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Evaluation and Testing of Rail Transit Undercar Fire Detection and Suppression Systems

Ketron, Inc.
58 Charles Street
Cambridge, MA 02141

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Final Report

UMTA Technical Assistance Program

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16. Abstract

This document presents the results of a comprehensive review and evaluation of transit undercar fire detection and suppression methods. The evaluation of fire detection methods resulted in a recommendation that continuous wire type linear thermal detectors be applied to critical components in the undercar area. Halon 1301 extinguishing systems were identified as the best choice for control of fires occurring in enclosed equipment compartments, e.g., the motor control group.

A laboratory test program using an instrumented motor control group box from a NYCTA transit car was conducted at the Budd Company Technical Center under subcontract to KETRON. The laboratory program included tests on flow and thermal characteristics of the box; power arc-induced electrical cable fires; linear and spot thermal detector performance; Halon 1301 extinguishing system performance; and testing of a novel suppression concept involving the use of a portable nitrogen gas generator to provide an inerting atmosphere in the motor control group box for continuous protection. A field test program of selected methods at a transit property is recommended.

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PREFACE

Prevention of fires on rail transit vehicles constitutes one of the most significant safety issues for the U.S. Department of Transportation and the transit industry. The Urban Mass Transportation Administration (UMTA) through the Transportation Systems Center (TSC) has estimated that approximately 70 percent of rail transit vehicle fires occur in the undercar area. This report presents a comprehensive study of fire detection and suppression methods applicable to the rail undercar environment.

The overall study was completed in three separate steps including: identification and evaluation of fire detection and suppression methods that are feasible and practical for rail transit system operations; testing of several promising detection and suppression methods in a laboratory setting; and development of a proposed field test program for evaluation of the recommended fire detection and suppression system in an operational setting.

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METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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EXECUTIVE SUMMARY

Prevention of fires on rail transit vehicles constitutes one of the most significant safety issues for the U.S. Department of Transportation and the transit industry. The Urban Mass Transportation Administration (UMTA) through the Transportation Systems Center (TSC) has estimated that approximately 70 percent of rail transit vehicle fires occur in the undercar area. The need for a comprehensive study of fire detection and suppression methods applicable to the rail undercar environment was indicated through previous research studies on transit car fire safety.

The overall study was completed in three separate steps:

1) Identification and evaluation of fire detection and suppression methods that are feasible and practical for rail transit system operations.

2) Testing of several promising detection and suppression methods in a laboratory setting using a typical undercar component -- the motor control group enclosure.

3) Development of a proposed field test program for evaluation of the recommended rail transit undercar fire detection and suppression system in an operational setting.

The rail transit undercar environment consists of two basic types of equipment or components; those exposed to ambient air and those contained within enclosures or compartments. The detection and suppression of fires in components exposed to ambient is very difficult due to high speed air flow in the undercar area whenever there is train movement, particularly in a tunnel. Equipment fires originating within an enclosure are simpler to detect and suppress.

A review of the technical literature identified a number of components that have been identified as predominant sources or areas where undercar fires originate including traction motors,

resistor grids, brakes, current collectors, propulsion motor control group, cable and wire insulation and storage batteries. In many instances, the actual cause of fire initiation is the accidental formation of persistent electrical power arcs that ignite any nearby combustible materials such as debris from the trackbed lodged in the undercar area or cable/wire insulation.

Heat-based fire detection devices are most applicable to the undercar environment. Many transit systems already use overheat devices to protect components from damage, therefore, this technology represents an extension of current practice. Smoke detection devices are likely to be affected by the particulate matter found in the ambient air, while flame detectors may be affected by the wide spectrum of radiant energy associated with electrical arcing under normal operating conditions.

The suppression of undercar fires can be accomplished in the following two-step sequence:

1) Removal of electric power from the affected component upon detection of a pre-alarm signal that indicates an unusually high temperature level; and

2) Release of an extinguishing agent directed at the affected component upon detection of an alarm signal that indicates a dangerously high temperature level.

The extinguishing agent most appropriate for application to components exposed to the ambient (tunnel air) environment is Halon 1211 since it is discharged as a liquid and is more effective in an environment where there is air movement. The extinguishing agent recommended for application in enclosed compartments is Halon 1301 because it is more effective than Halon 1211 or carbon dioxide, while dry chemical agents are inappropriate for application to electronic and sensitive electrical equipment.

An unconventional approach to protecting enclosed compartments was identified involving the use of an on-board nitrogen-enriched gas generating system to maintain an inert atmosphere. A commercially available unit designed for aircraft application could provide a continuous supply of dry, nitrogen-enriched gas within a compartment providing a clean positive-pressure environment conducive to extending the life of electrical equipment, while also preventing any combustion due to the low oxygen content of the gas.

The recommended detection and suppression system installation for components exposed to the ambient is an undercar-mounted system involving heat detectors, with the extinguishing agent (Halon 1211) discharge nozzle(s) located no more than 10 feet from the area to be protected. The system should not provide for automatic release of the extinguishing agent upon alarm detection because it might be deployed while the train is moving.

Compartment fires can be handled with a Halon 1301 system coupled to a heat detection system. The Halon 1301 is supplied from a small spherical storage container mounted outside the compartment. An automated release is recommended for the compartment application.

The laboratory test program was based on the use of a motor control group enclosure as the test environment because it had been identified as being involved in numerous serious undercar fires. An electric arc was used as a heat source in order to develop a realistic test environment.

A total of 26 laboratory tests were conducted at the Budd Company Technical Center to test the performance of representative heat detection systems, a Halon 1301 extinguishing system, and the compact nitrogen-enriched gas generating system.

The test results demonstrated that heat detection systems are feasible and that linear thermal detectors (continuous wire-type) are better suited for large compartments, such as the motor control group enclosure, than spot-type detector units.

The Halon 1301 extinguishing system tested provided complete suppression and was far more effective than required to suppress the small fires that could be initiated using the laboratory apparatus.

The nitrogen-enriched gas generator tests demonstrated that it is possible in a reasonably short time (less than 2 hours) to reduce the oxygen content of the air in the motor control group enclosure to a level which will not support combustion (less than 8% oxygen).

The proposed field test program includes pilot testing (2 units) of the recommended linear thermal detection system in the motor control group enclosure application. Successful pilot testing will be followed by 6 months of operational testing with approximately 30 units to obtain sufficient data to predict long-term reliability and estimate the rate of false alarms anticipated for full scale deployment. After successful testing of the detection system, an additional 6 month testing period of a combined detection/suppression system is proposed. The system will cut off electric power to the motor control group upon detection of a pre-alarm signal, and deploy Halon 1301 upon sensing of an alarm signal.

SECTION 1
INTRODUCTION

1.1 BACKGROUND

The Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation (USDOT), through the Transportation Systems Center (TSC), has conducted numerous studies and analyses related to rail transit system safety. A primary focus area in rail transit safety is the problem of vehicle fires. Studies sponsored by UMTA have covered a broad range of topics in rail transit vehicle fire safety including the following:

- Analysis of Transit System Data to Identify Specific Fire Threats;
- Fault Tree Analyses of Transit Vehicle Fires;
- Development of Recommended Fire Safety Practices for Rail Transit Materials Selection;
- Testing of Electrical Wire and Cable Insulation for Flammability and Toxicity; and
- Review of Specific Transit Car Fire Safety Characteristics.

The results of these activities have pointed to the need for a comprehensive study of fire detection and suppression for rail transit vehicles. Particular emphasis was indicated for those fires which originated in the undercar area, based on an UMTA/TSC estimate that approximately 70 percent of rail transit vehicle fires occur in the undercar area.

1.2 SCOPE OF WORK

The scope of work for the project consisted of the following tasks:

1. A review of the pertinent literature, transit system information, and available data on transit car fires to determine the undercar environment and potential fire locations on transit vehicles.

2. Identification of detection systems that are applicable to undercar fires.

3. Identification of fire suppression methods that are applicable to undercar fires.

4. Evaluation of fire detection and suppression methods and systems that are feasible and practical for rail transit system operations.

5. Selection of one or more fire detection and suppression methods and systems for laboratory testing.

6. Development of a test plan for demonstration of the selected concept(s) in a laboratory setting.

7. A laboratory test program conducted in accordance with the plan.

8. Preparation of a plan for field testing of the fire detection and suppression methods which were demonstrated to be feasible in the laboratory test program.

The presentation in this technical report generally follows the outline of the scope of work as presented above. Key results, conclusions, and recommendations are presented in each section of the report, as appropriate.

1.3 CURRENT STATUS OF TRANSIT CAR FIRE SAFETY

The overall technical approach to the project was directed at ensuring that any recommendations for installation of fire detection and suppression systems on transit cars would be both feasible and practical from a transit system's perpective. Therefore, major emphasis was placed on reliability, maintainability, costs, and potential operational impacts of all fire detection and suppression methods evaluated.

During the course of the project, it became apparent that transit systems and the car builders have been increasing their emphasis on fire safety. With the encouragement, guidance, and technical assistance provided by UMTA, new car designs are emphasizing design requirements and materials selection specifically directed at minimizing both the frequency of fire and smoke incidents and the consequences/damages of those incidents that cannot be prevented.

