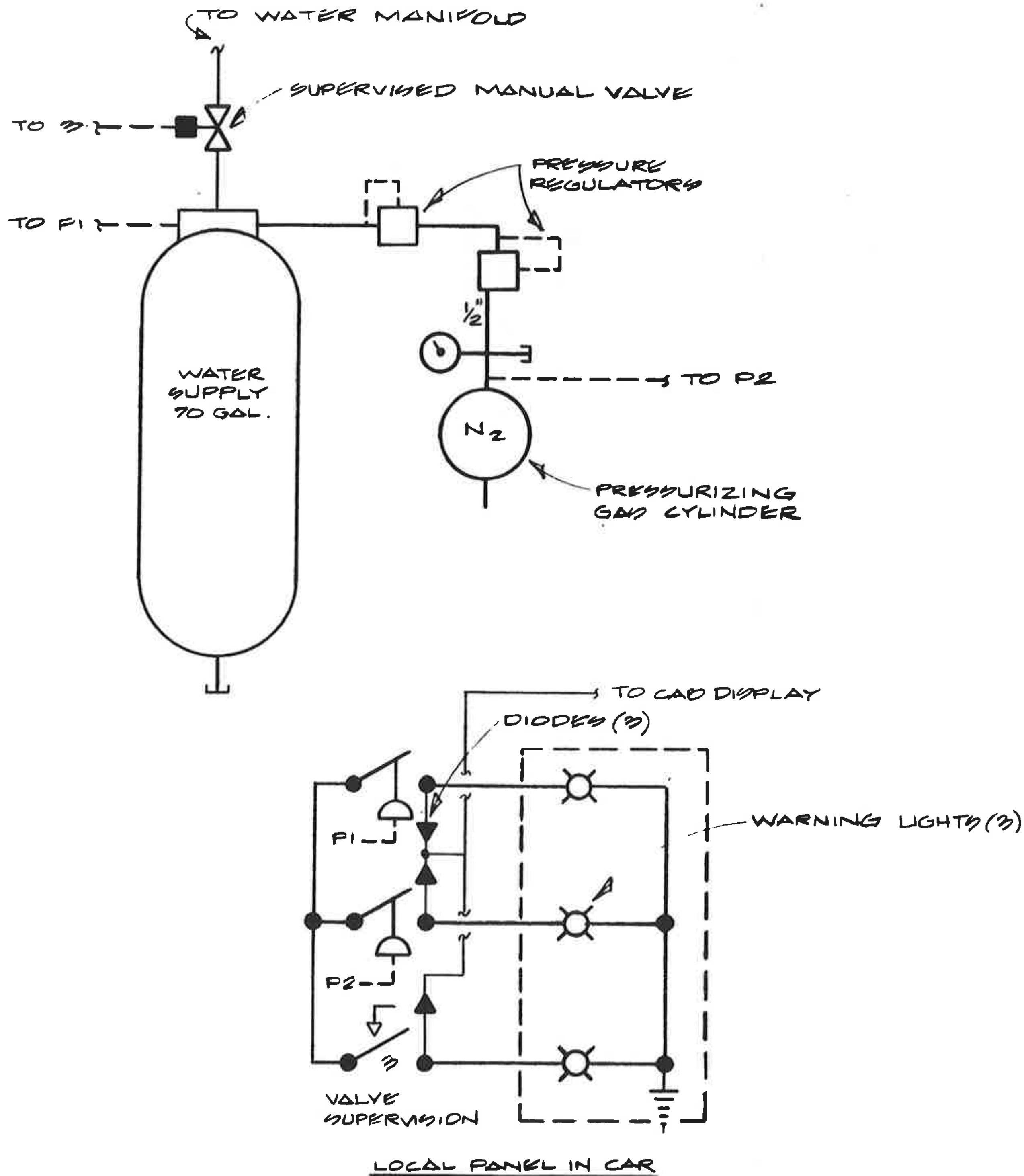


FIGURE 7.2 70 GAL WATER SUPPLY

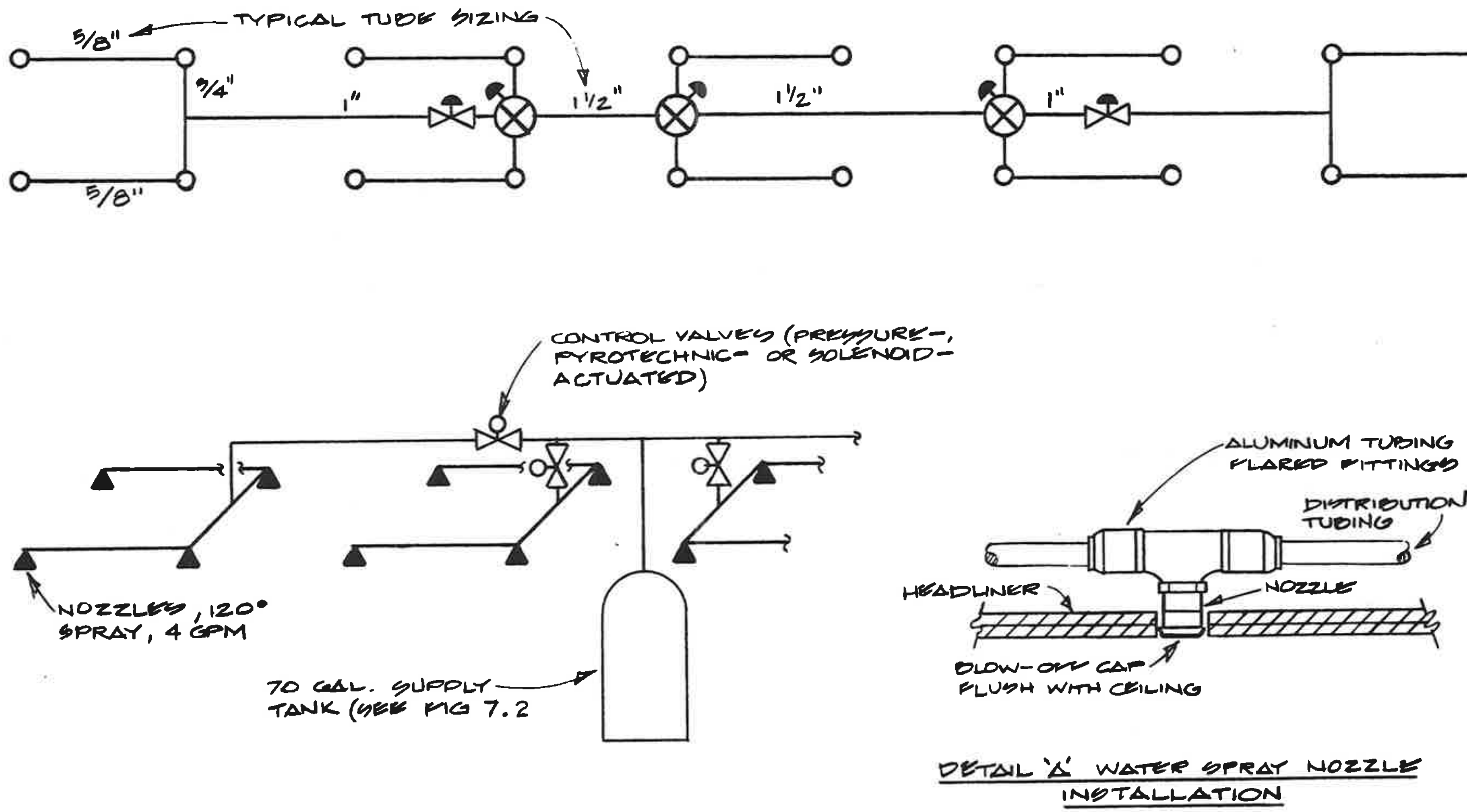


FIGURE 7.3 INTERIOR WATER SPRAY SUPPRESSION SYSTEM

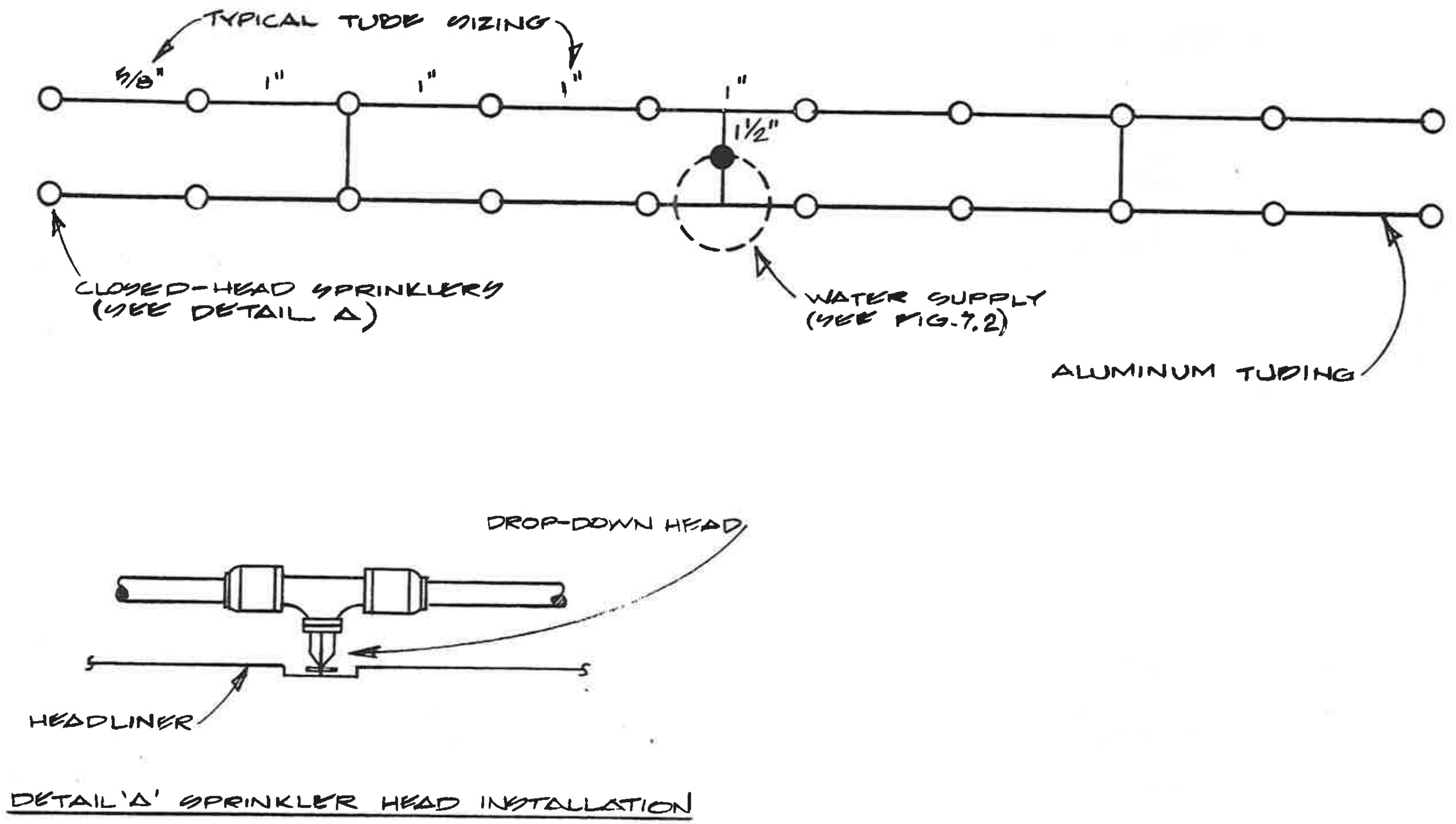


FIGURE 7.4 INTERIOR AUTOMATIC SPRINKLER SYSTEM

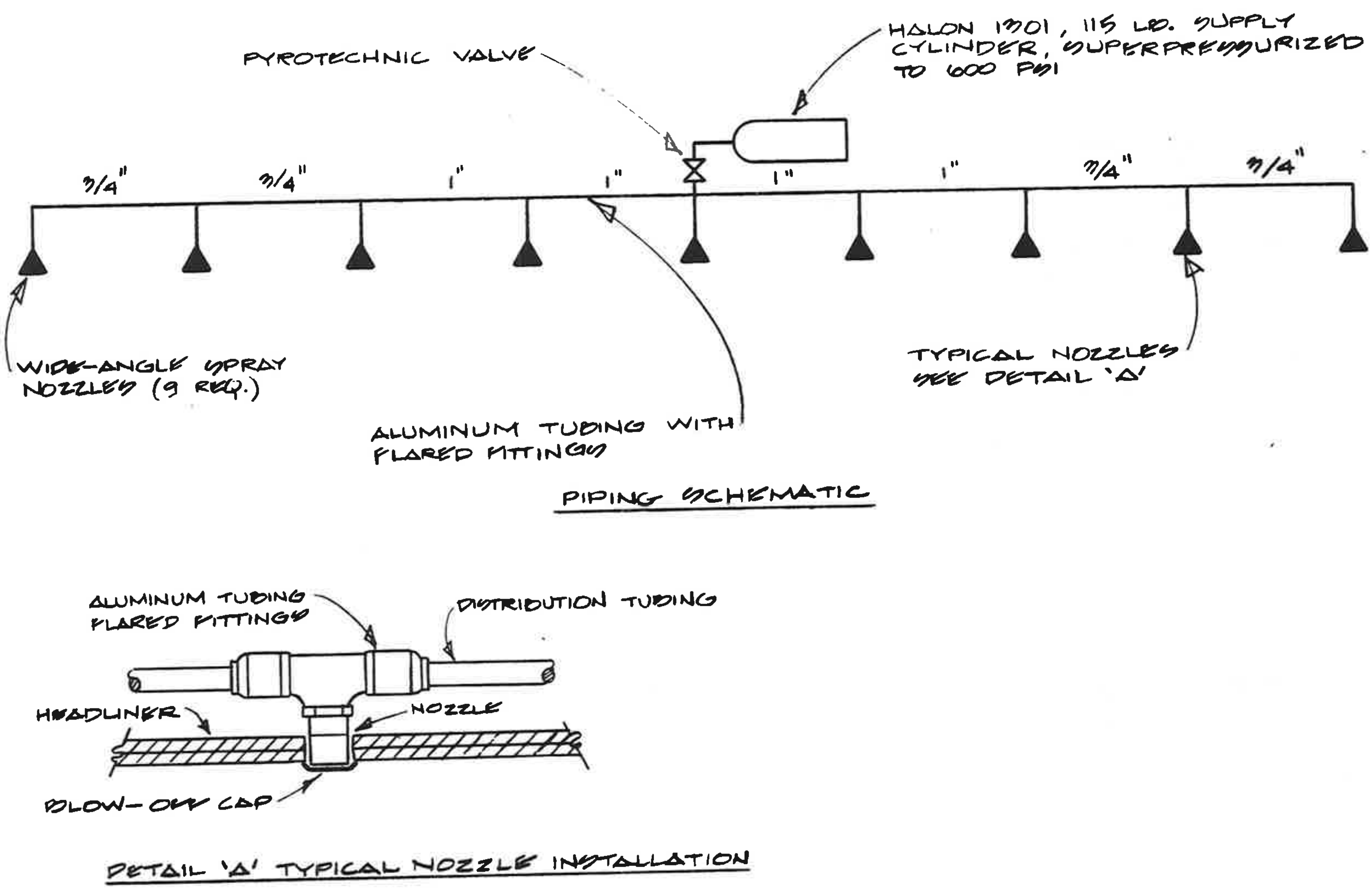


FIGURE 7.5 HALON 1301 INTERIOR SUPPRESSION

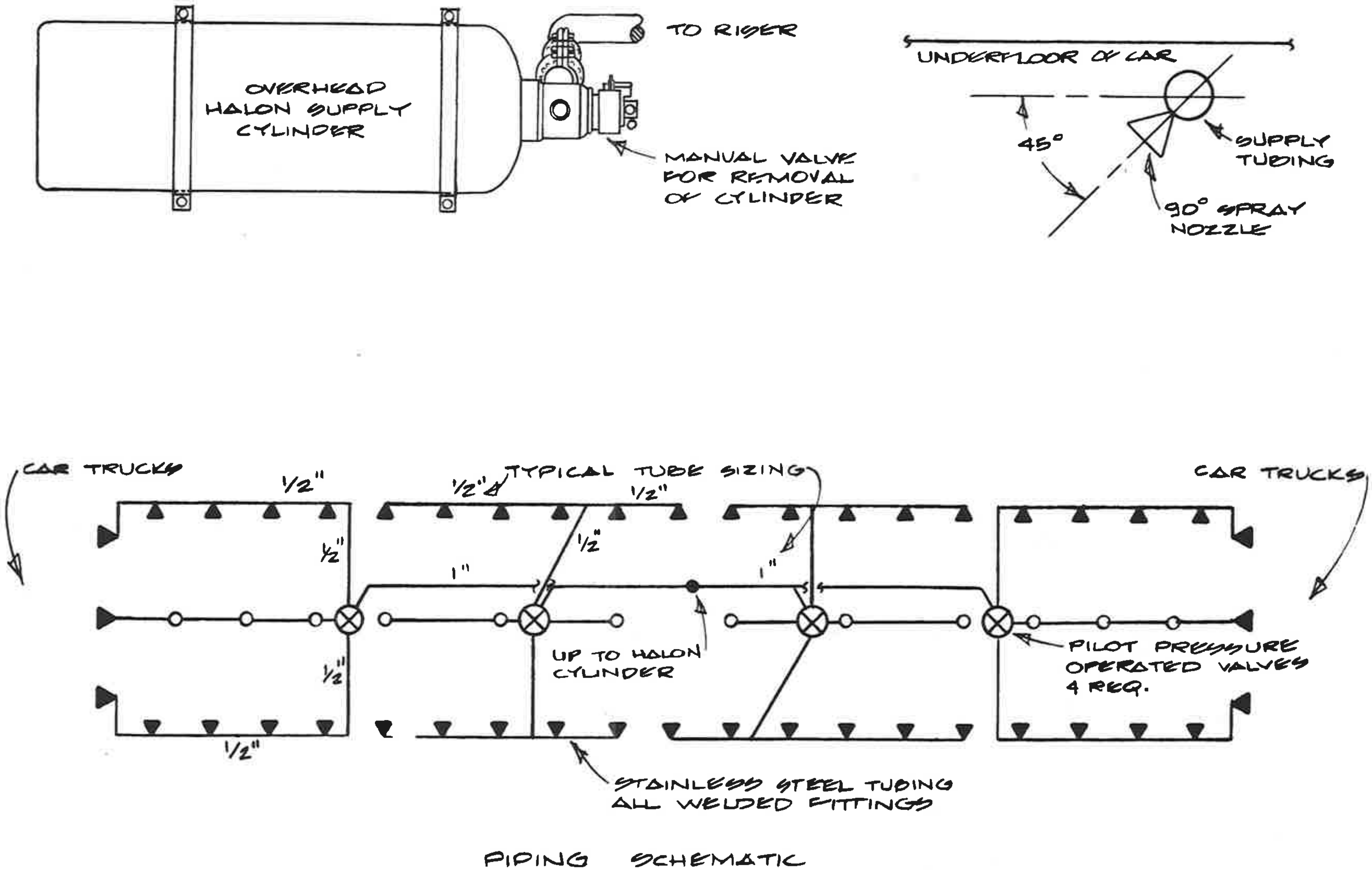


FIGURE 7.6 HALON 1211 UNDERCAR SUPPRESSION

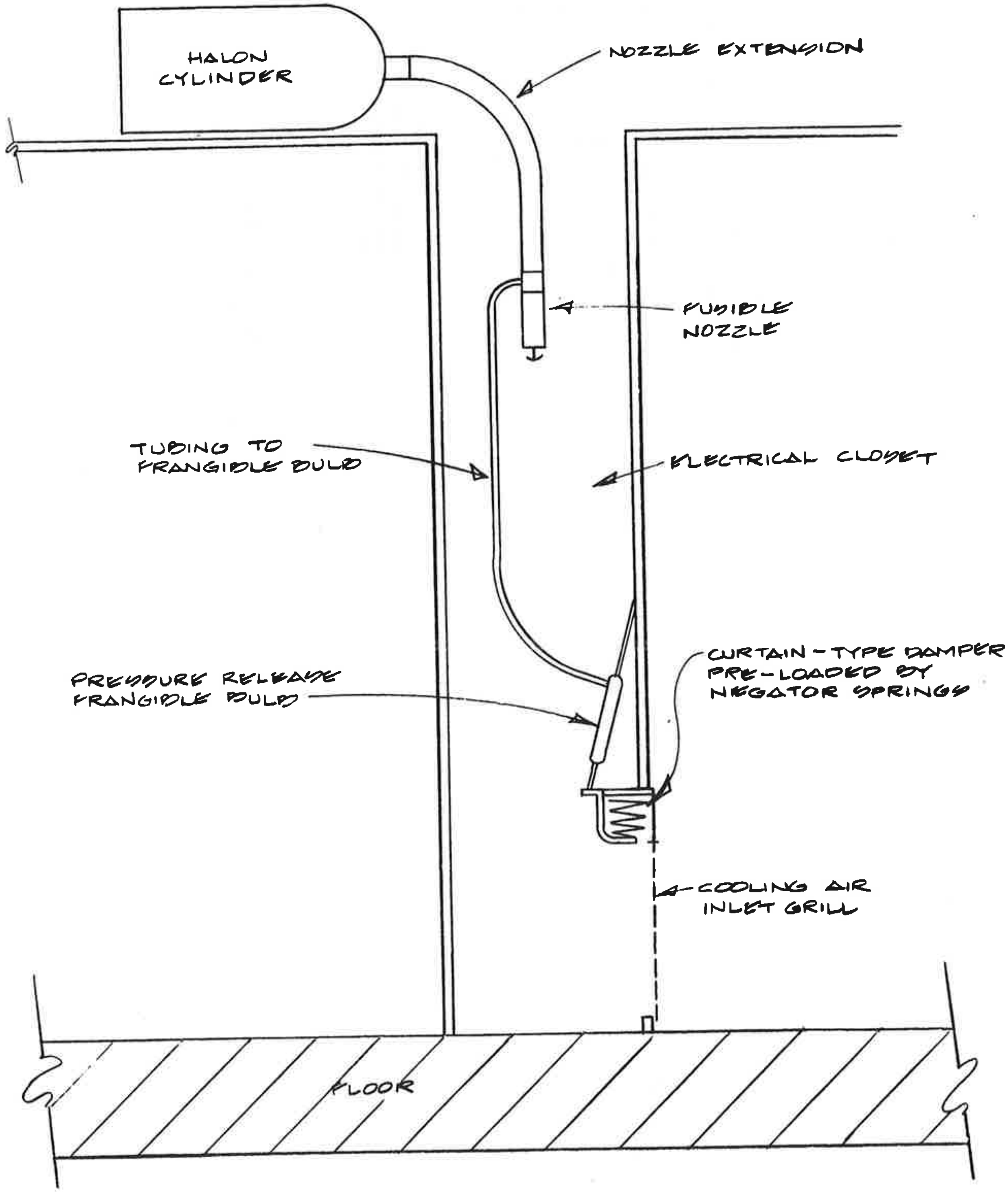


FIGURE 7.7 SPOT PROTECTION FOR ELECTRICAL CLOSET

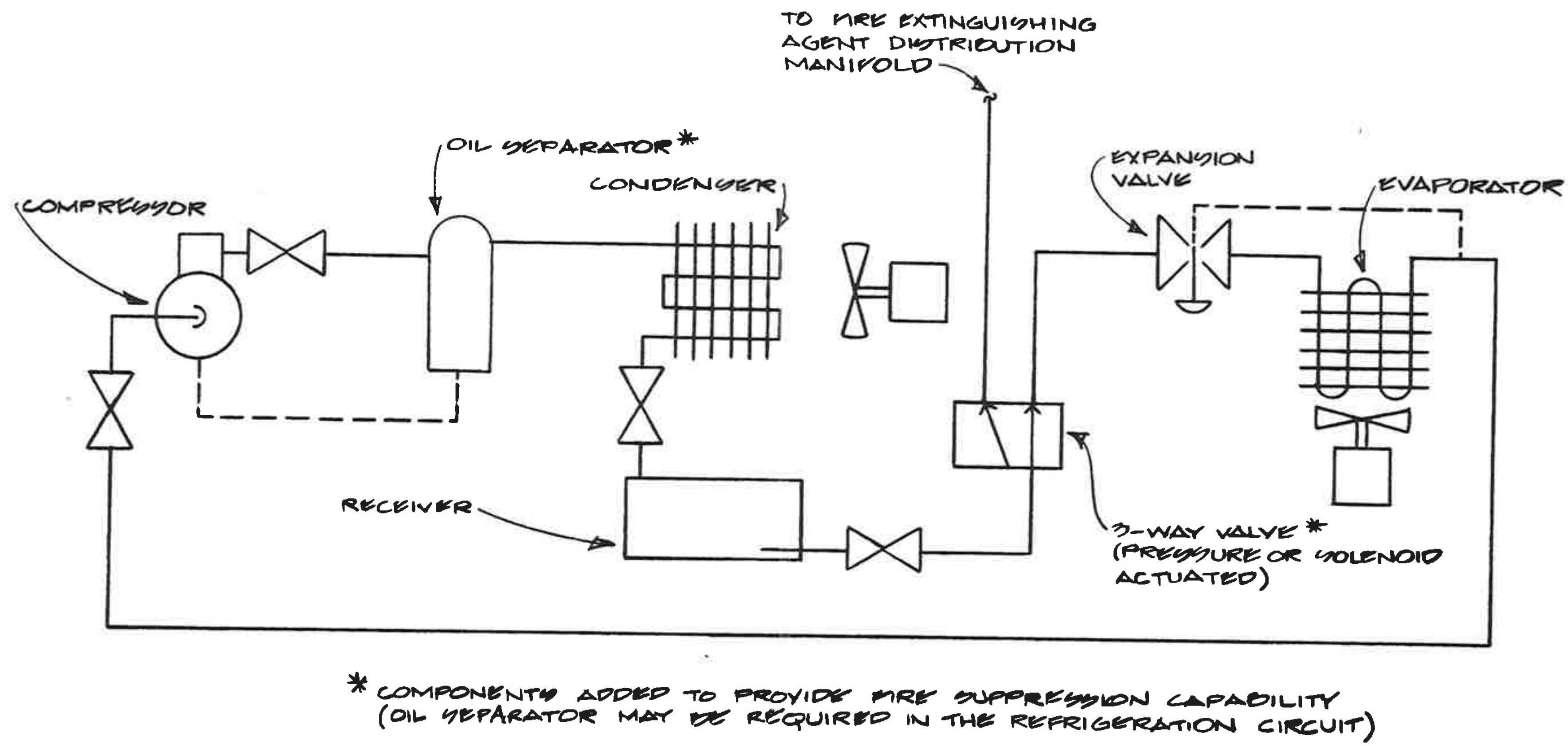


FIGURE 7.8 REPRESENTATIVE FIRE EXTINGUISHING SUPPLY USING ON-BOARD REFRIGERANT

The undercar water suppression System, Figure 7-1, is divided in four zones each of which would be individually activated by the undercar detection system. Normally only the zone in which the fire is sensed would operate; however, if a fire occurs between two zones, both zones would be expected to actuate to suppress the fire. Water would be supplied to this system from a 70 gal. storage tank with an expulsion gas supply similar to that shown in Figure 7-2. Pressure and valve position switches would supervise the status of the system and display the information in the operator's cab. The water storage tank could be stored in a closet, overheat space, under the seats or even under the car, depending on the most efficient arrangement for a particular transit vehicle. It would also be possible to use one water supply to serve both cars of paired transit cars.

The interior water suppression system has been arranged in five zones for the representative car as illustrated in Figure 7-3. This system would be actuated by interior fire detectors. Only one zone would normally operate unless the fire was located between zones. All tubing and nozzles would be concealed above the headliner of the car. The interior automatic sprinkler system, Figure 7-4, is essentially a standard structural fire sprinkler system closest to the fire would operate and discharge water. This sprinkler system would use the same basic water supply as the undercar and above car waterspray system.

The Halon 1301 interior car suppression system, Figure 7-5, will discharge the agent through nozzles to flood the entire passenger compartment with a 6 percent concentration of Halon 1301. The Halon cylinder could be stored in overhead compartments, closets, undercar or under the seats, just as the water supply for the waterspray and sprinkler systems can be stored. Storing the suppressant as a refrigerant is a potential alternative.

The Halon 1211 undercar fire suppression system, Figure 7-6, is similar in nozzle, piping arrangement, and zoning to the waterspray system illustrated in Figure 7-1. Only the sizes of nozzles and tubing have been varied. The Halon 1201 would be stored in a cylinder or cylinders in one of the same location options enumerated for water or Halon 1301.

A typical spot protection system using either Halon 1211 or Halon 1301 to cover an enclosure is shown in Figure 7-7 installed in an electrical closet in a typical rapid transit car. This is a modification of an off-the-shelf suppression system that is currently used to protect engine compartments on boats, small electrical spaces in buildings, and some heavy duty mobile equipment. A fusible nozzle, similar in function to an automatic sprinkler head, is used to sense the fire and to discharge the agent. A pressure switch can be located on the nozzle to actuate an alarm or perform other functions. In this particular example, pressure from the fused nozzle is used to close a damper and shut off supply air into the electrical closet.

Refrigerant from the transit car air conditioning system, Freon 22, might be used as supply agent to any enclosed space using distribution tubing and a fusible nozzle similar to the spot protection system. (A detector-valve actuated nozzle could also be used if desired.) The arrangement would be essentially the same as used in the spot protection system shown in Figure 7-7. The modification of a typical air conditioning circuit to accommodate these features is illustrated in Figure 7-8. An oil separator (impactor) would be necessary to remove the crankcase oil from the refrigerant before it is used as an extinguishing agent. Hot crankcase oil is combustible. An alternative is the use of silicone based lubricants. Liquid refrigerant from a receiver downstream of the condenser would be routed through a three-way valve which would either direct the Freon to the expansion valve-evaporator in normal service or to the fire extinguishing manifold. A nitrogen pressure boost system may be desirable in some applications.

The features of each major system are itemized in Table 7-3. The waterspray system for undercar and interior protection is the heaviest and most costly system but also the one with the highest current design confidence and availability of hardware for the undercar portion of the system. There is still a definite uncertainty about the conductivity and possible combustibility of the organic antifreeze-water solutions which would be necessary in freezing climates. In climates where freezing is not a problem, demineralized water could be used which would have even a lower conductivity than fresh water. A demineralized water system is judged quite safe from an electrical conductivity viewpoint.

For interior protection, both the automatic sprinkler and the Halon 1301 total flooding system would be very effective and, with the exception of the vibration susceptibility of the sprinkler heads, require only state-of-the-art hardware. The Halon 1301 system would be effective and would incur a relatively low weight and cost penalty compared with the other system. The risk of toxic decomposition products from Halon 1301 is judged significantly less than the risk of toxic decomposition products produced by any fire. A 6 percent concentration of Halon 1301 meets nationally recognized standards for discharge in occupied spaces. The cost effectiveness of Halon 1301 refrigerant suppression systems must be determined.

The design parameters used for the Halon 1211 undercar protection have a very high degree of uncertainty. Although general experience in the use of Halon 1211 on electrical fires has shown it to be very effective, there are no adequate experimental or field data on which a reasonable design can be established. Nationally recognized standards for Halon 1211 systems require experimental determination of both the application rate and duration of discharge.

For spot protection of a few small enclosures, either Halon 1211 or Halon 1301 can be quite satisfactory. The cost of such systems is quite low and the hardware is practically off the shelf. If a large number of large enclosures are to be protected, the Freon 22 system might become attractive since it requires no additional onboard agent storage.