Protective devices incorporated in the design of new cars and retrofitted in older cars are directly related to the fire detection and suppression methods evaluated. Specifically, temperature (thermal) detection devices are being used increasingly to detect overheat conditions in critical components. This is the first stage in the deployment of a complete fire detection and suppression system. The willingness of transit systems to install protective devices indicates that they are likely to accept fire detection and suppression devices as soon as they are demonstrated to be feasible, maintainable and cost-effective.

Fire experience on transit systems also has resulted in retrofit programs to add specific safety features intended to prevent fire initiation and/or limit fire damage. Both new car designs and safety retrofit programs have been considered in this project.

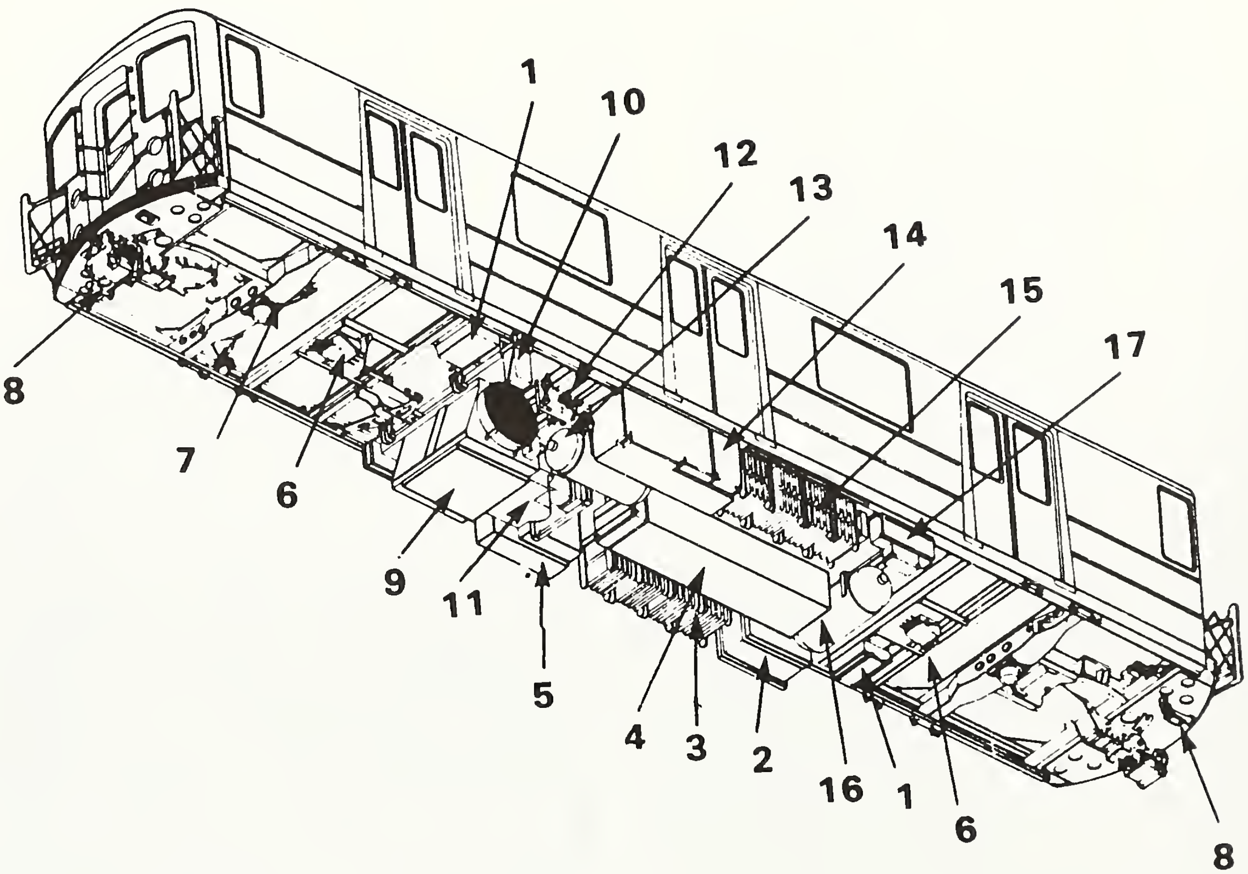
SECTION 2
RAIL TRANSIT UNDERCAR FIRE ENVIRONMENT

2.1 INTRODUCTION

The fire environment under the car has been characterized on a component-by-component basis in order to examine various approaches to fire detection and suppression in rail transit undercars.

For the purposes of this study, fires that originate in enclosed spaces are differentiated from those that occur in an environment exposed to ambient air; this difference is critical since transit cars typically are moving more often than not. Any fire that occurs in a component or area of high-speed air flow will be very difficult to detect and suppress compared to a fire that occurs in an enclosed compartment. Since most components under a transit car are exposed to ambient air, this analysis begins with these components.

Typical fire problems that can be expected with each component are illustrated with specific incidents reported in the literature. Some of the major undercar components of a typical rail transit vehicle are illustrated in Figure 2-1. The underfloor equipment consists of the following: undercar junction boxes (1), battery box (2) resistor grid assembly (3), main control group (4), HVAC motor start/control box (5), traction motor junction box (6), load sensor (7), horn (8), HVAC compressor/condenser unit (9), load weigh group -- controls for passenger load adjustment (10), air compressor unit (11), air brake operating unit (12), main air reservoir (13), converter (14), resistor grid assembly with inductive shunt (15), supply reservoir (16), and knife switch/fuse box (17).



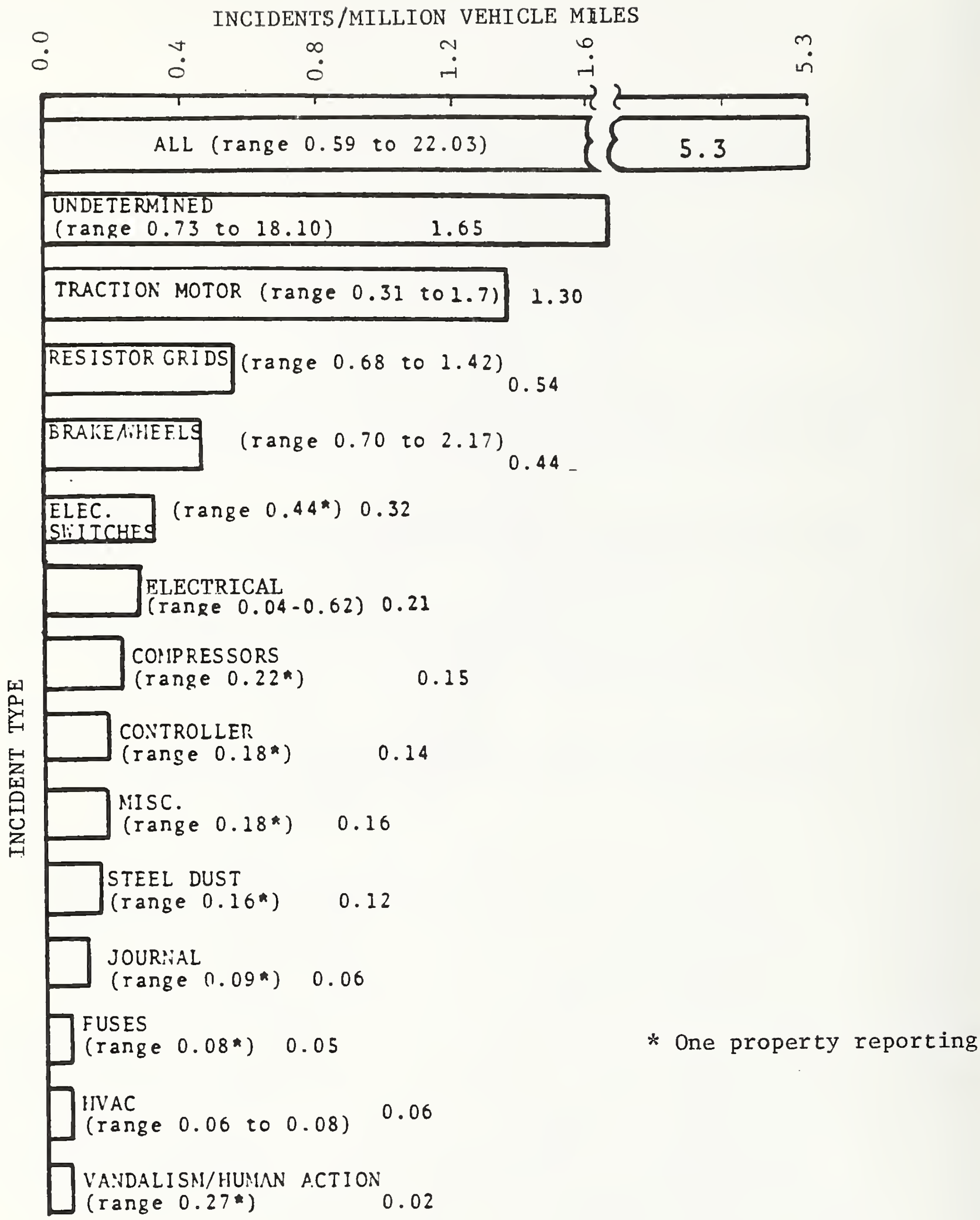
Courtesy: New York City Transit Authority

FIGURE 2-1. UNDERCAR EQUIPMENT INSTALLATION

Several studies refer to specific incidents involving undercar fires. The following reports were particularly relevant to the present study because they included detailed accounts of causes and effects:

- o Hathaway, William T. and A.L. Flores, Identification of the Fire Threat in Urban Transit Vehicles (Reference 1);
- o National Transportation Safety Board, Special Investigation--Eight Subway Train Fires on New York City Transit Authority with Evacuation of Passengers (Reference 2);
- o National Transportation Safety Board, Railroad Accident Report--Bay Area Rapid Transit District Fire on Train No. 117 while in the Transbay Tube, San Francisco, CA, January 17, 1979 (Reference 3);
- o Port Authority Trans-Hudson Corporation, Special Investigation Report: PATH Car No. 725 Fire, March 16, 1982 (Reference 4);
- o Mniszewski, K. et al., Study of Smoke Detection and Fire Extinguishment for Rail Transit Vehicles (Reference 5); and
- o Hathaway, W.T., S.H. Markos, and J.B. Baker, Review of BART "C" Car Fire Safety Characteristics (Reference 6).