TABLE 7-3 FEATURES OF MAJOR FIRE SUPPRESSION SYSTEMS

System No.	System Type	Coverage	Special Features	Weight lb.	Installed= Cost $	Effect on Occupants: Inadvertent Discharge	Effect on Occupants: Discharge On Fire	Effect On Transit Vehicle		Confidence In Design & Performance	Estimated Annual Maintenance Costs $	Susceptibility to Damage: Normal Operations	Susceptibility to Damage: Vandalism
1	Water Spray, Open Head	Undercar	---------	805	11,900	N.A.	N A.	Could Damage a Hot Grid	State of the art	Density only fair, duration of discharge uncertain	900-1800	Slight to moderate	Nil
2	Water Spray, Open Head Nozzles	Undercar, Passenger Compartment & Concealed Spaces	Common agent supply, selectable zone of application	875	18,000	Some will get wet	Some will get wet	Could damage a hot grid; others will be wet down	State of the art	Undercar same as 1; Interior density: good, duration of discharge fair	1700-2600	Slight to moderate	Same as any other interior components
3	Water Spray Closed Head Heat Actuated Nozzles	Passenger Compartment & Concealed Spaces		645	6,600	A few will get wet	A few will get wet	Wetting down	State of the art except nozzles are not qualified for transit vibration	Density: good; Duration of discharge: fair	250	Nil	Easy to set off but perpetrators will get all wet
	Water Spray, Open head nozzles under car & closed head inside	Undercar, passenger compartment & concealed spaces	Common agent supply, selectable zone of application	865	16,100	A few will get wet when interior system goes off	A few will get wet when interior system goes off	Wetting down	State of the art except interior nozzles not vibration qualified	Undercar same as 1; Interior same as 3	1150-2050	Slight to moderate undercar; nil interior	Nil undercar; interior same as 3
5	Water Spray open head nozzles	Passenger compartment & concealed spaces		655	8,500	Some will get wet	Some will get wet	Wetting down	State of the art	Density: good; duration of discharge: fair	500	Nil	Same as any other interior components
6	Halon 1301 total flooding	Passenger compartment & concealed spaces		265	6,500	Minor toxic risk to those with heart problems	Slight risk of toxic product exposure	None	State of the art	Good	800	Nil	Same as to other interior components
7	Halon 1211 Direct Application	Undercar		630	13,800	N.A.	N.A.	Slight chance to damage hot grid, possible corrosion	State of the art	Density & duration uncertain	1100-2000	Slight to moderate	Nil

7.3 ALTERNATIVE SYSTEMS

Considering that most systems proposed in Table 7-3 are estimated to add upward of 10 percent to the cost of a new rail vehicle, it is estimated that the full implementation cost of onboard detection/suppression systems may range in the tens of millions of dollars for medium size metropolitan passenger rail systems. Maintenance can add as much as another 0.5 to 1 percent to these costs on an annual basis. Systems in this form may be difficult to justify, unless major fire incidents have occurred in the past. Most passenger rail systems have not had enough serious fire accidents to justify this level of expenditure, overall.

These overall cost constraints and the fact that, although rail system fire experience is significant, serious passenger incidents are relatively infrequent and 75 percent of all fire incidents are undercar [10] suggest the need for more cost-effective alternative systems with emphases on the undercar fire problem.

Alternatives here may include systems where detection devices are limited (or possibly remote) or not used at all, and suppression systems only are provided in partial form or as off-board "fire stations" located at each passenger station or lesser distance. Removing the necessity for a complete suppression system on each rail car may reduce the estimated cost of providing protection for an entire passenger rail system by one or two orders of magnitude, depending on the alternative chosen. However, the added requirement for most alternative systems is an added level of human interaction, which may reduce reliability and effectiveness if not properly taken into account.

Table 7-4 lists some possibilities for these types of alternative fire detection/suppression systems, including candidate detection mechanism, alert mechanisms, suppression system mechanisms, and other comments for undercar as well as passenger compartment application.

Most of the systems described here depend on quick action following the alarm to maneuver the rail car to a firestation. There either a semi-automatic system or additional manual action must be provided to connect the rail car system to a suppression agent container. The life-saving effectiveness for each of these systems depends upon locating firestations so that fire in a passenger compartment can be attacked before it reaches a dangerous level. References 11 and 12 indicated that several minutes of time might be available in the worst cases, giving strength to an argument for firestations located perhaps at each passenger station or at lesser distances, as in a long open tunnel. Fires originating undercar usually develop more slowly and longer firestation intervals are acceptable for this problem.

---

[10] National Materials Advisory Board, "Case Study Report-Fire Safety and Fire Hazards Related to Polymeric Materials in Cars of Washington Metropolitan Area Transit Authority", National Academy of Sciences, 1975

[11] Nelson, G.L. et al, "Material Performances in Transportation Vehicle Interiors", Journal of Fire and Flammability, July 1977.

[12] Brown, E., "A Fire Hazard Evaluation of the Interior of WMATA Metrorail Cars", National Bureau of Standards, PB-249 776, Dec., 1975.

TABLE 7-4 ALTERNATIVES TO ON-BOARD FIRE DETECTION/SUPPRESSION SYSTEMS

Detection Mechanism	Alert Mechanism - Action Taken	Suppression System	Other Comments
UNDERCAR APPLICATION			
1a) Continuous Thermowire sensor spanning the underside of each car (1-2 zones per car)	annunciator panel in cab--operator drives train to nearest "fire station", maneuvers activated zone over system	"in-guideway" water spray system, installed at each station or between: nominally 1-2 car lengths, providing $\sim$1.2 gpm/ft^2 upwards; system can be activated manually or remotely (can be automatic also)	depends on a trained crew for success
2a) Infra-red Detectors mounted to guideway at each station, scanning the underside of each car as it passes (for fire and/or excessively hot operating equipment)	can activate annuciator in cab or can activate an alarm light/horn/bell at station.-- then operator maneuvers train to nearest "fire station" as in (1)	same as 1a)	can use a secondary IR sensor to find exact location of -- depends on trained crew for success
3a) Similar to 1a) or 2a)	same as 1a) or 2a)	dry-pipe under carriage water spray system, activated manually by connection to hose station, with use of quick connect fittings; design for 1.2 gpm/ft^2; separate system for each car	higher dependence or trained crew (1) or (2)
4a) Rely on crew and passenger detection	rely on crew and passenger detection	same as 1a), 2a), or 3a)	manual detection
PASSENGER COMPARTMENT APPLICATION			
1b) Dual-head (microprocessor controlled) smoke detectors in each car	annunciator panel in cab--operator drives train to nearest "fire-station" (1 zone for each car)	dry-pipe open-head spray nozzle or sprinkler system in each car; activated manually by quick connect fittings to hose station; designed for 0.8 gpm/ft^2 operation; system must be manually connected at each fire station	depends on trained crew for success
2b) Same as in 1b)	same as in 1b)	at each "fire station" are pre-positioned hydraulic lances ($\sim$ in a configuration 1-2 cars long), with water nozzles within the tip of each lance. The operator position the burning car underneath the fire station, activates the lances which penetrate the top or sides of the car and provide water spray inside at about 0.8 gpm/ft^2	depends on trained crew for success
3b) Same as in 1b)	same as in 1b)	similar to 1b), except that nozzles are not connected by common piping. Each nozzle has a separate exterior car quick-connect fitting.	simpler than (1)
4b) Rely on crew and passenger detection	rely on crew and passenger notification	same as 1b), 2b), or 3b)	manual detection/ alert
5b) Same as 1b)	same as 1b)	similar to 2b) or 3b), except that Halon 1301 or 1211 is used as an agent	

Potential systems for the undercar application include:

1. Undercar Protection: Thermowire/Waterspray

A continuous thermowire sensor spans the underside of each rail car (one to two zones for each car), perhaps looping around the more critical components. In a fire or high heat condition, this thermowire insulation melts locally, shorts its two leads together, and operates an alarm and a zone-indicating annunciator light in the cab. At this point, the operator makes a judgement whether to stop at the nearest firestation which in this case is an in-guideway undercar spray system. Upon stopping at this location, the suppression system is either actuated manually by turning a valve or remotely from the cab.

2. Undercar Protection: IR Detection Alternative

This system utilizes off-board IR detectors for undercar fire/overheat protection, similar to hot box detectors used for conventional rail transport. These devices could be installed at each or every other passenger station. Upon response to fire or overheat, the approriate level of alarm could be given to the operator through a panel in the cab or by a station alarm/warning light. A continuous alarm with a warning light to indicate only when the trouble spot is directly over the detector is the ideal combination. Once the operator knows where the fire is located, he can proceed to the nearest firestation or to the system in 1a above.

3a. Undercar Protection: Undercarriage Dry Pipe Alternative

This system utilizes detection means of either 1a or 2a. Here, the suppression system is a dry-pipe, open head undercarriage sprinkler system, activated manually by connection to a hose station located at each firestation. The connection hardware must also be compatible to fire department hookup.

4a. Undercar Protection: Manual Detection Alternative

Here, no automatic detection is present. Passengers and crew are relied upon for detection and to alert the operator. Suppression systems can be similar to that in 1a or 3a.

Potential systems for passenger compartments include:

1b. Passenger Protection: Automatic Detection/Dry Pipe System

A system of dual-head (microprocessor controlled) smoke detectors is installed in each rail car (as described in Section 5.1). Upon detector activation, an annunciator panel and alarm horn in the cab sound the alert and identify which car has the fire problem. Upon notification, the operator proceeds to the nearest firestation, where a hose is manually connected to a full compartment dry-pipe, open-head sprinkler system. Passengers, of course, can be evacuated simultaneously.

2b. Passenger Compartment Protection: Automatic Detection/"Lance" Suppression

Detection and alarm systems here are the same as in 1b. The unique item is the off/board suppression system located at each firestation, consisting of a set of prepositioned hydraulic lances with water nozzles within the tip of each lance. Upon alarm the operator maneuvers the train to the nearest firestation where the burning vehicle is positioned under the lance configuration. Upon system activation, the lances penetrate the top of the car and provide water spray internally at a prescribed density. Perhaps soft poke-through panels could be prepositioned on each car to facilitate the use of low power lances.

3b. Passenger Compartment Protection: Automatic Detection Dry Pipe System

This system uses the same detection mechanism as in 1b. The suppression system is a dry-pipe, open-head sprinkler system similar to that of 1b in principle, but the nozzles are not connected to a common manifold. Each nozzle here is directly connected to an exterior quick-connect fitting. Sidewall sprinklers are probably best because of the side mount possibilities. Connection should be made easily and should be compatible with fire department equipment.

4b. Passenger Compartment Protection: Manual Detection/Dry-Pipe System

This system utilizes similar suppression-station concepts as in 1b, 2b, or 3b, except that no detection system exists. Here detection and alerting functions are dependent on the crew and passengers, as in 4a (undercar system).

5b. Passenger Compartment Protection: Halon Suppression Alternative

This system is identical in most respects to 2b or 3b, except that Halon 1301 (or 1211) is used as an agent.

Passenger rail systems with high frequencies of serious compartment fires may elect to utilize the more sophisticated and reliable systems. (Onboard detection/suppression). Others with a lesser fire problem may be best suited for a composite of alternative undercar and passenger compartment systems. A great advantage is seen in the utilization of the IR detection sensors listed in 2a. Since these detectors can be monitored easily for different levels of radiation, they may be invaluable as "preventive maintenance/preventive fire measure" devices to warn of component high operating temperatures, long before their actual failure or fire occurrence.

8. TEST PLAN OUTLINE

The initial steps in the development of an effective test plan are:

1. Establishing the need for the experimentation,
2. Establishing the optimum budgetary, manpower, and time requirements of the project, and
3. Modifying or adjusting the scope of the experiment to actual budget, manpower, and time schedule constraints.

This test plan outlines several approaches which may be pursued or adjusted, based upon available budget, manpower, and time limitations. The iterative procedure should provide the best application of effort to the problem and minimize non-optimum expenditures. The objectives of each test plan are to initially verify the conditions that are anticipated in fire situations and to verify that proposed system components have the capability of responding or performing as required under operating conditions.

Subsequent objectives are to:

1. Establish the primary variables which must be measured,
2. Determine the accuracy and number of measurements required for data analysis,
3. Prepare a data reduction and analysis program to determine whether program objectives are met,
4. Analyze possible experiment outcomes to ensure accuracy and reliability prior to testing,
5. Develop the desired hardware and software items and configurations,
6. Perform initial tests to assure all components function within anticipated specifications,
7. Execute test protocol, and
8. Analyze results in terms of program objectives.

A detailed test plan can only be prepared when the requirements of a specific property and rail transit vehicle have been examined and hardware options narrowed to those most likely to fulfill requirements. It is expected that detailed test plans can be prepared which respond to each of the criteria stated above. The test plans to be outlined address the principal problems of passenger compartment and undercar fires. Details regarding specific approaches are covered in appropriate sections of this report. Detection and suppression systems are treated separately. It is assumed that subsequent research may lead to the integration of these systems into more complete response capabilities, depending upon the cost effectiveness of the protection offerred and required by the transit property.

8.1 PASSENGER COMPARTMENT DETECTION SYSTEMS

1. Determine the "fire signature" of passenger compartment fires for the rail transit vehicle and property selected for demonstration. The determination should be based upon laboratory and field tests or equivalent information on materials and construction methods used in the compartment. The significance of specific variables to reliable fire sensing will be based on available hardware and applicable to pre-fire conditions, fire initiation, and fire build-up. The intent is to identify the dependent variables which can be most reliably used to discriminate passenger compartment fire conditions from ambient conditions.

2. Determine and describe the ambient environment encountered in the passenger compartment during operations and storage. Variables include temperature, humidity, vibration, shock, airborne contaminants including aerosols, particulates, liquids and gases which may affect sensor discrimination, operation, and reliability.

3. Identify detector sensors with the capability of reliably discriminating between fire and ambient conditions on the basis of the previously identified variables. Acceptable generic sensing head types are described in the appropriate section of this report. Devices presently available as commercially produced components are desired.

4. Prepare a microprocessor based sampling algorithm which will utilize the identified detectors to continuously determine the fire status of the passenger compartment and identify the location of sensing heads. A self-checking routine should be incorporated which will regularly test the integrity of all circuits and components and determine whether detector status is correctly transmitted.

5. Design a microprocessor based fire detection system. The system will use the detector heads and algorithm described to identify passenger compartment fires. Hardware must be capable of withstanding the rail transit environment. System output must be in a form useful for analysis and correlation with independent variables.

6. Build a prototype fire detection system. The prototype should be suitable for application to laboratory and field performance testing and evaluation. The prototype should be based upon the multiple sensor/multiple head design outlined in this report. A minimum of two heads per passenger compartment are required to provide adequate input to the logic program.

7. Demonstrate the sensitivity, false signal rejection capability and reliability of the system by means of suitable controlled tests. Initial tests may be with individual fire signature simulants under laboratory conditions. Final testing will be performed comparing system response to combustion products of replicated passenger compartment fires and with ambient compartment environment characteristics.

8. Demonstrate the prototype detection system by equipping two passenger compartments with a complete detection system. Independent recording of the fire signature variables will be compared with recorded output of the detection system. Statistical analysis of the system response to simulants may be used to determine false alarm probability.

8.2 PASSENGER COMPARTMENT SUPPRESSION SYSTEM

1. Establish the fire suppression requirements for the rail transit car and property under consideration.

2. Using published documentation and best engineering practice, prepare a design capable of responding to car fires. A Halon 1301 flooding system is contemplated.

3. Prepare test fires based upon previous tests. Test fires will represent worst case fires. Instrumentation will provide data on habitability of the space as well as rate and extent of fire buildup and suppression.

4. Prepare an on-board suppression system with provisions for monitoring reliability and maintainability.

5. Demonstrate the application of the system by performing extended field testing with a rail vehicle. Develop predictions of reliability, maintainability and system costs for property with implementation.

8.3 UNDERCAR FIRE DETECTION

1. Prepare a description of fire parameters for the specific rail transit undercar electrical system selected for study. The description must address operating requirements such as cooling air, inspection access, and design for maintainability. Component reliability and failure modes must be assessed.

2. Using operating requirements and electrical system characteristics as guidelines, select a sensing approach providing best information about incipient and fire conditions with maximum false alarm rejection.

3. Design a microprocessor based system, using continuous wire, temperature, voltage/current, and other sensors as required. The output to the operator should include information about equipment conditions in addition to indications of incipient and actual fire.

4. Fabricate a prototype system and install in a test bed representing or simulating the anticipated fire producing conditions.

5. Perform tests demonstrating the repeatability and reliability of maintenance and fire condition warnings by inducing equipment failure.

6. Perform an extended operational demonstration of the system. Data collection will be adequate to describe the range of environmental conditions experienced and response of the system in terms of output and reliability.

7. Estimate the cost-effectiveness of system implementation based upon maintainability and fire detection improvements.

8.4 UNDERCAR SUPPRESSION SYSTEM

1. Establish the undercar suppression requirements for the rail transit car and property under consideration.

2. Prepare alternative suppression system concepts for evaluation and select a candidate system based on cost-effectiveness and reliability for the specific application.

3. Fabricate and test a prototype system. Response time and capacity under adverse and ambient conditions must be determined and related to projected fire conditions.

4. Install and demonstrate a prototype system on an operational rail transit vehicle. Acquire and analyze operational experience including reliability, maintainability and projected system costs.

8.5 PREPARE FINAL REPORT

Optimized systems will be described and compared with the results of testing and operation of the prototype systems. Specific areas to be addressed will include:

a. The relative and absolute cost-effectiveness of each system

b. False alarm and inappropriate activation susceptibility

c. Impact of systems on property operations

d. System reliability and maintainability

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

Fire deaths in rail transit vehicles are presently infrequent. There is a very high potential for catastrophic fire in which large numbers of people could be killed or injured in a single incident. The possibility of catastrophic loss will increase if trends to deferred maintenance, unmanned transit vehicles, and the use of new materials and construction methods continue. A direct approach to reducing catastrophic risk, regardless of the causation mechanisms, is provision of reliable fire detection and suppression capability. Current and continuing advances in fire response system designs indicate that effective onboard systems can be developed which will have a minimal adverse impact upon property operations. Effective contributions can be achieved through improved fire detection, suppression or combination systems.

Microprocessor based detection systems incorporating multiple detector heads and a fire signature algorithm are feasible and can provide systems with high resistance to false alarms and improved reliability and maintainability.

Onboard Halon-based suppression systems can be developed which will not present habitable space hazards. Unmanned spaces can be effectively protected by Halon and other suppression systems with cost-effective agents. Under special circumstances it is possible that water-based systems may represent an effective approach.

Identifiable objectives for rail transit vehicle fire response systems include:

1. An essentially zero false alarm rate to prevent disruption of operations,
2. High reliability in a severe operating environment.
3. Very low maintenance requirements, and
4. A degree of cost-effectiveness based upon preventing or mitigating rare but potentially catastrophic fire situations.

New technology has made available high-reliability sensors and logic devices which can be used to develop sensitive systems highly resistant to false alarms. Data from multiple sensors measuring two or more parameters of a 'fire signature' can be processed by an algorithm which discriminates between "fire" and "non-fire" conditions. Output can be processed to provide the amount of information and format most suitable for the operator's use. Detector systems can be developed which combine the relevant parameters for application to specific fire scenarios. This approach can provide improved sensitivity and greatly enhanced false alarm rejection.

On-board fire suppression systems must be concerned with toxicity, noise, impediments to evacuation and electric shock hazards as well as effectiveness in suppressing fire activity.

Halon 1301 based systems presently offer the best combination of attributes matching rail transit requirements for passenger spaces.

Undercar suppression systems can utilize a wider range of approaches including Halon 1211 and possibly water-based systems. Applicability of water-based systems is likely to be very limited, with maintainability penalties and agent delivery problems that require substantial research and development.

Undercar detection systems can be devised which offer some advantages by providing warning of impending electrical failure. If the information is used to prevent interruption of operations and to facilitate maintenance, the improvement, coupled with the fire detection function, may have significant value.

9.2 RECOMMENDATIONS

The high false alarm rates and poor reliability of existing fire detection systems render them unsuitable for rail transit vehicle application. Recent developments in the application of microprocessors to process control have shown that reliability and accuracy of sensing of detection functions can be greatly improved with little increase in cost. An improved detection system designed for the environment of a specific property and rail transit car offers an excellent opportunity for testing the feasibility of these concepts.

An undercar detection system offers wider potential application because the failure indications can be used for maintenance purposes as well as for fire detection.

Passenger compartment detection systems can employ the same concepts with different sensors specifically selected for the fire and ambient environment characteristics.

Development and testing of these systems will provide basic information and capabilities that will be urgently needed if a catastrophic fire produces demand for improved fire safety.

Fire suppression systems present fewer problems in the area of inadvertent or accidental operation but do pose significant cost, weight, and space problems which must be resolved while providing a supportive or friendly atmosphere for evacuation.

The trend to onboard Halon-based suppression systems for many different large and high-cost transportation systems and vehicles reduces development costs and risks for their application. The demonstration of a Halon-based system has particular relevance to automated guideway transit systems where an operator is not available to make judgmental decisions or take actions to insure passenger safety. Application of these systems to undercar fires requires greater effort but, as with undercar detection systems, may yield savings through reduced extent of damage.

A program demonstrating the benefits of improved detection and suppression systems has significant potential for meeting the changing requirements of rail transit properties.

Several significant fires have occurred since the completion of the transit fire survey. The likelihood of a catastrophic rail transit fire appears to be increasing. The results of a demonstration program can be of significant use in assuring that best efforts, consistent with available time and money, are made to avert catastrophic fire losses.

APPENDIX A

FIRE DETECTION DEVICES
A SUMMARY DESCRIPTION

APPENDIX A: FIRE DETECTION DEVICES, A SUMMARY DESCRIPTION

Device	Description	Applications	Unique Characteristics	Reference
I. **MANUAL FIRE DETECTION**				
Manual fire alarm stations (manual device)	a. Familiar fire alarm pull boxes utilizing coded or noncoded alarm switching. For coded operation, they contain mechanically or electrically driven motors which turn a code wheel to successively open and close an electric circuit to identify location (also, digital transmission can be used). Location is generally in the normal path of exit travel, and not more than 200 ft apart.	- Manual fire detection - Watchmen supervisory service - Fire control equipment actuation	- False alarms caused by people are a problem in some areas - Only effective where people are present - Generally high operational reliability - Low maintenance - In common use for a long time - Overall effectiveness is dependent on the people in the area	1 2 3 4
	b. Fire alarm call boxes, which provide direct voice communication with caller to gain specific information	- Manual fire detection	- relatively new to fire communications use	
II. **HEAT ENERGY DETECTORS**				
A. **Fixed Temperature Types**				
	Designed to alarm when the temperature of the operating element reaches a specified point. Specified actuation temperatures range from 135-375°F	- General spot detection - General area detection (small area) - Suitable for releasing device service	- Subject to fewer inadvertent alarms than other detector types due to its simplicity of design - Limited to environmental temperature conditions - Very high reliability - All of these types are in common use today - Low sensitivity to Class A and C fires, high sensitivity to Class B fires	5 6 2 7 8 3
1. Eutectic metal type	Eutectic metals, alloys of bismuth lead, tin, and cadmium, are the operating elements which melt rapidly at a predetermined temperature. Electric alarm actuations are commonly designed in two ways: a. eutectic metal is placed in series with a normally closed circuit; fusing of the metal opens circuit and triggers alarm b. eutectic metal is used as solder to secure a spring under tension; fusing releases spring and opens circuit.	- Most common in sprinkler head element - Very common in restaurant automatic kitchen systems as fusible links - General spot detection - General area detection	- Device requires replacement after actuation - Somewhat slow in operation compared to other detectors (especially in well-ventilated and air-conditioned buildings) - Maintainability and stability is generally very high - In common use	8 2

Device	Description	Applications	Unique Characteristics	Reference
2. Glass bulb type	Frangible glass bulbs similar to those used in some types of sprinkler heads can be used as actuating mechanisms. The bulb contains a liquid and a small air bubble. The bulb is used as a strut to maintain circuit contacts. As heat is absorbed, pressure is built up in bulb due to the bubble expansion; the rapid increase in pressure actuates the alarm upon the bulb's shattering.	- Common in high temperature applications - Some general spot detection - General area detection	-Requires replacement after activation	8 2
3. Continuous line types	Alternative to spot fixed temperature detection using various designs:	- Used where continuous line heat detection is desirable		
	a. A pair of wires in a normally open circuit. Conductors are insulated from each other by a thermoplastic of known fusing temperature, twisted and installed under tension. When design temperature is reached insulation melts, actuating the alarm.		- Reliability, stability, and maintainability not yet established - Not self-restoring - "Twisto-wire" - "Protectowire"	2 8
	b. Similar device using semiconductor material and a stainless steel capillary tube. The capillary tube contains a coaxial center conductor. A small current normally flows through the semiconductor, except under fire conditions where the semiconductor resistance decreases, allowing a larger current to flow and thus actuating alarm.	- Used successfully in aircraft engine cells - Used successfully in cable trap	- Self-restoring	2 8
	c. Special capacitor cable, a ceramic core surrounded by a metal wire and covered with a metal sheath. The line capacitance at any point varies directly with the local temperature. Sophisticated electronics continuously polls several points along the line and displays results on an oscilloscope initiating an alarm when temperature is too high in any area.		- Self-restoring - New on market - Location of high temperature areas are accurate within 1 or 2 ft	8 9 10 11

Device	Description	Applications	Unique Characteristics	Reference
3. Continuous line types (concl)	d. Thermoplastic fire-sensing hose, pressurized with 30 to 50 psi air pressure. Heat due to fire softens the hose which will ultimately rupture when T is approximately equal to 170°F. The decrease in pressure initiates an alarm at the control box via a low pressure switch	- Designed for coal mine use	- Very durable in situations where adverse conditions prevail which are destructive to electronic circuits - Hose requires replacement after actuation	12
4. Bimetal type	The bimetal mechanism is a sandwich of two metals having different coefficients of thermal expansion. When heated, differential expansion causes stresses in the assembly which are resolved by bending or flexing toward the metal with the lower expansion rate. There are generally two common designs:	- General spot detection - General area detection	- Self-restoring	8 2
	a. Bimetal Strip: placed directly in line of circuit. Heat may cause expansion in the direction of the contact points which are then opened.		- Lack of positive rapid action - The gradual bending as heated may result in inadvertent alarms from jarring or vibration before design temperature is reached	8
	b. Snap Disc: a bimetallic disc found in a concave shape in its unstressed condition. As disc is heated stresses developed cause convex reversal of disc, which is used to actuate alarm (cone reversal is instantaneous at design temperature)		- Not as susceptible to inadvertent alarms as bimetal strip - In common use	8
	c. Rate Compensated: a metal cylinder containing two metal struts which are the alarm contacts. With a rapid increase in temperature the shell expands, rapidly closing the struts. Under slowly increasing temperature both the shell and struts expand until the contacts close. The cylinder and struts are the two metals, but they are not bonded together.		- In common use - Rate compensated heat detection - "rate anticipation" type	

Device	Description	Applications	Unique Characteristics	Reference
5. Synthetic filament transducers	Synthetic thread type transducers may be of use in fire detection. Device would consist of thread(s) under tension. Heat due to fire causes the threads to stretch and ultimately fail. Loss of tension can initiate an alarm.		- Research conducted in Russia on this principle (~1970) - Some U.S. patents on this principle - None are known to be on the market	13
6. Metal oxide thermistors	Certain metal oxides whose electrical resistance decreases orders of magnitude within a few degrees of a reasonable alarm point can be used as a fixed temperature fire detector.	- Spot type applications	- Low cost	14
7. Laser types	(See Smoke & Fire Gas Detectors)			
B. Rate of Temperature Rise Types				
	One effect a fire has on its surrounding environment is to generate a rapid increase in temperature of the air above a fire. The rate of rise detector will function when the rate of temperature rise exceeds approx. 15°F (8.33°C)/min. Normal changes in ambient temperature are compensated for within the detector.	- General spot detection - General area detection - Suitable for releasing device service	- Reacts to rate of temperature rise for faster operation than fixed temperature device - Inadvertent alarms may be caused due to heating systems, machines, etc. - High stability - Average reliability - Low maintenance - In common use - Medium sensitivity to Class A fires; high sensitivity to Class B fires; low sensitivity to Class C fires - Less sensitive if ambient temperature is high	8 5 6
1. Pneumatic	The expansion of gas when heated in a closed system is used to generate the mechanical force and actuate alarm contacts. Line systems consist of a metallic tubing in a loop configuration attached to the ceiling. Spot applications consist of heat-collecting air chambers.	- General spot and line detection - General area detection	- Self-restoring - In common use - Spot type units become more sensitive with age if dust clogs vent hole	8

Device	Description	Applications	Unique Characteristics	Reference
2. Thermoelectric type	Various thermoelectric properties of metal have been successfully applied in devices for heat detection. The properties used are the generation of voltage between bimetallic junctions (thermocouples) at different temperatures, and variations in rates of resistivity change with temperature.	- General spot detection - General area detection - Some line type applications	- Series-linked thermocouples (thermopiles) greatly increase sensitivity of detection	15
III. SMOKE SENSING DEVICES				
1. Ion chamber type	Reacts to the aerosol components of combustion. Responds best to particle sizes between 0.01 and 1.0 micrometer. Normal sensitivity range is 0.5 to 3.5%/ft obscuration. The basic detection mechanism of an ionization detector consists of an alpha or beta radiation source in a chamber containing positive and negative electrodes. The radiation in the chamber ionizes the O_2 and N_2 molecules in the air between the electrodes causing a small current flow when voltage is applied. When aerosols and smoke enter the chamber ion mobility is decreased, and the resulting decrease in current actuates the alarm.	- General spot detection - General area detection - Suitable for some releasing device applications in limited cases	- Most models have adjustable sensitivity within a narrow range - Some designs are subject to changes in sensitivity with varying velocities of air entering the chamber - Sensitivity also affected by humidity altitude (low pressure) - Average maintainability and stability - Some designs are not applicable for applications where high ambient radioactive levels are present, resulting in reduced sensitivity - Self-restoring - In common use - High sensitivity to Class A and B fires and medium sensitivity to Class C fires - More sensitive to flaming fires than smouldering fires	8 2 6
2. Photoelectric type	Reacts only to aerosol components of combustion. Responds best to particle sizes greater than 0.5 micrometer. The presence of aerosols generated during the combustion process affects the propagation of light as it passes through the air. Two effects of the aerosol/air mixture are utilized to detect the presence of fire: a. Attenuation of the light intensity integrated over the entire beam path length b. Scattering of light in the forward direction and at various angles to the beam path	- General spot detection - Projected beam detection over large open areas - Intermittent sampling in multizone systems with one central analyzing device	- Continuous exposure of light accelerates the aging of photocells, which implies increased maintenance and possible failure - Average sensitivity, maintainability, and stability - Foreign matter in air may cause inadvertent alarm - Self-restoring - In common use - High sensitivity to Class A fires; low sensitivity to some Class B fires; medium sensitivity to Class C fires (better than ion type)	8 2 5 6

Device	Description	Applications	Unique Characteristics	Reference
2. Photoelectric type (concl)	Smoke detectors which utilize item a., consist of a light source, collimating lens system, and a photosensitive cell.			
	Smoke detectors utilizing item b. operate on the forward scattering of light which occurs when smoke particles enter a normally dark chamber. They basically consist of a light source, photocell, and a special chamber to utilize the scattering principle. Normal range of sensitivity is 0.5 to 2.5% light obscuration/ft		- More sensitive to smouldering fires than flaming fires - New LED types offer more reliability than older types	
3. Resistance bridge type	Employs an electron grid-bridge circuit. Increases of smoke particles and moisture present in products of combustion, bring about impedance changes which upset the balance of the grid-bridge circuit causing an electronic triggering device to initiate an alarm. Atmospheric changes due to normal environmental conditions are accepted by the grid-bridge circuit and the bridge is kept in balance.	- General spot detection - General area detection	- Some difficulty with inadvertent alarms due to moisture and airborne contaminants - Average sensitivity, maintainability, and stability - Self-restoring - Less sensitive to plastics fires than cellulosic fires - Continually losing popularity	8 2
4. Particle ionization type	Determines submicrometer particle concentration by measuring the variation in electrical charge due to the pressure of ionized particles. Positive and negative ions are separated and the negative ions are used to measure a potential which is related to the concentration of particles present.	- Volume sampling (single and mutizone applications)	- Alarms in incipient stage of fire	8
5. Condensation nuclei type	Uses a technique in which micrometer or submicrometer particles can be made to act as condensation nuclei on one particle-one droplet basis; the concentration of particles is measured by photoelectric methods (normally set to alarm at 2.2×10^{10} particles/ft^3).	- Intermittent sampling in multizone systems with one central analyzing device - High valued areas, e.g., museums, art galleries, etc.	- Gaining popularity - High maintenance required - Alarms in incipient stage of fire - Extremely sensitive - Wide range of sensitivity	15 8

Device	Description	Applications	Unique Characteristics	Reference
6. Quartz crystal incipient type	Air is pumped through a separator which selectively directs only submicron sized aerosols (~0.7 micron) to a jet nozzle type impactor, where 50% of the mass products greater than 0.3 micron in size are deposited on the face of the sensing crystal. The addition of mass through impaction of the sensing crystals causes a decrease in the resonant frequency of that crystal. A difference between the beat frequency of the sensing crystal and an identical reiterative crystal, caused by a fire condition will actuate an alarm. Normally set to alarm at 1800 g/m^3.	- Volume sampling (single zone) - Multizone intermittent sampling systems should be feasible - Developed for use in space shuttle; has been shelved due to Device 7	- False alarm free operation claimed - Insensitive to changes in gravity - Alarms in incipient stage of fire - Has alarm reset to reconfirm incipient fire condition - Insensitive to changes in air currents and dust (can operate in air currents up to 1000 ft/min) - Initiates fail-safe signal when maintenance is required - Relatively new - Requires 5 watts power consumption - Has been shelved due to Device 7	16
7. Modified ion chamber type	Predecessor of Device 6 . Uses same type of impactor and air pump mechanism, but with ionization chambers substituted in place of the quartz crystals. Only particles less than 2 microns in size are directed through the sensing chamber.	- To be used in the space shuttle and in advanced naval craft	- Has same characteristics as Device 6	17
8. Laser types	Detects heat by reaction to changes in the index of refraction of the air along the beam of the path. This refractive index can cause variations in the velocity of the laser beam. This phenomenon is utilized by monitoring the changes in the beam path due to heat. Detects smoke by responding to the presence of visible products of combustion of a fire in the same manner as an ordinary light beam. This phenomenon is utilized by the use of photocells in the same manner as with an ordinary light beam.	- Projected beam detection across large areas	- Ambient light can have an adverse effect on smoke detection - Detection time varies with air velocity and ambient light - Reliability, maintainability, and stability are not established - Relatively new - Not known to be commercially available yet - Excellent for large, open area detection	8