The only methodical attempt to characterize the frequency of specific fire incidents was reported in Reference (1). This study included a detailed survey of the accident records of nine transit properties to establish data on the location and causes of specific undercar fires. Figure 2-2 presents a summary of the results based on the most frequently reported incidents. The total number of fire and smoke incidents included in the survey was 1,742, representing the experience of nine transit properties over one year. The frequency of fire and smoke incidents as presented in Figure 2-2 is used in the remainder of this section as the structure for presenting component-by-component data on the fire environment.



Source: Reference 1

FIGURE 2-2. RAIL RAPID TRANSIT FIRE/SMOKE INCIDENT RATE (1978 DATA)

In addition to the analytical data on fire incidents cited above, other reports and references identify potential causes of fire and smoke incidents in other components. Therefore, all the major undercar components were reviewed and evaluated as part of this effort.

In the following section, information about typical causes of fires in undercar components is followed by a discussion of the current state of the art of design features and protective devices used to prevent or limit fire or smoke incidents. The application of fire detection systems to these components is discussed in Section 3, while the application of extinguishing/suppression systems is discussed in Section 4.

The distinction between a protective device and a fire detection device is important. A protective device is intended to prevent damage to a particular component while a fire detection device is the first stage of a system designed to stop fires before they can cause major damage to the transit vehicle or endanger passengers and operating personnel.

2.2 COMPONENTS EXPOSED TO AMBIENT ENVIRONMENT

The components considered in this section have been reviewed and analyzed for causes of fire and smoke incidents, and the extent of any propagation of fire to other parts of a transit car. The data presented represents a synthesis of information from the reports cited in References 1 through 6. In general, the following components usually are exposed to the ambient environment under the transit car:

- o Traction motors;

- Resistor grids;
- Friction brake/handbrake;
- Current collectors;
- Heating, ventilating, and cooling; and
- Alternating-current source.

2.2.1 Traction Motors

Traction motors used on transit cars typically are 600- to 1000-volt-dc motors controlled by field circuits energized from the motor control group. A typical undercar installation contains two motors which are directly geared to the wheel axle through simple, direct-reduction gear boxes. To reduce motor-assembly size and weight, forced-air cooling systems fed from a central blower are used. Otherwise, motors are self-ventilated by a built-in fan.

Causes of fires in traction motors include malfunctions or failures in brush-commutator contact, insulation failures or defects in the windings and commutator, and flashover from brushholders to the frame or around the commutator during severe load and speed conditions. Mechanical failures such as clogged air filters or seized bearings can cause armature windings to overheat, which subsequently breaks down the insulation. The outcome may be an electrical fault, arcing, and fire unless some form of protective device (ground-fault detector) is in place which removes power to the motor.

Traction motor fires also can be caused by a malfunction in the motor-control system that draws excessive current through the motor, leading to overheating and breakdown of the insulation. Another potential cause of fires is a loose or broken electrical power lead to the motor. If the power lead is broken or loose, it can contact a ground point such as the carbody and create an arc which may ignite flammable material near the motor.

Very few instances are reported in the literature of a traction motor fire propagating to other parts of the transit car. One instance, noted in Reference (1), involved the overheating of a traction-motor shaft, which led to ignition of residual lubricant and cable insulation near a transit-car underfloor constructed of wood. This type of situation is unique since few, if any, transit cars in operation today have exposed wooden flooring.

In general, traction motors are constructed to withstand the high temperatures and stresses of transit operations. As a minimum, insulation materials of Class H are used which are suitable for high-temperature applications and are made of a fire-resistant material. The limited amount of combustible materials (such as insulation) used in traction motors when ignited do not support fire for long. The typical traction motor fire is likely to be smoky due to the ignition of accumulated grease-laden dirt and debris and the insulation on the power cables and motor surfaces.

The protective devices that have been applied to traction motors include both overcurrent (fault current) and over-temperature detection. These devices remove power to the motor whenever excessive currents or temperatures are detected.

2.2.2 Resistor Grids

Resistor grids are used to control acceleration and provide dynamic braking. Under normal conditions the resistor grids can become very hot, especially when used in service at rush hours and when ambient temperatures are high. If the resistor grids are not protected, this heat can ignite foreign combustible materials that accumulate in the grids. A local failure of the resistor grid can cause arcing and result in very high temperatures which can ignite any nearby combustible materials. Control failures can cause one car to enter a dynamic braking mode while the remaining cars are in a propulsion mode. This condition will cause severe overheating and possible fires due to the extreme temperatures at the resistor grids on the affected car.

Resistor grids usually are shielded so that they cannot ignite adjacent components or burn through the car floor. Even with these precautions, the damage caused by overheating and igniting resistor grids can be substantial.

A number of transit systems have incorporated overtemperature detection devices to protect the resistor grid. The details of these applications are presented in Section 3.3.

2.2.3 Friction Brake/Handbrake

Friction brake subsystems are designed according to transit system preference:

1. Tread brakes, where a brake shoe is forced against the tread of a wheel with various degrees of pressure to retard the motion of the car. This is accomplished either by use of a brake unit or package and shoe at each wheel, or by levers actuating brake beams to which brake shoes are attached.

2. Disc brakes, where one or two discs are attached to each axle, with shoes or pads contacting the rotating disc to retard the motion of the car.

3. <u>Drum brakes</u>, where a brake drum is attached to the drive shaft of each motor, with shoes contacting the rotating drum to retard the motion of the car.

Friction brakes are actuated pneumatically, hydraulically, or electrically, as specified by the transit system. In friction-brake subsystems, if the brakes are not fully released while the vehicle is in motion, the wheels, discs, or drums will become extremely hot and could ignite combustibles in the area. If the brakes are activated hydraulically, any leakage of hydraulic fluid will provide an additional fuel source.

A handbrake (sometimes called a parking brake) is actuated independently of the main friction brake control. This brake mechanically or hydraulically actuates all or part of the friction brake system when applied, as specified by the operating agency. If the handbrake does not release correctly and the train moves, friction from the applied brake will generate heat and may serve as an ignition source. There are no protective devices applied to the friction brake or handbrake.

2.2.4 Current Collectors

Current collector fires usually can be attributed to three major causes:

- Materials;
- Design; and/or
- Maintenance.

The National Transportation Safety Board (NTSB) cited the introduction of a new current collector design and materials by a new vendor as a cause of numerous fires at the New York City

Transit Authority (NYCTA) (Reference 2). The problems were caused by the design and the materials used. The solution was complicated by the need either to retrofit design changes, or replace the current collector with a model that had been used successfully on earlier car models. Most transit systems specify proven current collector designs as part of their new car specifications. Other current collector fires have been attributed to the accumulation of road grit and dust which creates a creepage path between the current collector and ground, resulting in arcing.

In current practice, the collector assembly is designed to withstand the adverse conditions that sometimes occur, such as an obstacle on the third rail. If striking an obstacle breaks off the current collector, and the current collector cable (energized from other collectors) does not contact the body structure (ground) and create a potentially dangerous arc, then it is likely that damage will be limited to the immediate current collector area.

Fuses typically are used to protect current collectors by opening the circuit if a fault current to ground is detected. Reference (6) noted two conditions that would circumvent the fuse. In one condition, the current collector breaks off and becomes wedged between the power rail and the running rail. This enables the current collector cable to arc against the vehicle structure. In the second condition, a creepage path develops, caused by an accumulation of conductive materials such as steel grit and brake-shoe dust at the mounting bracket. Both of these potential fire hazards are usually mitigated or avoided by securely clamping current collector cables, and by providing a breakaway notch on the current collector paddle to preclude detachment of the entire assembly on impact.

2.2.5 Heating, Ventilating, and Cooling

Current transit car designs use integrated air treatment units for all heating, ventilation, and cooling (HVAC) requirements; these units are mounted under the car. Typical problems with HVAC systems that have led to fire or smoke incidents include overtemperature at the heaters caused by heater defects, and arcing caused by failure of heater elements. Either malfunction can ignite nearby combustible materials such as heater ducts. Other potentially serious HVAC problems include overheated drive motors and compressors.