Device	Description	Applications	Unique Characteristics	Reference
IV. FIRE GAS SENSING DEVICES				
1. Catalytic semiconductor gas detector	Uses a bulk N-type catalytic semiconductor thermistor, which responds with a large decrease in resistance when exposed to reducing or combustible gases, due to catalytic oxidation. In simple application, the operating element is placed in series with an alarm device and the power source in the quiescent condition acts as a high resistance to block the flow of current to the alarm circuit. During a fire the element resistance drops and current flows to the alarm circuit.	- General area detection - General spot detection	- Relatively new - Value as a detector is not fully established - Self-restoring - Possible contamination of sensor - Inadvertent alarms possible due to response to gases which are not fire signatures - Reliability, maintainability, and stability have not been established but are questionable - e.g., "Taguchi" - Research needed in developing gas selective catalysts - Offshoot from gas leak detection - Poor response to plastics fires	8
2. Infrared type CO_2 detector	IR energy in the range of 4.22 to 4.31 micrometers is used to detect CO_2, the only gas to have an absorption in this range. Increased CO_2 concentration is measured by an exponential decrease in voltage due to photodetector resistance. Can detect a wide range of CO_2 concentrations	- Volume detection - Used successfully in African gold mines	- Extremely sensitive - Very expensive - e.g., "Spanair System" developed for gold mines recently - Requires more power than conventional detectors - Continuous monitoring - Has advantages over conventional mine air sampling systems due to the elimination of the time lag due to air travel through sampling hoses - Similar devices are being developed to detect methane and carbon monoxide	18
3. Field effect transistor hydrogen sensor	Smoke contains a small amount of hydrogen, the amount depending on the degree of combustion. More hydrogen is evolved in the early and dying out stages of fire development than during the developed fire condition. Because of this, the hydrogen output can be used to detect the early stages of a fire. Pd-gate n-channel silicon field effect transistors can be used for this purpose. Hydrogen gas is adsorbed to the metal surface and metal-oxide interface which causes a change in the threshold voltage of the MOS transistor and this change is easily measured. Concentrations as small as 1 ppm can be detected with this setup.	- Should be useful for general fire detection	- Value as a fire detector is not established - Spinoff from hydrogen leak detection - New concept - No mention in literature of possible false alarm problems - No mention in literature of sensor contamination problems - Self-resetting - 150°C temperature necessary for sensing element operation	19 20 21

Device	Description	Application	Unique Characteristics	Reference
4. Argon type detector	Operates on the principle of ionization of foreign molecules by collision with high energy Ar atoms leading to high concentrations of Ar (see Ref. 4 for additional explanation of operation) Gas sensor beta or alpha radiation is used as a background current source.	- Should be useful for general fire detection	- New concept (probably not on market) - CO and CO_2 cannot be detected by this method - Best suited for very small concentrations of gases - Ref. 4 indicated that hybridization of this type and ionization type would be a very good combination reducing false alarms	22
5. Flame ionization type	An H_2-O_2 flame, which is used as one of the electrodes, is used to induce electron emission in various types of organic and inorganic molecules having low work functions. Electrodes under imposed voltages are used to collect the resulting ions.	- Should be useful for general fire detection	- No fire detectors developed using this principle are known - High sensitivity, reasonable stability, moderate flow insensitivity, and linearity are reported for these devices - Continuous flow of H_2 is necessary for detector operation - Might be of value in a hybrid setup	22
6. Thermal conductivity sensors	A set of matched metal filaments or thermistors is used to follow changes in thermal conductivity. A reference gas is passed over a reference junction while the gas in question passes through the detection element. Resistance of the detection element changes in reference to the reference junction.	- Should be useful for general fire detection	- Ref. 4 explains how this device could be incorporated as a fire detector	22
7. Fuel cell devices	Analogous to an electrochemical cell where conventional fuels react at the anode while O_2 or air reacts at the cathode. Carbon monoxide fuel cells may be feasible in this type of fire detection.	- Should be useful for general fire detection	- Ref. 4 explains how this device could be incorporated as a fire detector	22
8. Oxygen depletion type	Oxygen depletion occurring in a fire situation may be useful for detection purposes. Probably best in a hybrid setup. Detection mechanisms may be primary galvanic cell: a type of battery in which electricity is generated in proportion to O_2 partial pressure (many variations with different anodes and cathodes).	- Should be useful for some fire detection applications	- e.g., solid electrolyte fuel-cell device similar to Survivair's device used in underwater diving	23 8

Device	Description	Applications	Unique Characteristics	Reference
V. **FLAME DETECTORS**				
	Several methods are used to detect fires by sensing the radiant energy from smouldering or flaming combustion. Spectra used are in the IR (0.7 to 1.40 micrometer) and the UV (0.001 to 0.4 micrometer) bands	- General area detection - Best applied in areas where flame will initiate before smoke	- Fiber optics may be used in conjunction with these - Self-restoring - Interference from solar radiation is a major problem, causing inadvertent alarms - Advantage of large area surveillance by rapidly responding to the designed level of actuation anywhere in its range of vision.	8 5
1. Infrared type	Basically consists of filter and lens system to screen out unwanted wavelengths and focus incoming energy on photocells. Normally designed to receive either the total IR component of flame or flame flicker in the range of 1.5 to 10 Hertz or 4 to 15 Hertz.	- General area detection	- Generally high sensitivity and speed of response - Generally low stability - Low sensitivity to Class A and C fires; high sensitivity to Class B fires - Medium reliability and maintainability	8
2. Ultraviolet type	Same operating principle as IR type except operating in the UV range (0.7 to 0.30 micrometer) in which they are insensitive to both sunlight and artificial light	- General area detection	- Problems with responding to electric arcs and lighting, causing inadvertent alarms - High sensitivity and speed of response - Low sensitivity to Class A fires; high sensitivity to Class B and C fires - Medium reliability, maintainability, and stability	8
3. Combination IR-UV	Combination of the above types into one unit	- General area detection - Applied successfully in hyperbaric chambers, and aircraft minicomputers	- High sensitivity and speed of response	8
VI. **MISCELLANEOUS DETECTORS**				
1. Ultrasonic type	Sets up a stable standing wave in the area to be supervised. Movement of air caused by hot gases from a fire disturbs the wave pattern. The disturbance is monitored by an ultrasonic receiver which is used to trigger an alarm. A spinoff of intrusion detection technology.	- Volume surveillance	- High sensitivity - Supervised area must be unoccupied, for the sensor detects any movement	22 24

Device	Description	Applications	Unique Characteristics	Reference
2. Rate of temperature rise, fixed temperature combination	Combination of two different detection mechanisms described previously, incorporated into one unit. The two most common types are: a. Vented hemispherical diaphragm for the ROR mechanism, and spring retained eutectic metal as the fixed temperature mechanism	- General spot detection - General area detection	- Advantage of quick response to rapidly developing fires by use of the ROR mechanism, while the fixed temperature elements respond to the slowly developing fires - Generally high maintainability, stability and reliability - In common use - Medium sensitivity to Class A fires; high sensitivity to Class B fires; low sensitivity to Class C fires.	8
3. Resistance bridge-ionization combination	Combination of the two previously described devices into one unit; each mechanism having its own bridge circuit which together must trigger a main electronic gate.	- General spot detection - General area detection	- Reduces inadvertent alarms due to the required activation of both mechanisms - Stability, maintainability, and reliability are average - In common use	8
4. Electrostatic detection	An insulated wire grid placed over and under the entire surveillance area can be used to measure "charged particles" extracted from flames. Charged particles accumulate and are detected in the form of an electric current.	- Fire surveillance of entire gridded area	- Speculative idea from Ref. 62 - Many possible sources of inadvertent alarm such as household appliances - Device may only be useful at nighttime (low activity) - Possible security applications of this device. - None of these devices have been marketed	25
5. ionization/ fixed temperature combination	Combination of two different detection mechanisms described previously, incorporated into one unit. Activation of alarm is by either mode of detection	- General spot detection - General area detection	- Added thermostat serves as a backup detector in case of ionization failure, or as a primary detector in case of high heat buildup without smoke	
6. Photoelectric/ fixed temperature combination	Combination of two different detection mechanisms described previously, incorporated into one unit. Actuation of alarm is by either mode of detection	- General spot detection - General area detection	- Added thermostat serves as a backup detector in case of photoelectric smoke detector failure, or as a primary detector in case of high heat buildup without smoke.	
7. Catalytic semiconductor/ fixed temperature combination	Combination of two different detection mechanisms described previously, incorporated into one unit. Activation of alarm is by either mode of detection.	- General area detection	- Added thermostat serves as a backup detector in case of gas detector failure, or as a primary detector in case of high heat buildup without gases.	

Device	Description	Applications	Unique Characteristics	Reference
8. Acoustical Fire Detection	Sound waves of various frequencies are emitted by the combustion of materials. With the advent of new technology in acoustical transducers, it may now be economically feasible to utilize them as fire sensors, either using combustion generated sounds or degradation sounds of a doped material as a fire signature.	- General area detection	- Speculative IITRI idea - Fire signature is sound; thus detection is with speed of sound - Does not require a line-of-sight configuration as other quick response detectors - Possible false alarm problems - Doping agents with characteristic degradation frequencies may eliminate false alarms, if necessary	

REFERENCES USED IN APPENDIX A

1. NFPA, National Fire Code 72B, "Auxiliary Signaling Systems", 1975.
2. Bryan, J. L., "Fire Suppression and Detection Systems", Glencoe Press, 1974.
3. Jensen, R., "Fire Protection for the Design Professional", Cahners Books, 1975.
4. Handbook of Industrial Loss Prevention, 2nd Edition, Factory Mutual.
5. Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, National Academy of Sciences, April 11-12, 1972.
6. NFPA, National Fire Code 72E, "Automatic Fire Detectors", 1974.
7. Fire Protection Handbook, 14 Ed., NFPA.
8. Custer, R., R. Bright, "Fire Detection - The State of the Art", NBSA Center for Fire Research, NBS Tech Note 839, June 1974.
9. System Senses Temperature Along a Line, Instruments and Control Systems, 1975.
10. "1000 Ft Wire That Detects Fire", Business Week (Ind. Ed.) 1975.
11. Sanford, J., "Thermistor Defines Temperature Profile", Design News, November, 1975.
12. Stitt, T., "Air Hose Replaces Electric Circuit in New Fire Detection System," Coal Age, p 88, September 1973.
13. Veselov, A., Taradaiko, V., "Synthetic Filament Transducers for Automatic Fire Extinguishing Systems and Protective Devices, Principles of Fire Prevention and Fire Fighting," Translation of Pozharnaya Profilaktika I. Tushemi, Pezarov, Moscow, 1968.
14. Lipman, J., "Build a Simple Fire Alarm with Metal-Oxide Temperature Sensors, Electronic Design," p 88, April 1976.
15. Ludewig, F., "New Concept in Fire Protection Fire Journal," 69(4), p 87, July 1975.
16. Barr, L. G., Development of a Quartz Crystal Incipient Fire Detector, Celesco Industries, Inc., Costa Mesa, California
17. Design Discussion, Mark 2, Production Smoke Detector, Brunswick Corp., Defense Div., Report 01-579, January 1977.
18. van der Walt, N. T., "New Ways of Detecting Underground Fires Prove Their Worth in South African Mines", E/MJ, p 80, February 1976.
19. Lundstron, I., Shivaraman, M., Stiblert, L., Svensson, C., "Hydrogen in Smoke Detected by PD-Gate Field Effect Transistor".

20. Zatek, J., "How to Measure and Monitor Combustible and Toxic Gases," Fire Command, p 21, April 1973.

21. Waterman, T., Degenkolb, J., and Stickney, C., "A Study - Early Warning Fire Detection Performance in the Hospital Patient Room," Fire Technology, p 287, November 1974.

22. Wagner, J. P., "Survey of the Principal Operating Characteristics of Fire Detector Mechanisms", Fire Research Abstracts and Review, 23(2), 2971.

23. Giles, A. F., Electronic Sensing Devices, 1966.

24. Bagno, S., Gilbert, R., and Demers, E., "Fire Detection by Ultrasonic Doppler", IEEE Convention Record, p 193, 1964.

25. Greason, W. and Inculet, I., "Electrostatic Fire Detection", IEEE Trans. IGS-7 (1), p 89, January/February 1971.

26. Hurle, I. R., et al, "Sound Emission from Open Turbulent Premixed Flames", Proc. Roy. Soc. A. 303, 409-427, 1968.

27. Strahle, W. C., "A Review of Combustion Generated Noise", AIAA Aero-Acoustics Conference, Seattle, Wash., October, 1973.

APPENDIX B

FIRE SUPPRESSION AGENTS
A SUMMARY DESCRIPTION

Appendix B

FIRE SUPPRESSION AGENTS, A SUMMARY DESCRIPTION

Agent	Composition	Fire Classification	Extinguishing Mechanism	Comments	Ref.
GASES					
Nitrogen, Argon, etc.	Industrially pure gases	- Satisfactory on Class B fires - Satisfactory on Class C fires	Blankets fuel (reduces oxygen)	Seldom used	2 1 4-Sec 13 7 6-Chap 1 5-Chap 14 Chap 15
Carbon Dioxide	Industrially pure CO_2	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Cools and blankets fuel	- Does not react with most substances - Only mildly toxic; however, 9% conc. is threshold limit of anoxia - Can be applied locally to blow out flame or used in total flooding at 30-75% conc. - Stored as both liquid and gas; high pressure storage, 850 psi, requires heavy cylinders; low pressure, 300 psi requires refrigeration to $0^{o}F$ - Possible cold shock to sensitive electronic parts - No residue	23-p14-16 24-p36-37 25-p13-14 26-Table 7-1
HALOGENATED HYDROCARBONS:					
Bromotri-fluoromethane (Halon 1301)	CF_3Br	- Satisfactory on some Class A fires - Satisfactory on Class B fires - Satisfactory on Class C fires	Inhibits flame reactions	- Can be used locally or in total flooding system - Least toxic Halon; normal extinguishing concentrations (7%) present no immediate problems, higher concentration may cause health problems, especially after decomposition - Second most effective Halon - Most commonly used Halon today - Low extinguishing concentrations required (3-20%) - Slight decomposition products (not particularly corrosive)	

Bromodifluoro methane (Halon 1211)	$CBrClF_2$	- Satisfactory on Class B fires - Satisfactory on Class C fires	Inhibits flame reactions	- Too toxic for total flooding in occupied area - Common in local applications - Low extinguishing concentrations required (3-20%) - Slight decomposition products (not particularly corrosive)	
LIQUIDS (aqueous)					
Water (solid stream)	H_2O	- Satisfactory on Class A fires - Limited use on Class B fires where flash point is 150°F	Cools fuel	- Oldest and most widely used agent - High latent and specific heats - High availability - Some problems with high freezing points - Poor blanketing characteristics - Problems with electrical conductivity - Solid streams make long range accessibility - Possible equipment damage due to presence of water	4-Sec 13 7 6-Chap 1 5-Chap 10 23-p18 24-p34 25-p14 26-Table 7-1
Water (spray or fog)	H_2O	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class D fires	Cools and blankets fuel	- General properties of water plus blanketing characteristics	
Water and detergent (wetting agent)	H_2O and synthetic detergents	- Satisfactory on Class A fires - Limited use on Class B fires	Covers or coats, and cools fuel	- Lowers surface tension of water - Foam deposits, delay water run-off, increases cooling effect - Film form tendency precludes its use against electrical hazards - Low on toxicity	23-p18 24-p43 15