HVAC protective devices include temperature (overheat) detection and air flow sensing devices. Overheat detectors remove power from the heaters when the temperature reaches a preset level. Similarly, air flow sensors open the heater circuit when air flow falls below a minimum acceptable value. Additional protection is provided by a fusible link which will melt and remove power from the heater circuit if the temperature in the vicinity of the heaters reaches a preset level.

2.2.6 Alternating Current Source

Many components on transit cars are designed to operate with ac power. This power typically is supplied by a motor-alternator set; on some newer cars, such as the BART "C" car, static inverters are used. Motor-alternator sets are subject to the same types of problems that occur with traction motors and HVAC motor compressor units. These include commutator problems resulting in flashovers (arcing) and overheating of motors caused by control or lubrication problems. Available data indicate that motor-alternator sets usually are not involved in fire and smoke incidents; for example, Reference (6) cites only one fire and smoke incident attributable to the motor-alternator used on the BART "A" and "B" cars over the 10-year period from 1975 to 1985.

No information is available regarding specific protective devices that have been applied to motor-alternators. It is expected that circuit protection devices and ground-fault detectors, which remove power to the motor alternator if the current levels become abnormally high, are the only suitable protective devices.

2.3 COMPONENTS IN ENCLOSED COMPARTMENTS

The major components involved in smoke/fire incidents within enclosed compartments include:

- motor control group (controller);
- wires and cables; and
- storage batteries.

The NTSB report on Subway Fires at the NYCTA (2) and the report on the PATH Controller Fire (4) indicate that a very serious potential fire hazard is associated with the motor-control group. Furthermore, data from the NYCTA suggest that serious propulsion control equipment fires occur more frequently than the survey data illustrated in Figure 2-2.

Wires and cables are discussed under a separate heading in this section because the insulation materials used are the major source of combustible materials (fire load) in the undercar environment. Wires and cables are used extensively in the propulsion motor-control group, while connecting wiring and cabling typically is routed through conduit. Therefore, most wire and cable can be considered to be contained within an enclosure.

2.3.1 Propulsion Motor Control Group

The motor control group, which controls traction power for acceleration and braking, has received considerable attention as a result of fire incidents at both NYCTA and PATH. It is usually difficult to determine the exact cause and origin of a motor control group fire because all components are typically shielded from view; by the time a fire is discovered, damage is extensive.

Propulsion motors in the transit industry typically have been controlled by mechanical devices that employ either electric or air-operated motors to drive cams. The existing fleet of transit cars in the United States is predominantly equipped with these cam-controlled propulsion motor systems. With their fleet of more than 6,000 cars, representing approximately 60 percent of all rail transit cars operating in the United States, NYCTA has the most experience with cam-controlled motors. Recent developments in solid-state power electronics has made the chopper control system for propulsion and braking the choice of some of the newer systems in the country such as BART, Baltimore, and Miami. Except for the data reported in Reference (6), little information is available about fire incidents in chopper control systems; however, as noted below, numerous serious fire problems have occurred with both air-operated and electrically driven cam-controller systems.

A contributing factor in motor control group fires is the use of air-operated cams. Under certain fire conditions, the air supply lines will rupture and provide an unrestricted supply of air to intensify and spread the fire. The NYCTA has initiated a program of retrofitting air-velocity fuses that will interrupt the air supply when a line is ruptured. PATH is also installing air-velocity fuses and using stainless-steel hoses to avoid their rupture.

The motor control group normally is protected by circuits that detect ground faults and overloads. These circuits shut down the entire propulsion system before unsafe conditions develop. To prevent service disruptions, the propulsion-system control is normally resettable after shutdown from a non-ground-fault condition. After three resets, the reset feature is locked out and special maintenance is required to return the propulsion system to normal operation.

Propulsion-motor control group undercar fires have been a serious problem. The incidence of fire/smoke events involving the motor control group has been particularly high at the NYCTA. Although many motor control group fires have been investigated, no definitive research has been conducted to identify the specific mechanisms involved in serious fires in the motor control group compartment. Most reports theorize that arcing takes place, which ignites combustible materials and melts any metals near the arc.

The PATH Car Motor Controller Unit Investigation (7) attempted to probe more deeply into the causes of controller fires by instrumenting a motor control group and testing it for 2 months. It was anticipated that some power arcs would be observed which could be linked to the initiation of a fire. The test program yielded no results that would indicate the presence of any power arcs. Another part of the investigation revealed that induced currents up to 90 amperes were produced in the motor controller case for durations of 1 to 2 milliseconds. The investigators postulated that the currents were induced in the box during interruptions of the collector shoe voltage when passing over a gap in the third rail, or by changes in current to the propulsion motor.

Further research of the literature provided additional insight into the involvement of electric arcs in fires. A series of papers by Beland (8, 9), examined the causes of electrical fires involving arcs. He concluded that an arc could be initiated between adjacent conductors when heating was present that could melt some of the insulation and form carbon particles and other vapors that would permit arc initiation. The arcs would draw current that was substantial but not high enough to trip a circuit breaker or open a fuse. An arc of this type burning for several minutes or more could inflict considerable damage because the temperature of the arc would be high. The research by Beland has been used to explain the fact that the orgin of many household fires attributed to electrical causes actually are caused by some other mechanism such as fires from other sources that permit arcing to occur. Beland also demonstrated that short circuits cause little damage, compared to that caused by an arc, because the current drawn is so heavy that protective devices are triggered immediately.

Research on arcs in relation to fires in the motor control group box indicate that a power arc can be established and sustained for several minutes in numerous scenarios. Under special conditions the arc could draw hundreds of amperes with a voltage drop close to the full potential available in the system, which may be as much as 1000 vdc. Under such conditions an arc of 3 to 5 inches could be produced. This scenario is not likely since long arcs are very difficult to establish and maintain. Another set of conditions would cause a series of multiple arcs that ignite and extinguish randomly depending on the movement of ionized gases and combustion products in the area where arcing initiated; these arcs would be much shorter, with arc voltages on the order of 50 to 100 volts. This scenario is considered to be more representative of the conditions that exist in the motor control group when abnormal power arcing is present. Multiple shorter arcs could have the same net effect as one longer arc in terms of power input and the resulting heating effects.

2.3.2 Wires and Cables

The electrical insulation materials surrounding a wire or cable provide a fuel source for propagation of undercar fires. From 1978 to 1982, UMTA sponsored extensive tests on a wide variety of electrical wires and cables (10, 11). The tests included ignition/flame spread, electrical failure, corrosivity of fire products, generation of fuel vapors, generation of heat and toxic gas combustion products, and light obstruction by smoke. Some of the newer insulation materials (and combinations) tested showed significant improvements over conventionally used insulation materials, particularly in ignition/flame spread and light obstruction. Although the results were very detailed, no overall combined hazard index could be recommended without further testing and confirmation.

The test reports on electrical wires and cables referenced above are cited as a source of information pertinent to the selection and specification of electrical insulation for use in the rail transit environment.

Many transit authorities are upgrading the electrical wiring and cabling on undercar sections where existing materials have either proven troublesome or are wearing out. Little overall information is available from the transit industry concerning the replacement cable materials being used; however, in a meeting of the Propulsion Control Group Fires Task Force held in 1983 (12), several transit properties reported that they were changing to crosslinked polyolefin (XLPO) cables. The material shows generally good results in ignition/flame spread, electrical failure, and light obstruction when compared to Hypalon, which was used in numerous rail transit cars manufactured in the last 10 to 15 years.

2.3.3 Storage Batteries

Transit-car storage batteries typically provide the low-voltage source for the following:

- The operating control functions of the propulsion controller;
- General lighting;
- Lighting control;
- Door control and operation;
- Train control communications; and
- Any other electric function requiring low-voltage.

The storage batteries usually are mounted under the car in their own compartment. In fleets of single-unit cars, each car has its own set of batteries. With married-pair or other captive configurations of cars, the battery set usually is delegated to a specific segment of the consist, with low-voltage power fed from the battery-equipped car through the electric couplers or jumpers at the end of the car to the other cars in the captive consist.

Overcharging, heavy load cycling, lack of water in the cells, shorted cells, or incorrectly matched battery charges can be responsible for high electrolytic temperatures and can create conditions conducive to explosion or ignition. A broken battery wire can move around the battery-box area, touch ground, generate an arc, and cause ignition.

Protective devices that have been specified for the battery compartment include an overtemperature device in the battery box and an overvoltage device in the charging circuits. When the overtemperature sensor is activated, the battery is isolated from the charging circuits; when the overvoltage sensor is activated, the charging circuits are disconnected.

SECTION 3

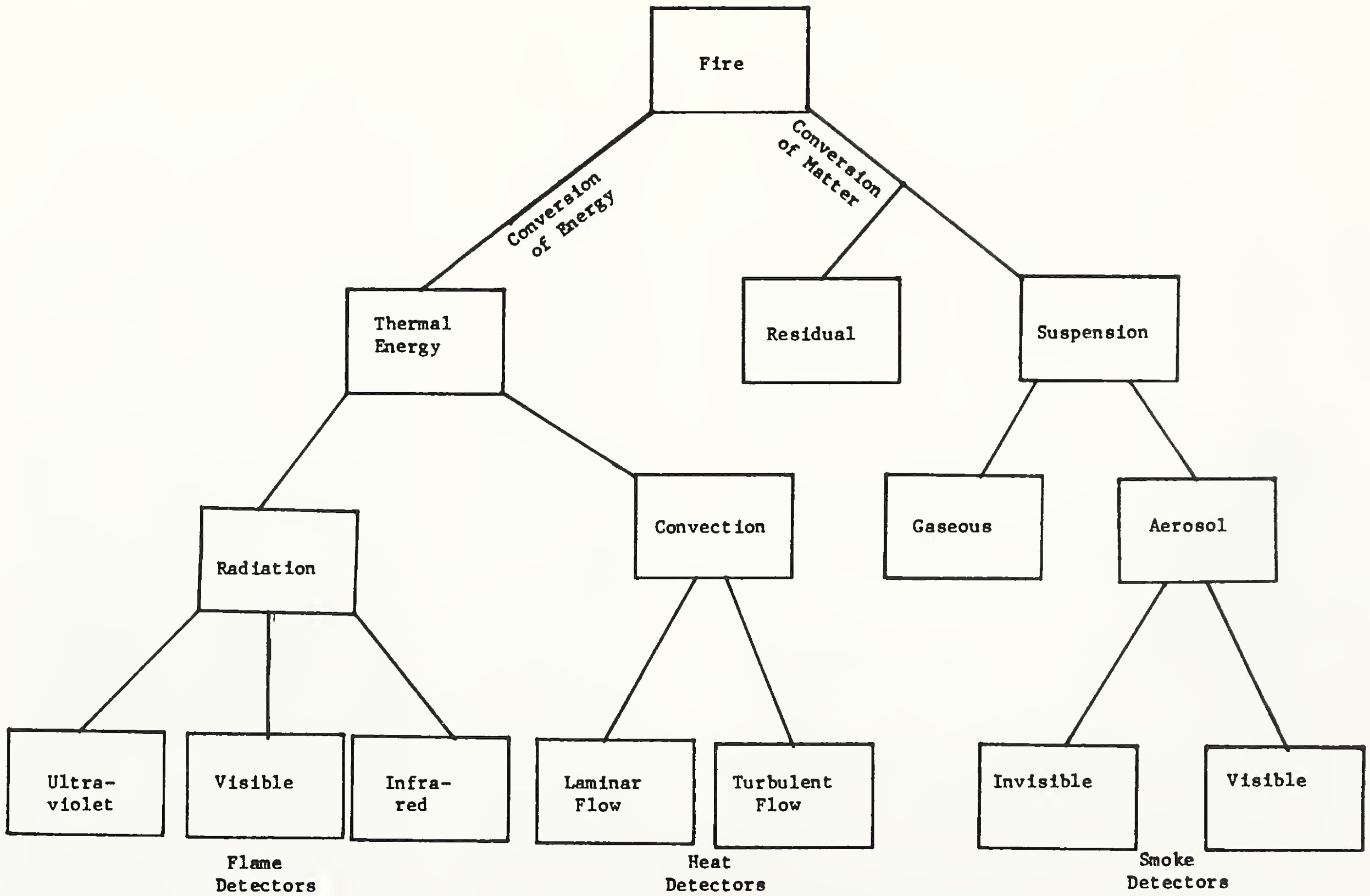
FIRE DETECTION METHODS

3.1 INTRODUCTION

Fire detection methods can be categorized according to the three principal types of energy and matter characteristics of a fire environment: flame, heat, and smoke. This classification scheme has been adopted in the National Fire Protection Association Standard on Automatic Fire Detectors. Products-of-combustion detectors are classified with smoke detectors. Figure 3-1 is a graphic depiction of the fire environment with detector classifications inserted directly below the energy or matter phenomenon to which they are most responsive. Flame detectors are included under ultraviolet, visible, and infrared radiation energy; heat detectors are under laminar and turbulent convection flow of thermal energy; and smoke detectors are under aerosol visible and invisible particles.

Sensitivity, reliability, maintainability, and stability are the critical variables in the selection of a detection system that will give optimum performance. Grabowski (13) has defined these critical variables for detection devices:

> **SENSITIVITY** - The sensitivity of the detection device is generally established by the physical design, except in the case of products of combustion units that must be adjusted. All of the thermal devices have fixed spacing ratings based upon the approval testing and the easiest way to increase sensitivity is by reducing the spacing. This greatly reduces the response time to a fire and assures the application of the agent before extensive damage is done. Reduction in spacing is also recommended for the products of combustion units since reliance on the sensitivity adjustment alone can result in a false alarm problem. Sensitivity of the flame detectors is inherently high so this is not a major factor in equipment selection.
>
> **RELIABILITY** - This factor is not normally considered for fire protection equipment and a requirement cannot be found in any standard, code, specification or approval



Source: Reference 17, p. 327

FIGURE 3-1. FIRE DETECTOR FAMILIES AND THE ENERGY AND MATTER OUTPUT OF A FIRE requirement. It is, however, important that it be considered in automatic systems and worthwhile for discussion in this presentation.

Reliability relates to the ability of the system and each individual component to be in proper working condition at all times ready to perform its intended function. The aerospace industry has developed reliability to a point where it is incorporated in their system equipment specifications and their methods of analysis should be employed in the selection of the detection units. This generally has not been accomplished and it is only possible to present a general comment on the reliability of available detection units.

The units with the highest reliability are the fixed-temperature eutectic units and rate-compensated units. The simplicity of the eutectic device gives it high reliability while the sealed construction of the other provides protection that allows the detector to withstand long service life under difficult conditions. The rate-of-rise units have a slightly lower reliability due to the more delicate nature of the sensing surface and possible failure of the rate function. All of the products of combustion and flame detectors employ electronic components which have a higher failure rate than mechanical devices and result in a much lower reliability.

MAINTAINABILITY - The maintainability of detection units varies directly as the complexity of the design. The thermal units have no periodic maintenance requirements and the degree of maintainability with these units is extremely high. The products-of-combustion and flame detectors require periodic inspection and servicing to assure that that the sensing element is in proper working order. This is not, however, an extensive effort, and therefore, does not detract from these devices.

STABILITY - The stability of a detector relates to its ability to sense fires over extended periods of time with no change of sensitivity. This follows the general patterns of the other factors, where the mechanical devices are better than the more complex electronic ones. In almost all the thermal units, there are no materials whose physical properties degrade with age or usage while this is a known fact with electronic components. Periodic checking of all units with electronic components is necessary in view of this reduced stability.

Table 3-1 provides a performance summary of the sensitivity, reliability, maintainability, and stability evaluations for seven types of detectors, based on the work reported in Reference (13).

TABLE 3-1. DETECTION 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
Particulate Matter	High	Medium	Medium	Medium
Visible Smoke	Medium	Medium	Medium	Medium
Flame-Ultraviolet	High	Medium	Medium	Medium
Flame-Infrared	Medium	Medium	Medium	Low

Source: Reference 11

The actual performance of a specific detector varies with the design, manufacturing procedures, quality and reliability control procedures, and the training and supervision of the persons who install the detection devices and systems. Actual performance testing of detection systems, and especially those detection devices and systems utilized in releasing-device service (where the detection device activates the release of an extinguishing agent), is an important job requirement. This is especially true when an expensive agent is involved, or when a sizable cleanup effort must follow the test application.

3.2 APPLICABILITY OF FIRE DETECTION METHODS TO THE TRANSIT UNDERCAR ENVIRONMENT

This section provides an analysis of the applicability of various types of fire detection methods to the typical fire environments found in transit undercar fire/smoke situations. It is important to distinguish between the detection of fires within enclosed compartments and the detection of fires exposed to ambient air.

Fire detection devices can be applied to rail transit cars in two ways:

1. The detection device provides a visual or audible signal. Operating personnel are instructed to take precautionary actions, examine the affected car(s), and decide whether to use an extinguishing agent.

2. The detection device provides a visual or audible signal when a specified pre-alarm (overheat) temperature is reached and automatically activates a suppression system when a much higher alarm temperature is indicated.

With either application, the effect of a detection device false alarm or failure that results in a pre-alarm signal is serious since, at a minimum, operations will be disrupted while system personnel search for the cause of the alarm. Detection devices thus must be extremely reliable.

3.2.1 Smoke Detectors

Smoke detectors are designed to detect the products of combustion ranging from small, invisible aerosol particles to larger ones that can be seen under normal lighting. Photoelectric and ionization-chamber smoke detectors are considered to have medium reliability (13).

A major concern in the application of smoke detectors is the presence of considerable amounts of particulate matter in the ambient air found in tunnels--the typical operating environment for a transit car. This includes dust, smoke, steel dust, and associated debris. Smoke detectors mounted in an exposed area under the car are subject to airstream effects from particulate-laden tunnel air, rendering them ineffective for determining the presence of smoke particulates from undercar sources.

Smoke detectors mounted inside equipment enclosures are not directly affected by tunnel air; however, provision usually is made for ventilation or penetrations (for cable and ducting, for example) of the enclosure wall, which permits some infiltration of tunnel air. In addition, if the enclosure contains high-voltage switches or contactors, the arcing that results from switch/contactor opening will create particulate matter.