Water and thickening agents	H_2O and viscosity agents such as: "CMC" (Sodium Carboxymethycel-lulose) "Gelgard", Gums Bentonite clays	- Satisfactory on Class A fires - Effective on fires where radiation is at an advantage, e.g., forest fires	Covers or coats, and cools fuel	- General properties of water and increased coating characteristics and resistance to drift	4-Sec 13 Chap 1 23-p20
Water Slurry	H_2O and a mixture of sodium and calcium borates	- Satisfactory on Class A fires only	Covers or coats, and cools fuel	- Similar to water and thickening agents, but after water is evap-orated, borate crystals lose their water of hydration, after which they form a glassy coating	4-Sec 13 Chap 1 6-Chap 1 25-p20
Water and alkaline salt	H_2O and alkaline salts, such as Potassium Carbonate	- Satisfactory on Class A fires only	Covers or coats, and cools fuel	- Salt solution weakens char particles which break off and are extinguished leaving underlying material wetted down, which when evaporated, leave a crystalline somewhat fire retardant barrier - "Loaded system" - Can be rendered non-freezing to -40°F	4-Sec 13 Chap 1 23-p20
Chemical foams	H_2O and aluminum sulfate "A" and sodium bicar-bonate "B"	- Satisfactory on Class A fires - Satisfactory on non-water soluble Class B fires	Covers or coats fuel	- No longer used due to economics and ease of handling of liquid foam concentrates - High salt content makes it a high conductor of electricity	4-Sec 13 Chap 1 6-Chap 1 23-p20
Protein foams	H_2O and protein base stabilizers made from slaugh-ter house products	- Satisfactory on Class A fires - Satisfactory on non-water soluble Class B fires	Covers or coats fuel	- A type of "air" or "mechanical" foam - Greater fire resistance than detergent base foam - Cannot be pre-mixed with water for an indefinite length of time - Applied in 3-6% solution; 7-12 x expansion	5-Chap 12 Chap 13 6-Chap 1 23-p20 24-p40
Fluoroprotein foams	H_2O and protein base stabilizers, plus a fluorinated surfactant	- Satisfactory on Class A fires - Designed for use on Class B fires	Covers or coats fuel	- Fluorinated surfactants give a fuel shedding property to the foam ex-cellent for use in Class B tank fires - Applied in 3-6% solution; 7-12 x expansion - Non-toxic, biodegradable	5-Chap 13 6-Chap 1 16-p30 23-p20

Synthetic detergent based foams	H_2O and a blend of aryl and alkyl sulfonates	- Satisfactory on Class A fires - Satisfactory on non-water soluble Class B fires		- Applied in 3-6% solution; 12-20 x expansion - Does permit pre-mixing for extended periods of time	4-Sec 13 7 5-Chap 13 6-Chap 1
Insoluble protein and detergent foams	Fatty acids, insoluble metallic salts, and insoluble soaps added to prevent soluble fuel from soaking up through foam	- Satisfactory on Class A fires - Satisfactory water-soluble Class B fires	Covers or coats fuel	- Applied in 3-6% solution, 7-12 x expansion - Effectiveness is limited by a short time factor (½-1 min) - Possible water damage	23-p23 4-Sec 13 7 5-Chap 13 6-Chap 1
High expansion foams	Synthetic detergent foam with very low density assemblage of bubbles	- Satisfactory on Class A fires - Satisfactory on Class B fires - Limited use on Class C fires	Covers or coats fuel	- Applied in 2% or greater concentrations - 100-1000 x expansion - Suited for use as flooding agent in enclosed and inaccessable areas - Slight clean-up problem - Extinguishing action is relatively slow - Provides protection from reignition	4-Sec 13 7 5-Chap 13 6-Chap 1 24-p40 26-Table 7-1
Combined foam and dry chemicals	A variety of foams are compatible with a variety of dry chemicals, but there are many incompatible cases	- Satisfactory on Class A fires - Satisfactory on Class B fires	Covers or coats fuel	- Dry chemical additives act as absorbants, thus lowering the evaporation rate of liquid fuels - Suitable for spill fires - Clean-up problem - Care must be taken in selection of compatible agents - Foam and dry chemicals are applied through separate means	16-p30 6-p83 23-p23
<u>LIQUIDS</u> (non-aqueous)					
HALOGENATED HYDROCARBONS:					
Chlorobromomethane (Halon 1011)	CH_2BrCl	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use of Class A fires	Inhibits flame chain reactions		4-Sec 13 7 6-Chap 1 21 5-Chap 15

Dibrometetra-fluoromethane (Halon 2402)	$C_2Br_2F_4$	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions	- Not used in U.S. - Limited applications in aircraft systems and extinguishers	23-p16 25-p14
Dibromodi-fluoromethane (Halon 1202)	CF_2Br_2	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions	- Most effective Halon - Used by USAF in aircraft systems	
Methyl Bromide (Halon 1001)	CH_3Br	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions	- Problems with toxicity	
Carbon Tetra-chloride (Halon 104)	CCl_4	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions	- Popular in past until its toxicological problems were defined	
Methyl Iodide (Halon 10001)	CH_3I	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions		
Bromochloro-fluoromethane (Halon 1211)	$CClBrF_2$	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Inhibits flame chain reactions	- In common use for local application - Also, used as a gaseous agent **Concerning all Halons:** - No criticality hazard - Low contamination spread hazard - Slight decomposition products (non-corrosive)	
Halon Foam	A mixture of halons and compatible surfactants	- Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class A fires	Covers or coats fuel, and inhibits flame chain reactions	- Developed for Air Force	3 23-p32

Synthetic Fluids	Cyclic boron compounds: -trimethoxyboroxine -tri-cresyl phosphate -dioctyl phthalate	- Satisfactory on Class A fires - Satisfactory on Class C fires - Satisfactory on Class D fires	Covers or coats fuel	- Developed for metal fires, e.g. molten sodium in atomic reactors; metal alloys in rocket fuels - Very toxic	6-Chap 1 23-p23
SOLIDS					
Sodium Bicarbonate Base Powder (Alkali)	$NaHCO_3$	- Satisfactory on Class B fires - Satisfactory on Class C fires	Cools fuel, inhibits flame chain reactions, and shields radiation	- Dry chemical powders range from 75-100 microns in diameter - Clean-up problem - "Standard" dry chemical - Very popular - Least expensive - Non-toxic - Non-conductive	4-Sec 13 Chap 5 7 6-Chap 1 5-Chap 6 6-Chap 1 18-p51 23-p25 24-p39 25-p13 26 Table 7-1
Potassium Bicarbonate Base Powder (Alkali)	$KHCO_3$	- Satisfactory on Class B fires - Satisfactory on Class C fires	Cools fuel, inhibits flame chain reactions, and shields radiation	- "Extra effective" dry chemical - "Purple K" - None-conductive - Clean-up problem	
Potassium Carbamate Base Powder (Alkali)	NH_2COOK	- Satisfactory on Class B fires - Satisfactory on Class C fires	Cools fuel, inhibits flame chain reactions, and shields radiation	- Twice as effective as most BC powders - Expensive - "Monnex" - Non-conductive - Clean-up problem	
Potassium Chloride (Neutral)	KCL	- Satisfactory on Class B fires - Satisfactory on Class C fires	Cools fuel, inhibits flame chain reactions, and shields radiation	- Clean-up problem - Super K - Corrosive - Non-toxic - Non-conductive	
(Mono) Ammonium Phosphate Base Powder (Acidic)	Ammonium dihydrogen orthophosphate $(NH_4)H_2PO_4$	- Satisfactory on Class A fires - Satisfactory on Class B fires - Satisfactory on Class C fires - Limited use on Class D fires (depending on fuel)	Covers or coats fuel, cools fuel, inhibits flame chain reactions, and shields radiation	- "ABC"; all-purpose dry chemical - Slightly corrosive when wet - Very popular - Non-toxic - Non-conductive - Clean-up problem	

Metal Extinguishing Agents	- Met-L-X powders - G-1 powder - Na-X powder - Lith-X powder - Pyromet powder - Ternary Eutectic Chloride powder - Talc powder - Graphite powder - Sand - Cast iron borings - Sodium Chloride - Soda Ash - Lithium Chloride - Zirconium Silicate - Dolomite - etc.	- Satisfactory on Class D fires	Covers or coats fuel	- Limited by gravitational forces in covering only generally horizontal areas (poorly suited for vertical) - Each agent must be carefully chosen for fuel involved - Clean-up problem Concerning all Solid Agents: - Possible damage to electrical components - General clean-up needed after use	4-Sec 13 Chap 6 23-p30 26-Table 7-1

COMBINATION AGENTS WORTHY OF INVESTIGATION

CO_2 and water fog Halon and water fog Foam and liquid halons	- Joint use of some of these agents could possible reduce the amounts of agent needed to effectively extinguish, due to the combination of separate extinguishing properties	23-p31 24-p45 23-p32

REFERENCES FOR APPENDIX B

1. "Aircraft Ground Fire Suppression and Recue Systems - Current Technology Review," F. Salzberg, J. Campbell, IITRI Technical Progress Report ACFSRS 70-1.
2. "A Study of Vaporizable Extinguishants," 1960, Dow Chemical Co., D. Engibows, T. Torkelson.
3. "Advanced Fire Extinguishers for Aircraft Habitable Compartments," S. Atallah, J. Hagopian, A. Kalelkar, Technical Report AFAPL-TR-72-62.
4. NFPA Fire Protection Handbook, 14th Edition.
5. "Fire Protection for the Design Professional," R. Jensen.
6. "Fire Suppression and Detection System," J.L. Bryan.
7. "Improved Fire Protection for Stationary Underground Equipment," Part I, Proposal No. IITRI-74-188J.
8. Foam Extinguishing Systems '74, NFPA 11.
9. High Expansion Foam Systems, '70 NFPA 11A.
10. Synthetic Foam and Combined Agent Systems, NFPA 1113.
11. Carbon Dioxide Systems '73, NFPA 12.
12. Halon 1301 Systems '73, NFPA 12 1A.
13. Halon 1211 Systems '73, NFPA 12 B.
14. Dry Chemical Systems '73, NFPA 17.
15. Wetting Agents '72, NFPA 18.
16. "Aircraft Fire Protection and Rescue Procedures," 1st Ed., '70 IFSTA.
17. "Controlling Mine Fires with High-Expansion Foam," '60, Bureau of Mines Report 5632.
18. "Improved Sensors and Fire Control Systems for Mining Equipment," Phase 1, FMP Corp., Dec. 1972.
19. "Aircraft Fire and Rescue Facilities and Extinguishing Agents," Dept. of Transportation, AC No. 150/5210-613, '73.
20. Wetting Agent '72, NFPA 18.
21. Vaporizing Liquid Extinguishing Agents '65, NFPA 182M.
22. Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, April '72, Nat. Academy of Sciences.
23. The Extinguishment of Fire, W. Haessler, NFPA #FSP-40.
24. Guide to Fire Protection in Got Cells, Canyons, and Caves, Atlantic Richfield, ARH-3020 RD1.
25. Hot Cell Fire Protection, DuPont, DP-1242.
26. Glovebox Fire Safety, '67 AEC, TID 24236.

APPENDIX C

DESCRIPTIONS OF RECENT RAIL TRANSIT VEHICLE FIRES

APPENDIX C

DESCRIPTIONS OF RECENT RAIL TRANSIT VEHICLE FIRES

1. Hamburg, Germany, 8 April 1980, 1612 hours
2. New York, New York, 16 March 1982, 0708 hours
3. Chicago, Illinois, 1982 CTA Undercar Fires

1. Hamburg, Germany, 8 April 1980, 1612 hours

This account of a subway fire in Hamburg, Germany is a translation of the report in:

> Zeitschrift der Vereinigung zur Foerderung des Deutschen Brandschutzes (Journal of the Association for the Advancement of Fire Prevention in Germany), 1980, 4, 134-138.

Anatomy of a Fire

- Rapid Transit Train Inside Train Station

  Hamburg, Altona

by: John-Peter Stapelfield
Fire Prevention Bureau, Hamburg Fire Department

ABSTRACT

Fire development from the incipient stage through flashover is usually conducted in controlled experiments in which variables can only be simulated. It is very seldom that a "real" fire can be documented authentically from minute to minute.

An amateur photographer happened to be present on the new underground platform (Station Hamburg-Altona) on 8 April 1980 when a rapid transit train entered the station and stopped; in one of the cars a seat was on fire - arson. The photographer captured the process of fire development from the incipient stage to flashover.

After a rather amateurish attempt to attack the fire with a hand extinguisher (dry powder) had failed, the last remaining people had to flee the platform due to the intense heat and heavy smoke development.

Several people had to be rescued by the fire department and evacuated to the outside. Twenty minutes after the train had entered the station, two of the lower platforms were so heavily engulfed in smoke that the fire department was only able to advance with air packs (long duration type) in the search for persons, evacuation to the exterior, and then to commence fire fighting.

In a very short time two modern cars of the rapid transit train, construction 1975, one first and one second class, burned out completely to the floor.

This fire had the following extraordinary indications:

- o rapid fire spread
- o very heavy smoke development
- o orientation difficulties for the firefighters within the smoke filled large underground transportation complex.

General Description

The Altona station is of new construction, a combination of a transportation installation, station building and a department store (Kaufhof) with approximately 19,000 m^2 of sales area over five levels. The new department store opened in October, 1979; the underground transportation complex of the new city rapid transit system in the Altona station was opened on 19 April 1979. The Altona station consists of several transportation levels.

Long distance travel originates from level "0" with four platforms and eight rails. The annexed perpendicular located platform at the south end is topped off with the station's main building and a department store.

The ramp to the city rapid transit tunnel (level 2) is located west of the long distance platforms. Approximately 70 meters south of the tunnel entrance is the start of the two city rapid transit platforms of the Altona rapid transit station. Both are within the same tunnel area. The usable platform length is 204 meters. Total length of the platform enclosure is 228 meters, width topping off towards the end, average 30.50 meters. The rough ceiling height is 3.75 meters, distance to suspended ceiling above platform is 3.50 meters.

Level 1 houses a lobby with automated token booths, kiosks, the downward connections to the rapid transit platforms, an upward connection to the station lobby with the long distance platforms on level "0". From this lobby two exits lead directly to the exterior, one 12 meters wide and the other 14 meters wide, another three stairways terminate at grade level outside the station.

Fire Occurrence

On 8 April 1979 at 4:12 p.m. a train entered the rapid transit station, Altona, coming out of a 6.5 kilometer long tunnel from Konigstrasse station. A double seat was burning in the first class section of a car at the front of the train.

A woman was the only passenger in this section. Fortunately she did not pull the emergency brake cord which would have resulted in unforeseeable consequences - instead she reported the fire after the train had entered the Altona station.

She testified later that she discovered the fire between the Altona station and Konigstrasse. She remembered seeing three young people at the point where she discovered the fire. She did not remember exactly if these people boarded the train at the Konigstrasse station (departure 4:10 p.m.)

or were already aboard at the Reeperbahn station (departure 4:08 p.m.). She indicated that they boarded at the station with the blue tile (Reeperbahn). Detectives concluded that arson was committed.

Time: 16:08 Regarding the testimony of the witness, ignition must have occurred just prior to the departure of the train at 16:08 p.m.

16:12 The train entered Altona station. The woman in the first class section opened the door, ran onto the platform and screamed for help. The train conductor was alerted. He ran to the first class car to survey the extent of the fire. He ran back and notified via radio communication the transportation systems' central station.

16:13 p.m. The fire encompassed two seats and extended approximately a vertical distance of 3 meters above the horizontal center of the windows.

An amateur photographer entered on the platform and took a series of pictures.

The fire spread from the first class car to the second class car possibly occurred through the roof areas; burning paint marks support this assumption. Both cars had aluminum superstructures; the material failure point of 600°C was rapidly reached. Flames penetrated the burned through roof, hitting the concrete tunnel ceiling 1 to 5 meters above. It is assumed that the flames were funneled, due to the ceiling construction, (a soffit above the face of the platform) onto the next car. The rapid fire spread in the second class car can be traced back, the same as in the first class car, to the fireload of the upholstery material.

The lead car, which was right in front of the area of origin (the first class car) survived the fire with minor exterior paint showing damage even though this car was also of aluminum construction.

It is assumed that the ventilating conditions during the fire were responsible for the minor damage to this car. (A draft was coming from the tunnel mouth.)

Two engine cars,Engines BR472 (aluminum construction) and BR470 (steel superstructure), at the other end of the fire, were also involved. BR472 burned down. Fire did not jump over to BR470. This may have been due to successful firefighting. Half of the paint on the steel roof blistered.

Material Testing

Regarding the evaluation of the photos, the rapid fire spread and the fire intensity can mainly be traced back to the upholstery of the seats and back supports.

The Fire Prevention Bureau, City of Hamburg Fire Department,conducted tests with the first and second class seats. Results support the above stated evaluation.

Smoke Development and Smoke Spread

The heavy smoke development and rapid spread of smoke proved to be extremely critical. All areas within the Altona station which had open connections to the fire area were filled with smoke within a short time. The department store was able to minimize smoke damage by switching its ventilating system. As a result of questioning the fire fighting force, it was established that at 16:30 p.m. the -1 Level was completely filled with smoke, while the -2 level remained free of smoke from above 1.50 meters over the platform. Accessibility was altogether impossible. The smoke was black, and initiated heavy coughing immediately.