The medium reliability of smoke detectors and the existence of particulate matter in the undercar-area ambient air combine to make smoke detectors a poor choice for detecting fires anywhere in the undercar area.

3.2.2 Flame Detectors

Flame detectors are designed to detect radiant energy from flames or glowing embers. The radiant energy can be detected as ultraviolet, visible light, or infrared radiation. Flame detectors are considered to be medium reliability devices (13), for conventional applications. In the undercar environment, they will be adversely affected by particulate matter which may obscure or alter the radiation patterns being sensed. The flame detector must be pointed at a fire source to be effective. The field of view usually must be traded for sensitivity; larger angles of view will increase the possibility that the device will sense extraneous radiation sources and give a false alarm. Flame detectors are most effective when a narrow field of view is used in conjunction with a mechanism to move the detector so that it can scan the entire area; however, addition of a scanning mechanism increases the cost and complexity of the detector.

The undercar environment contains several radiation sources which may interfere with the operation of a flame detector. Under normal operating conditions, electric arcs are created whenever electrical contact is broken; these electric arcs contain a wide spectrum of radiant energy which may activate a flame detector. For undercar application, a flame detector therefore must be insensitive to this short-duration high-power arcing, which normally occurs at the current collector, traction motor, line switch, or cam contactors. The timing logic required to achieve this insensitivity will increase the device's cost and complexity. These factors tend to make flame detectors a poor choice for use in the undercar environment.

3.2.3 Heat Detectors

The application of heat-based fire detection devices is an extension of current use of protective devices placed on transit cars to detect overheating of components such as the resistor grid, battery box, and HVAC system, as discussed in Section 2. Although an overheat detector is not a fire detector in the context of this study, the application of a temperature-sensing device in the undercar environment is an important precedent; unfortunately there are no statistical data available regarding the reliability of these devices.

Heat detectors are the most generally utilized form of fire detector for both stationary and mobile applications. All detectors in this class sense temperature through a variety of physical means including:

1. Displacement or changes caused by differential thermal expansion (e.g., bi-metallic strip);

2. Changes in the electrical resistance of a material caused by temperature change;

3. Changes in pressure caused by expansion or contraction of a liquid or gas caused by on temperature change; and

4. Changes in phase (e.g., melting caused by temperature changes.

Heat detectors may be set to respond to a particular temperature (fixed-temperature detector), to a rate of change in temperature (rate-of-temperature-rise detector), or to a combination of both (rate-compensated detector).

Heat detectors must be placed and spaced to ensure that a fire is detected quickly. A line-type heat detector, typically in the form of a narrow-diameter flexible wire that can be placed throughout all areas of high fire risk, meets this requirement. Line-type heat detectors can be categorized as follows:

1. Twisted wire. A pair of wires in a normally open circuit. Conductors are insulated from one another by a thermoplastic membrane which will melt at a specified temperature; the melted membrane energizes an electrical contact, which activates an alarm.

2. <u>Localized discrete temperature sensing</u>. Linear detectors in this category typically have a solid-center conductor surrounded by a porous aluminum oxide ceramic insulator, all of which is enclosed in stainless-steel tubing. The voids between tubing and the center core are filled with a eutectic salt mixture. The electrical resistance properties of eutectic salt drop sharply as the temperature reaches a specific point. A control unit impresses a small continuous ac voltage between the center and outer shell conductors, so that a current flows between the conductors when the rising temperature causes the impedance to drop sharply. The control unit senses the current flow and produces an output signal to activate alarms.

3. <u>Temperature-averaging devices</u>. These devices are smiliar to discrete-temperature sensing devices except that a thermistor material is placed between the two conductors. This material provides for a continuous decrease in electrical resistance as the temperature increases. A control unit provides a continuous small dc voltage; the voltage sensed by the control unit is a measure of the average resistance along the entire length of the detector. An alarm signal is generated when a small section of the detector is heated to a higher temperature (local hot spot) or when the entire length of the detector reaches a lower temperature.

A major consideration in the application of heat detectors in the rail undercar environment is the selection of a spot-type detector <u>vs</u>. a linear-wire-type detector. Most, if not all, temperature sensors currently used under rail cars to detect overheating are of the spot type. Spot-type devices are simple in design and are highly reliable. Many spot detectors incorporate rate compensation so that a rapid sustained increase in temperature will activate the detector more rapidly than would result when the detector reaches its set temperature more slowly.

Spot detectors appear to be ideally suited for those applications where the location of the fire threat can be specified precisely. For example, one transit system determined the key areas near the resistor grids where they wanted to place detection units from a combination of past fire experience and a temperature measurement program on instrumented vehicles in service. If no clear pattern of fire incidents in the undercar environment is identified, it is very difficult to select the appropriate locations. In lieu of placing a large number of spot detectors to cover a large protected area, a linear detector can be placed in a pattern that covers all critical areas.

Another major consideration is the use of restorable vs. non-restorable devices. A "restorable" detector will return to a normal state once the temperature returns to a value below the detector set point. In general, non-restorable devices such as the twisted-wire-type linear thermal detector are not applicable to the undercar environment because the detector must be replaced each time the device is activated.

3.2.4 Conclusion

The most effective fire detection devices for transit undercar application are based on thermal detection or temperature measurement. For components exposed to ambient air, the thermal detection device must be placed close to the expected sources of heating and/or flame. An air-flow barrier should be placed near the detection device so that the device is not cooled as the transit car moves.

Section 5 presents a more comprehensive discussion of the application of heat detection systems as part of an overall strategy for undercar fire detection and suppression.

3.3 RELATED FIRE DETECTION PROJECTS

This subsection presents a brief description of several related fire detection projects which have been initiated by different transit systems in response to undercar fires. These projects illustrate that a number of transit systems are actively participating in the development of undercar fire detection programs.

3.3.1 Thermal Detection

Due to extensive damage and downtime costs associated with resistor grid fires, the Washington Metropolitan Area Transportation Authority (WMATA) has installed temperature sensors above the resistor grids. When the temperature sensor reaches a preset level, it activates a circuit that deactivates the propulsion control on the affected car. The car then is in a "free-wheeling" state, propelled by other cars in the train. WMATA personnel have indicated that the temperature sensors have performed satisfactorily, but there are no statistical data available regarding reliability or effectiveness.

The new Bay Area Rapid Transit (BART) "C" cars also include overtemperature sensors that remove power from the resistor grids. As part of the vehicle fire-hardening program for their current cars, BART also changed some control system logic circuits in the dynamic braking circuits and installed a sheet metal/ceramic fiber heat shield between the brake and grid and the car floor. The Massachusetts Bay Transportation Authority incorporated resistor grid overheat protection devices in vehicles placed in service in 1981; the New York City Transit Authority requires similar devices in vehicles currently being placed into service (Reference 6). There are no statistical data available regarding the reliability or effectiveness of these devices.

3.3.2 Electrical Detection

The possibility of detecting incipient fires using electrical means has been considered in research efforts associated with the PATH Motor Controller Unit Investigation (7). In that investigation, it was recommended that the motor control enclosure (case) be connected to the car body through a single lead carrying a current detector. Except for the lead, the motor control case must be insulated from the car body. The current detector responds to any power arcing to the controller case by opening a fast-operating line breaker located outside of the motor control box. This form of detection, currently being considered by PATH, senses the presence of a power arc to the motor control case and extinguishes it immediately.

Determining the level of current/time-duration characteristics permitted before the fast-acting line-breaker switch opens is one of the most important design elements associated with this approach. If the current detector is activated in response to currents that are abnormal but not dangerous, this approach could cause frequent power cutoffs to the motor control box that are unnecessary for fire protection. The same precaution applies to the use of thermal detection to remove power. Either approach must be evaluated carefully to ensure that the pre-alarm temperature or current is not set too low, which would cause frequent shutoff of power.

3.3.3 Infrared Detection

An unusual application of a detection system, which was tested on NYCTA transit cars, used an infrared detector combined with a video camera and monitor to obtain a heat image or thermogram of the motor control switchbox (14). The test installation consisted of a viewing platform which attaches without modification to the motor control group box. The infrared imaging-system camera is mounted on the viewing platform and can be moved in front of any component by a linear, bidirectional drive motor. This type of installation is more a diagnostic tool that can be used to identify "hot spots" within the motor control group box while the car is in service than it is a fire detection system.

The test program was conducted over a ten day period and, showed that the normal operating temperatures of components within the motor-control box averaged about 11 degrees F. higher than the surrounding ambient air within the box. In tests where overheating problems were identified, the ambient temperatures within the box varied between approximately 70 and 210 degrees F. Temperatures above 160 degrees F. often led to a failure in the motor control box. Typical causes for overheating of components such as switches, clamps, and cables were defective components, loose or poor electrical connections, and inappropriate conductor materials. Since none of the motor control boxes tested failed during the test, predicting the eventual outcome and the time to failure based on the observed temperature patterns is very difficult.

SECTION 4
FIRE SUPPRESSION SYSTEMS

4.1 INTRODUCTION

The suppression of undercar fires can be accomplished in the following two-step sequence:

1) Removal of electric power from the affected component upon detection of a pre-alarm signal that indicates an unusually high temperature level; and

2) Release of an extinguishing agent directed at the affected component upon detection of an alarm signal that indicates a dangerously high temperature level.

The development of circuitry to remove high voltage power from a component without adversely affecting the operation of the car or train (control and communications) is a car engineering problem. The solution is dependent upon the specific design of the power and propulsion system for each individual car type.

This section of the report discusses the various extinguishing agents which are commercially available and applicable to the classes of fires experienced on rail transit cars. From the review conducted in this project, it is clear that there are commercially available agents which are highly effective for the transit car application. The use of newer extinguishing agents which have not been put through the rigorous process leading to the development of a standard approved by the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA) have not been considered in this study. This does not preclude the future consideration of newer extinguishing agents after they have been codified in the form of a standard. The extinguishing agents considered include carbon dioxide, nitrogen, dry chemical agents and various halogenated agents

(Halon 1301, Halon 1211, etc.). The feasibility of using these agents on different types of undercar component fires (i.e., those exposed to ambient air and those within enclosed compartments) is discussed at the end of the section.

4.2 APPLICABILITY OF EXTINGUISHING AGENTS TO UNDERCAR FIRES

This portion of the report draws extensively from the publications of the NFPA (References 15 through 19), and from Fire Suppression and Detection Systems, Second Edition, 1982 (Reference 20). The basic types of fires are classes A through D as defined by the NFPA. Table 4-1 presents a description of each class and the extinguishing agents which are typically used.

All classes of fires except Class D are applicable to the rail transit car environment. Extinguishing agents are classified for use on certain type of fires based on the classification and fire-extinguishment potentials as determined by fire tests. For example, the fire test for Class B involves the extinguishment of a fire which has been initiated in a square pan containing two inches (depth)of n-heptane. An extinguishing agent is selected for a given situation according to the character of the fires anticipated, the construction and occupancy of the individual property, vehicle or hazard to be protected, ambient temperature conditions, and other factors.

Proper transit system safety planning requires that all electrical equipment be de-energized in response to a transit car fire emergency. Since it may be necessary to move the train for evacuation, the electrical equipment may not be de-energized immediately, and the extinguishing agent could possibly be deployed on energized electrical equipment. For this reason the safest approach is to select an extinguishing agent which has proven effective on Class C fires. These agents include carbon dioxide, dry chemicals, Halon 1301 and Halon 1211.

TABLE 4-1. CLASSES OF FIRES AND APPLICABLE EXTINGUISHING AGENTS

FIRE TYPE	DESCRIPTION	EXTINGUISHING AGENTS
CLASS A	Fires in ordinary combustible materials such as wood, cloth, paper, rubber, and plastics.	Water, antifreeze, soda-acid, foam, multipurpose dry chemical, and Halon 1211
CLASS B	Fires in flammable liquids, oils, greases, tars, paints, and	Halon 1301, Halon 1211, carbon dioxide, dry chemical types, and foam
CLASS C	Fires involving energized electrical equipment where electrical non-conductivity is important	Halon 1301, Halon 1211, carbon dioxide, and dry chemical types
CLASS D	Fires in combustible metals such as magnesium, titanium sodium and potassium	Dry chemical types and carbon/graphite powder

4.2.1 Carbon Dioxide

Carbon dioxide extinguishes a fire by displacing the normal atmosphere, thus reducing the oxygen content to less than the 15 percent required for diffusion flame production. Carbon dioxide is a colorless, odorless, inert, and electrically nonconductive agent which is approximately 50 percent heavier than air. Carbon dioxide from either low-pressure (refrigerated) or high-pressure systems is stored and transported through a piping system or a hose to the nozzle(s) as a liquid. With the release of the pressure at the nozzle, the liquid carbon dioxide converts to a gas, with some minute solid particles. The finely divided particles of solid carbon dioxide that were discharged usually evaporate rapidly. A fog-like vapor condition often persists, however, caused by evaporation of the residue of the carbon dioxide "snow" and the solidified moisture of the atmosphere.

Because carbon dioxide is discharged in a gaseous form by internal storage pressure, and the vapors are heavier than air, carbon dioxide extinguishing systems usually are recommended for interior locations or equipment compartments.

Personnel and passenger protection are important when operating carbon dioxide extinguishing systems. In the undercar environment, a carbon dioxide system could be used to flood a compartment to a concentration between 30 and 60 percent, which is sufficient to suppress combustion. Although the carbon dioxide eventually would leak into the ambient air around the car, the resulting atmosphere probably would never contain as much as 3 or 4 percent (worst case) carbon dioxide because of the volume of the air in the tunnel and the mixing associated with air flow caused by train movement. This level would cause more rapid breathing in humans, but no other important effects result for relatively short exposures. A concentration of about 9 percent is the maximum most humans can withstand without losing consciousness within a few minutes (Reference 16, p.12-53).

Carbon dioxide for local application would also have to be restricted to such volumes which ensure that dangerous levels are not reached in any portion of the train or tunnel surroundings. Carbon dioxide is relatively inexpensive, nontoxic, noncontaminating, non-corrosive, leaves no residue, and causes no moisture or water damage.

4.2.2 Nitrogen

Nitrogen is not usually considered to be an extinguishing agent because it cannot be stored as a liquid unless it is cooled to about -325 degrees F, which is impractical for transit car application. However, a portable nitrogen-enriched gas generator could be used on board the transit car (this concept is discussed in detail in Section 4.3). The portable nitrogen-enriched gas generator would make it possible to fill an enclosed equipment compartment, such as the propulsion motor control enclosure, with nitrogen-enriched air.

The extinguishing effect of nitrogen is similar to that of carbon dioxide. Nitrogen-enriched air displaces the normal atmosphere within the compartment, reducing the oxygen content below the 15 percent required to produce a diffusion flame, thereby creating an inert environment.

4.2.3 Dry Chemical Extinguishing Agents

Dry chemical agents used to extinguish fires include sodium bicarbonate, foam-compatible potassium bicarbonate, monoammonium phosphate, potassium chloride, and urea-based potassium bicarbonate (Monnex). Dry chemical extinguishing systems are installed outdoors more often than carbon-dioxide systems, and they are installed more often as local application systems.

Of the applicable dry chemical agents, urea-based potassium bicarbonate (Monnex) is approximately twice as effective as conventional potassium bicarbonate (purple K) and potassium chloride according to Reference (21). Other studies (22) indicated that monoammonium phosphate (all-purpose or ABC) also is more effective than sodium bicarbonate. Therefore, either Monnex or all purpose (ABC) dry chemicals may be suitable for undercar application.

Residual deposits and corrosion are two characteristics of dry chemical agents which may cause problems if they are used to extinguish undercar fires. These factors have been cited in Reference 19 (NFPA 17 - Standard for Dry Chemical Extinguishing Systems) as follows:

1. Chapter 2-2.2.1 recommends that "before dry chemical extinguishing agent is considered for use to protect electronic equipment or delicate electrical relays, the effect of residual deposits of dry chemical on the performance of this equipment shall be evaluated."

2. Appendix A, Section A-2.2.3 also notes that different dry chemical agents in the presence of moisture can corrode metals such as steel, cast iron, aluminum, aluminum brass, aluminum bronze, and titanium. Prompt and thorough clean up of the agent is recommended to avoid corrosion problems.

Dry chemical agents should be considered for use only on those parts of the undercar that contain no electronic or sensitive electrical equipment, and where discharged chemicals can be cleaned up promptly and thoroughly after discharge.

4.2.4 Halogenated Extinguishing Agents

The halogenated extinguishing agents that have been considered for the rail transit application (Halon 1211, bromochlordifluoromethane; and Halon 1301; bromotrifluoromethane) are either vaporizing liquids or liquefied gases, capable of extinguishing and suppressing fires in various materials when applied at proper rates and in proper concentrations. Since the most commonly applied halogenated agent in the United States is Halon 1301, the following discussion of characteristics and extinguishing effects emphasizes this agent.

Halon 1301 is normally stored and applied as a liquefied gas which rapidly vaporizes when released from the storage container or piping system. When stored under pressure, Halon 1301 has a density of approximately 1571 kg per cubic meter (98 pounds per cubic foot), which is about twice the density of liquefied carbon dioxide. Like carbon dioxide, Halon 1301 is heavier than air, having approximately five times the vapor density of air. The vapor pressure of Halon 1301 at 21°C (70°F) is approximately 200 psi, and the atmospheric boiling point is -58°C (-72°F).

Geyer (23) indicates that the boiling point of a halogenated agent determines the effective discharge range, since the boiling point determines whether the agent is discharged as a liquid or flashes to a gas when discharged. For this reason, Halon 1301 is applicable for total flooding or local application in a confined area. Halon 1211 (boiling point of -4 degrees C) typically is applied to outdoor fires since it is discharged as a liquid and is effective at a longer range. Halon 1211 has an effective discharge range of 4.6 to 5.5 meters (15 to 18 feet). The discharge range for Halon 1211 is more than adequate for undercar fire suppression on a local application basis.