At 16:45 p.m. the -2 level was also completely filled with smoke. Black smoke was coming out of all openings in the station building at this time, engulfing the building completely. Visibility on the street at the station was limited to about 50 meters. According to the investigation by the fire department, at this time approximately 53,000 m^3 of volume including the -2 level, the -1 level and the area between the -2 level and the tunnel exit were completely filled with smoke, even though 246 m^2 gravity ventilating areas were part of the construction above the exits and the tunnel exit.

This extraordinarly fast buildup of a heavy smoke condition, even with relatively good ventilation capabilities, indicates an additional hazard to travelers and transit employees in the case that a rapid evacuation is not possible.

It also shows that the presence of smoke was an increased hazard firefighters. This fire showed that the search and reconnaissance groups can lose their orientation, can be split up, fall off the platform, and as the air supply in their air packs is used up, find their lives endangered.

Conclusions

Based on the experience gained by this fire, a close work program will be created between the Federal Railroad and the Hamburg Fire Department which will focus on tactical firefighting procedures and preventive fire protection in underground traffic installations. In the meantime the City Senate created a task force, which includes the transportation department. Their objective is to check the fire safety of all public transportation systems and all traffic related building construction. The leadership is by Fire Safety Director Gunther of the Hamburg Fire Department.

Illustration 1.

4:13 P.M. - Two seats in the first class car are burning. Seatcovering: Polyamid-Velour Upholstery: Polyurethane form with reinforced rubberized hair.

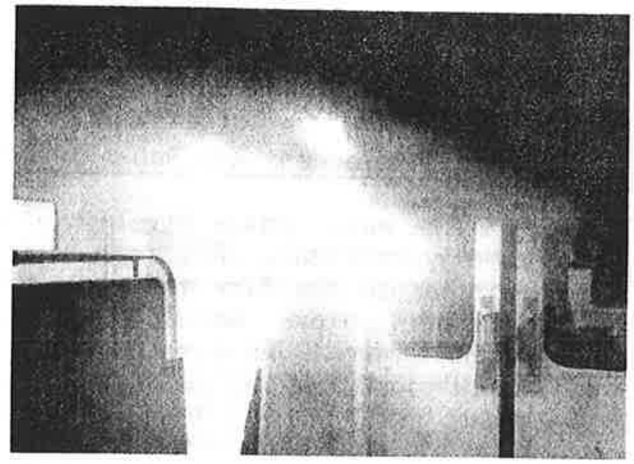


Illustration 2.

4:13 P.M. - Top of flames are already reaching the overhead luggage compartment. Oxygen supply thru the open door supports the fire development.

Fire duration approximately 5 minutes.

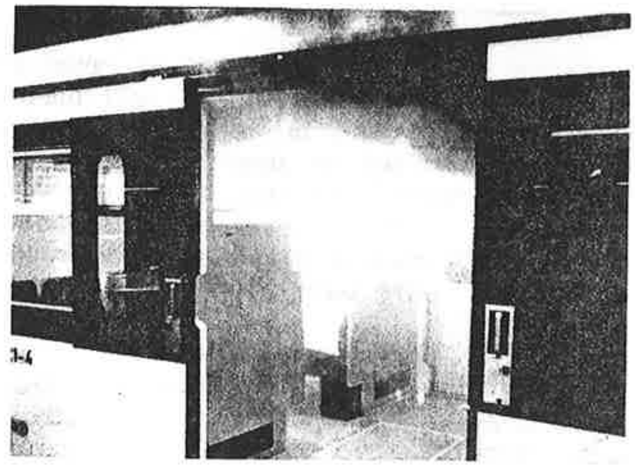


Illustration 3.

4:13 P.M. - Increasing fire intensity and spreading of smoke inside car. Persons are still present on the platform (see reflection on windows)

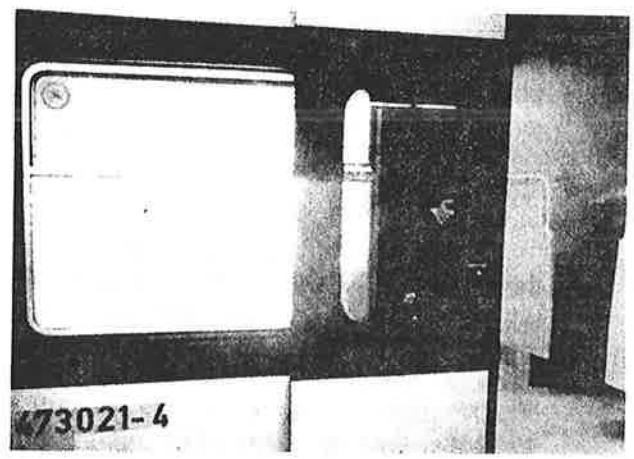


Illustration 4.

4:14 P.M. - (Time shown in reflection on original photo): Smoke escaping to exterior thru door and window slot. Fire already emcompasses adjacent seats.

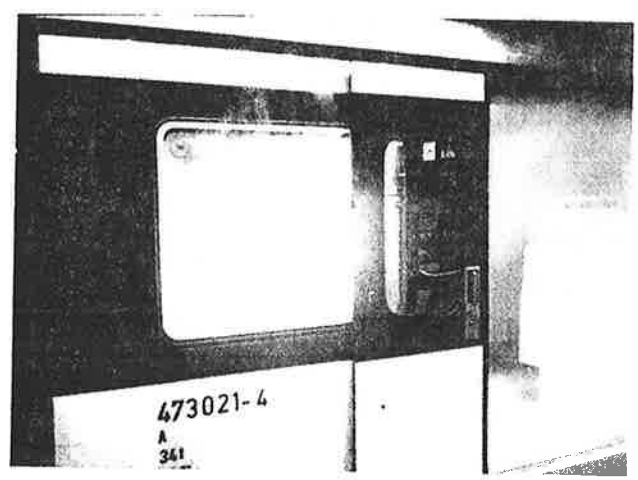


Illustration 5.

4:14 P.M. - 4:14 P.M. indicated on station clock. Extremely rapid spread of fire. Heavy smoke escape thru the second door.

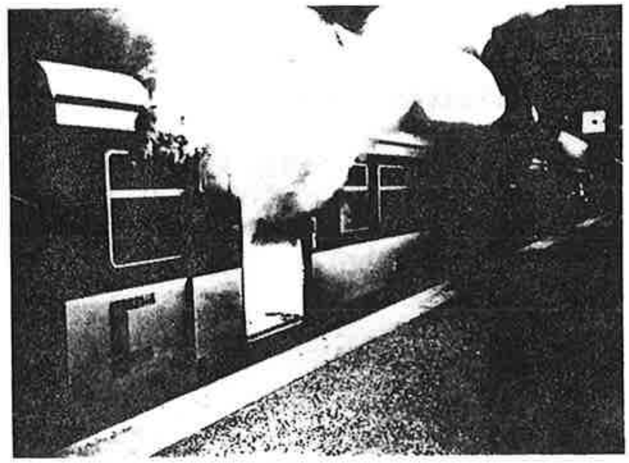


Illustration 6.

4:16 P.M. - Thermal breakdown of the adjacent seats and coverings was proceeding caused by radiant heat. The car is completely filled with particles of combustion (gas and smoke). The condition is shortly before flashover. Burning debris caused by collapse fell thru the open door onto the platform. (Enclosure over the platform was a metal pan type ceiling - debris did not originate from this ceiling enclosure)

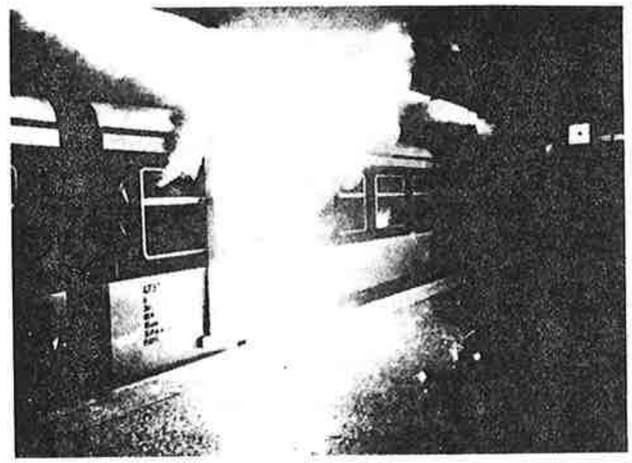


Illustration 7.

4:15 P.M. - Sudden flashover is in progress. Flames are coming out off the second door. Fire duration 7 minutes.

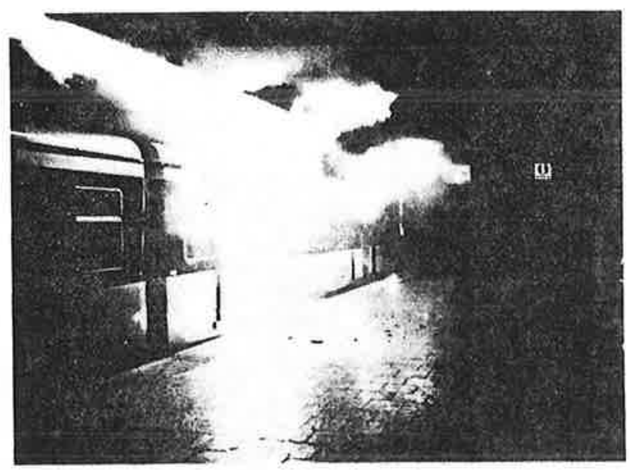


Illustration 8.

4:15 P.M. - First unsuccessful attempt to fight the fire with a hand extinguisher Increasing fire intensity.

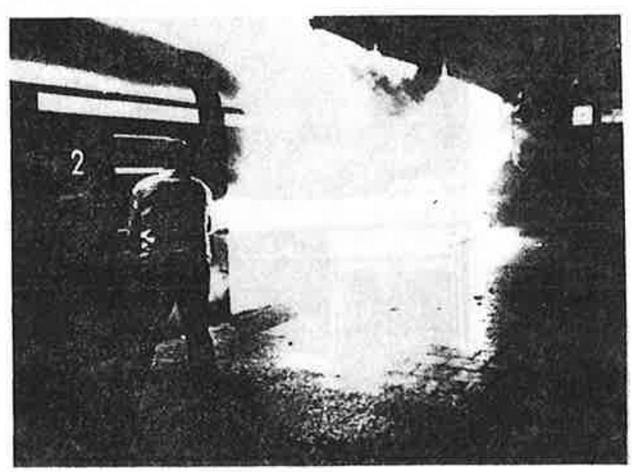


Illustration 9.

4:15 P.M. - Heavy smoke development during working fire. At this time the fire alarm is received by the responding fire station.

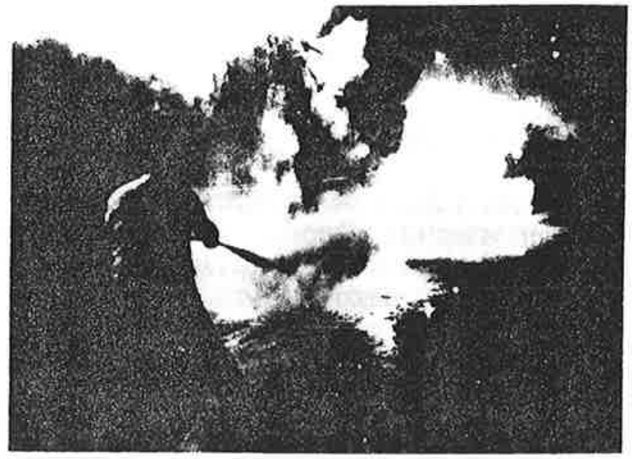


Illustration 10.

4:17 P.M. - Due to the fire development the station clock stopped at 4:17 P.M. The soffit over the edge of the platform and the metal pan type ceiling withstood the fire. The soffit wall deflected the heat coming thru the burned out car roofs the clock glazing remained intact.

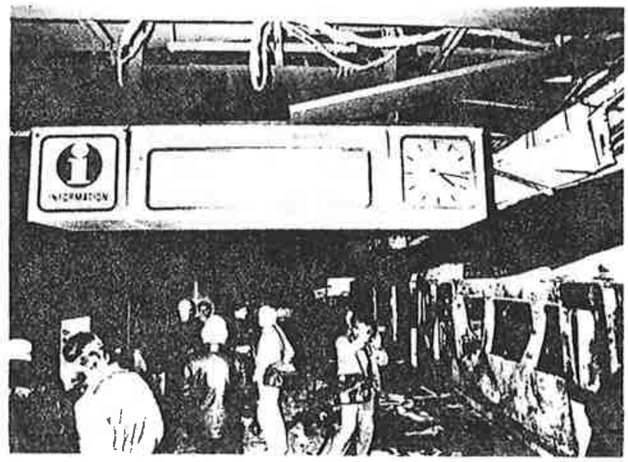


Illustration 11.
Billowing smoke encompasses large areas of the station exterior

2. New York, New York, 16 March 1982, 0708 Hours

This account was published in the New York Times 17 March 1982. No further details were published.

Hundreds Trapped by Fire in PATH Train

By WILLIAM G. BLAIR

Hundreds of Manhattan-bound passengers were trapped for more than an hour in a PATH train that caught fire under the Hudson River yesterday morning before rescuers led them in smoky darkness to safety through an emergency exit at the riverbank edge of Greenwich Village.

Eighty-four persons were treated for smoke inhalation and 19 of them were admitted to hospitals for observation. No serious injuries were reported.

Uptown service of the Port Authority Trans-Hudson line between Hoboken and Jersey City and West 33d Street in Manhattan was knocked out for six and a half hours after fire stopped the train at 7:08 A.M. The downtown service between New Jersey and the World Trade Center was not affected.

Pleas for Staying Calm

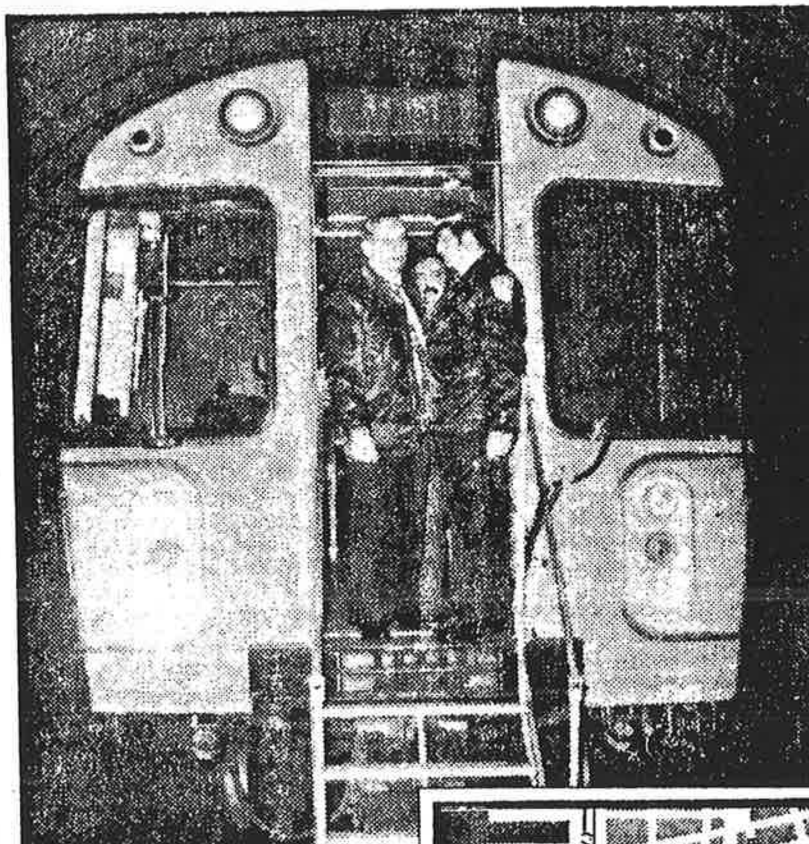
"People were shouting, 'Keep your head down, be calm, be calm,'" said Hercules Segalas of Morristown, N.J., who was in the last car of the seven-car train.

"We were all on the floor," said Louis Simonini of Hoboken, where the train originated at 7:03 A.M.. "I was trying to figure a way to get out. I thought it was the end."

Officer Peter DePazza of the Port Authority of New York and New Jersey, which operates the trains, was one of the first to descend the emergency shaft to the stalled train.

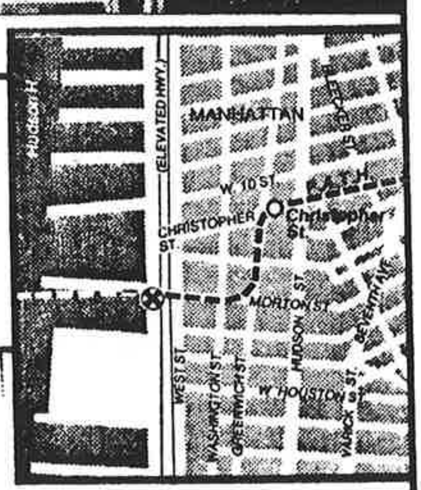
'Nervousness, but No Panic'

"When I arrived, the passengers shouted, 'What's happening?', and, 'How do we get out of here?'" he recalled. He said there was "a lot of nervousness, but no real panic," a statement corroborated by a number of commuters and other rescuers.



The New York Times / John Sotomayor

Police officers aboard PATH train after it was evacuated. Below, a rider who was caught in the fire getting oxygen. Cross on map shows site of mishap.



An electrical fire in the undercarriage of the train's middle car apparently brought it to halt, about 1,000 feet west of the first stop in Manhattan, at Christopher Street. Power was turned off immediately, according to Port Authority officials.

More than 30 pieces of firefighting and rescue equipment rushed to the concrete emergency exit kiosk on West Street, just south of Morton Street, creating heavy traffic congestion in the area.

Some Riders Fainted

Randall R. Hirth, of the Emergency Medical Service, said passengers were "coughing, choking and covered with soot" as they emerged single-file from the exit. "Some of them fainted when they got up to the surface," he said.

The emergency exit kiosk, which sits perhaps 100 feet above the tunnel, is connected to it by a narrow, spiral iron staircase. The firemen could not get down to the tunnel to fight the two-alarm fire until the passengers were all evacuated. The fire was declared under control two hours after it started.

Service was resumed on the affected PATH line at 1:45 P.M., the Port Authority said, after the crippled train was backed through the tunnel to the New Jersey side for repairs. A Port Authority board of inquiry was set up to look into the causes of the incident and how the emergency was handled. PATH officials could not recollect any other incident in recent years in which passengers had to be removed from a train halted in a tunnel by fire.

Leon Katz, a spokesman for the authority, said communications "remained open" at all times during the incident between the train's motorman, James Rybakowski; its conductor, Dennis Curry, and the PATH control center at Journal Square in Jersey City.

Raymond Schwartz of Maplewood, N.J., who is president of the PATH Commuter Organization, said he "unfortunately" was riding the 7:03 from Hoboken in the last car. He and other passengers were critical of what they described as "a lack of direction and communication" from PATH personnel.

"We are asking Governor Kean to set up a special commission to determine what transpired that caused a fire, dense smoke and the endangerment of some 400 commuters," he said, in a statement hours after his rescue.

Mr. Segalas of Morristown said he became apprehensive when, about 7:30, the train's lights went out and "just before the communications died" a voice shouted: "Be calm — walk up to the front of the train — there's an emergency exit about a car-length in front of the train."

With everything dark, he said, "some people tried to move forward and crashed into stanchions and stumbled over other people on the floor." The smoke in the cars was "very dense and acrid," he said. The 25 minutes it took him to get to the emergency exit staircase "seemed like 10 hours," he said.

3. Chicago, Illinois, 25 October 1982, 10 November 1982, 17 November 1982

The photographs of the three separate fire incidents presented below were taken in the vicinity of the CTA 35th Street Station during the months of October and November, 1982. Several other fires of similar nature are alleged to have occurred at other sites on the line within the past nine months. The point of ignition appears to have been in the vicinity of the collector shoes and ancillary equipment. Informal communication from CTA personnel indicated that deterioration of cable insulation was considered to be the principal cause of the fires. Fire attack and suppression in each instance was initially with hand pump water extinguishers. When water application was discontinued, the material would reignite. Complete suppression was not obtained until hose lines were brought to the scene.

Illustration 2 of the November 17, 1982 incident presents an interesting detail. Flames are visible at the upper left corner of the exit door directly above the fire site. Although the flames were definitely present, the car was subsequently reported to have sustained no internal fire damage. As shown in Illustration 3, the fire has burned a hole through the side wall of the car to completely penetrate the electric heater compartment. There is a possibility that burning gases were carried vertically between the inner and outer walls of the car to exit at the door opening mechanism.

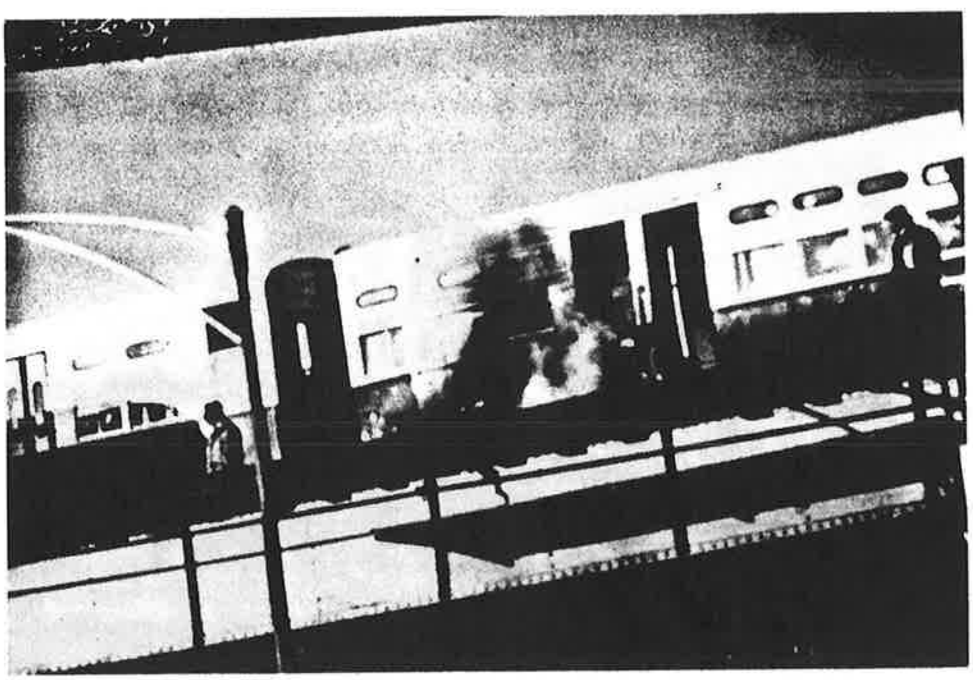


Illustration 1 Fire In Area of Collector Shoe
25 October 1982, Southbound CTA Car #6440 Fire

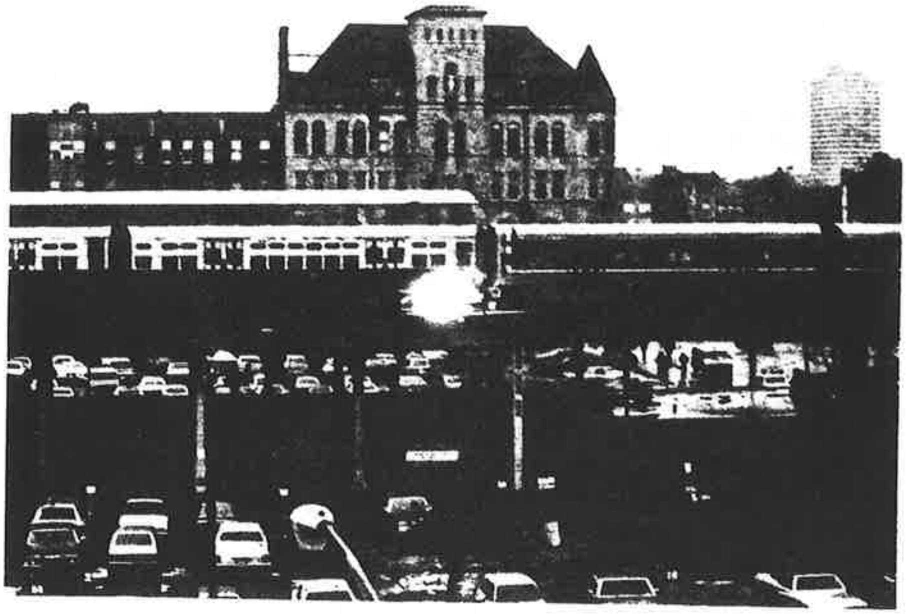


Illustration 1 Arcing Initiates Fire in Vicinity of Collector Shoe
10 November 1982, Southbound CTA Car #6405 Fire

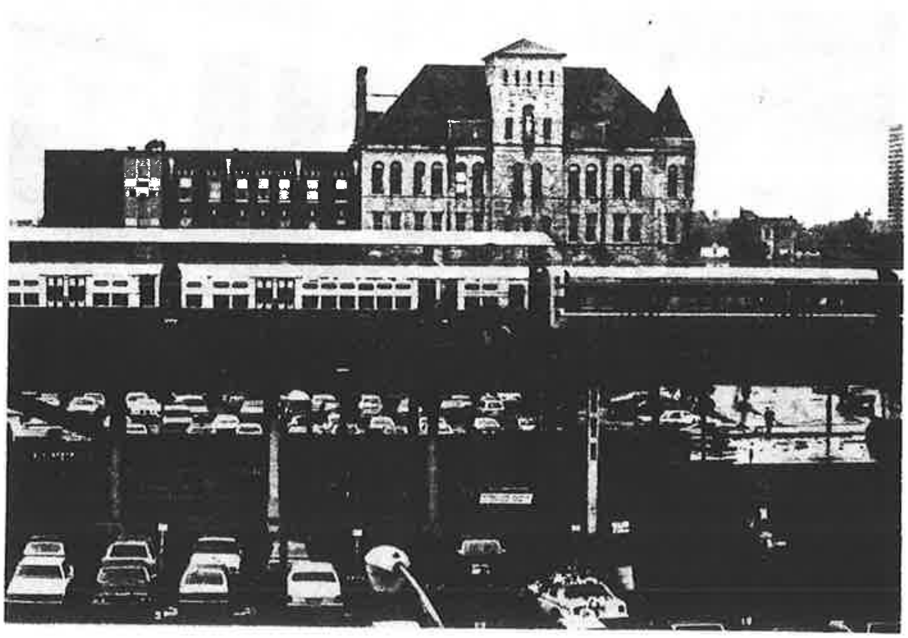


Illustration 2 Fire Department and CTA Personnel Inspect Damage
10 November 1982, Southbound CTA Car #6405 Fire

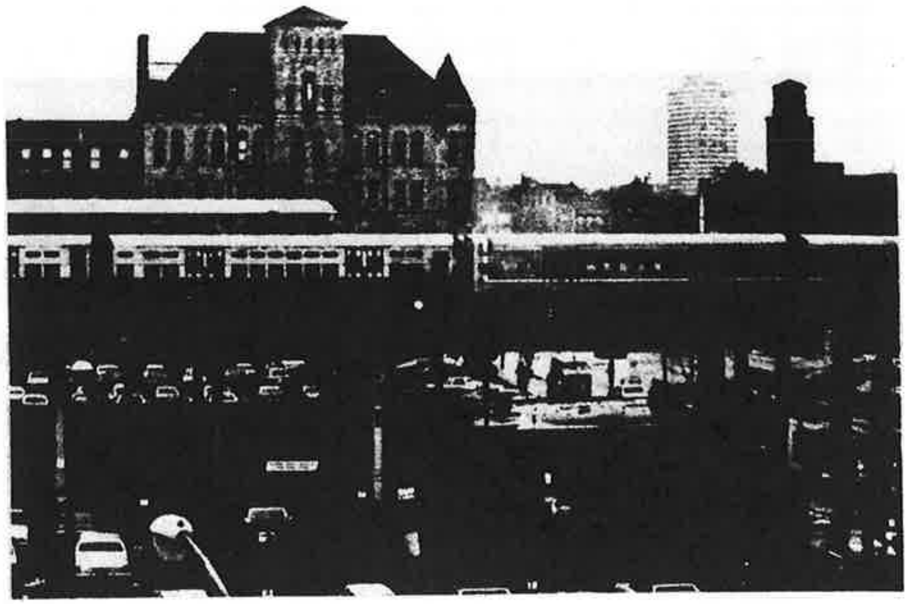


Illustration 3 Car #6405 Reignites as Power Is Applied While Train Is Moved To Siding
10 November 1982, Southbound CTA Car #6405 Fire

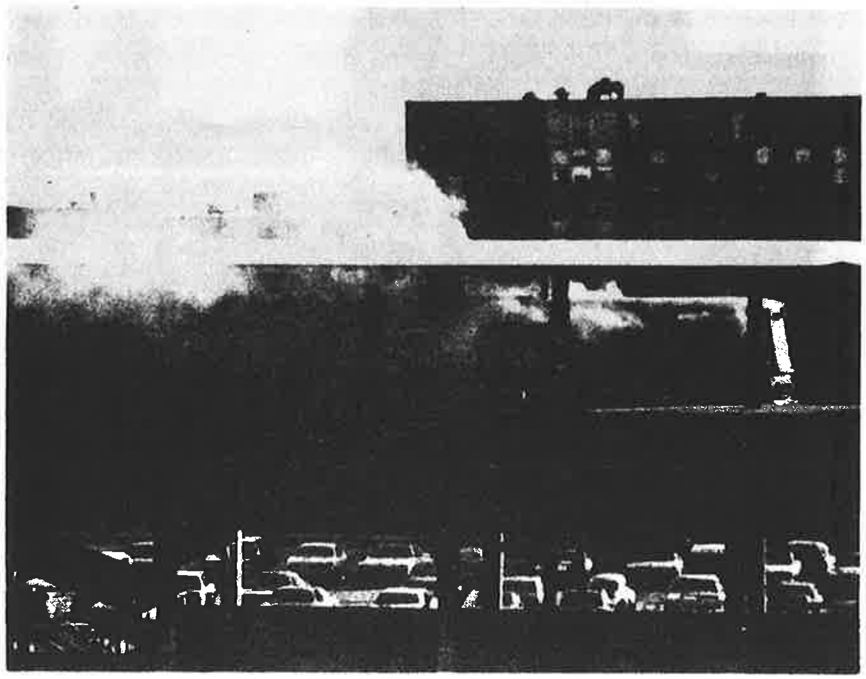


Illustration 1 View of Northbound Car #2099 Taken From West Side
17 November 1982

Illustration 2 Burning Gases Visible at the Top of Side Door
17 November 1982, Northbound CTA Car #2099 Fire

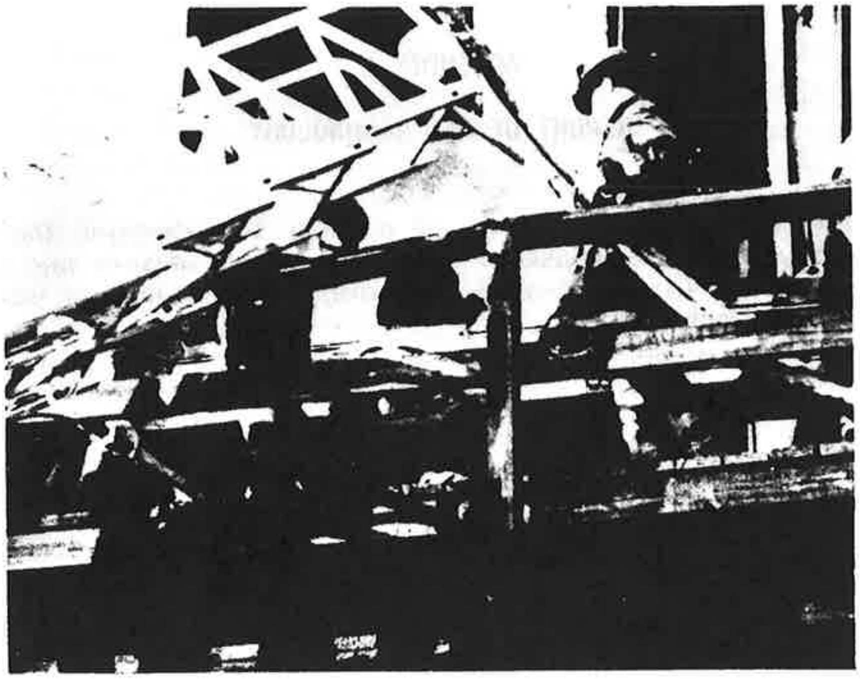


Illustration 3 Hole Burned Through Sidewall To Completely Penetrate
Electric Heater Compartment
17 November 1982, Northbound CTA Car #2099 Fire

APPENDIX D

REPORT OF NEW TECHNOLOGY

This report presents the results of a study to determine the feasibility and cost-effectiveness of the use of heat/smoke/fire sensors and automatic extinguishing systems in rail transit vehicles. No patents or inventions resulted from this work.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1983--602-252--182