A Halon 1301 concentration of 5 to 10 percent is required to extinguish surface flames on Class A materials. Typically, a 5 percent concentration of Halon 1301 will extinguish most fires within 10 minutes, unless it is a deep-seated fire. Deep-seated fires are defined as those where there is surface combustion resulting in a glow but where there is no flame (e.g., coals). Deep-seated fires usually require higher Halon 1301 concentrations, depending on the nature, density, and configuration of the fuel, the size of the compartment, the leakage rate from the compartment, and the length of time the fire has been burning. Some deep-seated fires may require concentrations of 20 to 40 percent with soaking times of 5 to 30 minutes or longer. Ford (24) reports that Halon 1301 concentrations of between 4 and 6 percent will control deep-seated fires in solid materials, which would be similar to surface flame extinguishment.

Halon 1301 achieves an extinguishing effect by decomposing to produce bromine radicals. This decomposition has created concern about personnel hazards when Halon 1301 is used in extinguishing systems.

In its manufactured state, Halon 1301 poses little health hazard to persons exposed to concentrations of less than 10 percent for less than 10 minutes. The committee that developed the National Fire Protection standard for Halogenated Fire Extinguishing Systems, Halon 1301, allowed the use of Halon 1301 in a total flooding system in normally occupied areas without restriction for concentrations up to 7 percent. Halon 1211 is considered to be slightly more hazardous than Halon 1301 because tests on humans have shown that Halon 1211 concentrations above 4 percent produce effects such as dizziness, impaired coordination and reduced mental activity with exposure of a few minutes duration (Reference 18).

Any application of Halon 1301 in the undercar environment should be restricted to enclosed equipment compartments. Use of Halon 1301 on a component exposed to the ambient is considered to be impractical because the gaseous vapor would rapidly dissipate in the surrounding tunnel air.

The amount of Halon 1301 required to suppress a fire in an enclosed compartment under the car is very small (less than 2 lbs.); therefore, the small amount of Halon 1301 and decomposition byproducts that could leak from an enclosed compartment is minute compared to the tunnel air volume. Considering the air volume and the natural air circulation in a subway tunnel, any leakage of Halon 1301 after discharge into an enclosed compartment would be diluted to a level where any byproduct effects would be insignificant.

4.3 EVALUATION OF UNDERCAR FIRE EXTINGUISHING AGENTS

For fires in components which are exposed to the ambient, agents discharged as a gas (carbon dioxide, nitrogen and Halon 1301) are impractical for two reasons:

1. If the train is moving, creating an air flow, the gaseous agent will be swept away from the target fire area.

2. Even in the absence of any air movement the gaseous agents, being considerably heavier than air, would drift down and away the fire area.

When directed at the target area Halon 1211, would remain in a liquid state until heated to the boiling point and thereby persist longer. The effects of the Halon 1211 decomposition byproducts on the safety of operating personnel exposed to tunnel air must be carefully considered since it is not an open air environment. The diluting effect of tunnel air on the Halon 1211 is expected to be very significant in this evaluation.

Use of dry chemical agents should be limited to the conditions cited in Section 4.2.3 regarding avoidance of electronic and sensitive electrical equipment, and ensuring rapid and complete cleanup of agent deposits. These conditions are very difficult to ensure, particularly if the dry chemical agent is subjected to tunnel air flow as it is being discharged. In addition, the cleanup of a rapid transit undercar after a discharge of chemical agent could not be accomplished until the train is removed from service and the car brought to an appropriately equipped maintenance facility.

After consideration of the above, it is concluded that the extinguishing agent most appropriate for application to components exposed to the ambient (tunnel-air) environment is Halon 1211. The amount of agent discharged should be limited to insure the safety of operating personnel working in the tunnel near the affected car.

The choice of an extinguishing agent for equipment compartment application is much simpler. Halon 1301 is much more effective than carbon dioxide and nitrogen (based on weight and volume of the storage system required), while dry chemical agents are inappropriate for application to electronic and sensitive electrical equipment in the compartments. Therefore, Halon 1301 is the preferred agent.

An unconventional approach to protecting enclosed compartments involves the use of an on-board nitrogen-enriched gas generating system to provide a continuous stream of nitrogen-enriched air to selected compartments. This concept is discussed in more detail in the following paragraphs.

As part of the basic research on methods for suppressing fires within enclosed compartments it was noted that some military aircraft make use of an On-Board Inert Gas Generating System (OBIGGS) unit manufactured by Clifton Precision. The unit can be used to supply either oxygen-enriched gas for aircraft personnel or nitrogen-enriched gas for inerting of fuel tanks to suppress fires in the event of penetration of incendiary materials. It was determined that use of an OBIGGS unit on board a transit car could provide an innovative alternative approach to the use of Halon 1301 in controlling electrical fires in the motor control group. Instead of flooding the compartment with a single charge of Halon 1301, the compact gas generating unit supplies a continuous stream of clean, dry, nitrogen-enriched gas, creating and maintaining an inert atmosphere in the motor control compartment. The continuous supply of nitrogen-enriched gas would cause a positive pressure within the compartment thereby preventing the entry and accumulation of steel dust and corrosion products that support arcing. Although the nitrogen-enriched atmosphere will not prevent arcing within the box, it will not support the combustion of wire/cable insulation or other combustible materials.

Aside from the obvious advantages of an inert atmosphere to prevent initiation and propagation of a fire, the continuous flooding of an electrical equipment compartment with filtered dry nitrogen-enriched gas was considered to be of potential benefit in protecting and extending the life of various electrical equipment components (contacts, relays) within the compartment.

SECTION 5
SELECTION OF APPROPRIATE DETECTION AND SUPPRESSION SYSTEMS FOR UNDERCAR FIRES

5.1 INTRODUCTION

Sections 2 through 4 have considered the undercar fire environment, analyzed fire detection methods that are applicable to the undercar environment, and evaluated the extinguishing agents that can be effectively used to suppress undercar fires. Based on this information, this section develops comprehensive recommendations for installing fire detection and suppression systems. The protection of components exposed to ambient air is considered separately from components within enclosed compartments.

5.2 GENERAL CONSIDERATIONS

A fire detection and suppression system for the undercar environment can be structured according to one of the following strategies:

1. The detection system alerts operating personnel, who make an informed decision regarding release of the extinguishing agent based on first-hand observation.

2. The detection/suppression system can be completely automated; i.e., the alarm level in the detection system causes an extinguishing agent to be discharged.

The essential difference between these two strategies is the involvement of operating personnel in the decision to actuate the extinguishing agent. Each transit system considering installation of a fire detection and suppression system will have to make a choice based on the following considerations.

In general, it is preferable to have the informed judgement of operating personnel involved in the decision to release an extinguishing agent. In order to provide maximum protection, it is likely that the system would be designed to allow operating personnel to release the agent even if the pre-alarm and alarm detection system signals or indicators were not activated. This would allow for situations where there is visible evidence of a fire emergency but some malfunction in the detection or annunciator circuits. On the other hand, this may lead to situations where the extinguishing agent is released but there is no fire emergency or it is in an area which can not be reached by the agent.

Another important consideration, which can not be addressed in a technical context, is the potential liability situation associated with having operating personnel responsible for a decision involving deployment of the agent. An automated release based on receipt of appropriate pre-alarm and alarm signals would remove any possible human error from the process. The automated release strategy would also remove the possibility of operating personnel hesitating to deploy an extinguishing agent because the fire is located in an equipment enclosure and there is no visible smoke or fire.

It should also be noted that it is extremely difficult for operating personnel to make a direct observation of the undercar area when the train is operating in a tunnel. A decision to release an extinguishing agent will be based on individual perceptions and attitudes in an emergency. Although premature or unwarranted release of an agent does not create a particular problem, once the agent has been released it is unavailable in a real fire emergency; furthermore, replenishing the extinguishing agent can be difficult.

As discussed in Section 2, protective devices such as overheat and overcurrent detectors that remove electric power have been engineered into certain components. The installed protective devices act as a fire detection system consisting of a pre-alarm indicator activating a power cutoff with no alarm signal for an extinguishing agent. This type of protection is a necessary first step in preventing electrical fires.

Overtemperature and overcurrent detection devices are intended to prevent electrical fires rather than to detect them. With some types, the only differentiation between overheat protection and fire detection is the temperature at which some preventive action is taken.

5.3 GENERAL RECOMMENDATIONS

It is recommended that any fire detection device used should have a pre-alarm signal which disconnects electric power input to the affected component. Disconnecting electric power eliminates the major source of ignition. In most cases, the environment surrounding the component contains little combustible material other than wire and cable insulation, debris from the roadbed, and accumulated grease or other lubricants. Therefore, removing power will extinguish the major ignition source.

The high temperature alarm stage of any fire detection system should indicate to operating personnel that critical temperatures have been reached at some protected component. It would also indicate release of an extinguishing agent in a fully automated system. Use of alarm indicators must be considered very carefully because an erroneous signal may cause operating personnel to take precautionary actions that will slow down or stop transit system operations. The recommended method is to mount indicators on the side of the car with appropriate signals to indicate whether a normal, pre-alarm, or alarm situation exists.

5.4 FIRE DETECTION AND SUPPRESSION FOR COMPONENTS EXPOSED TO AMBIENT ENVIRONMENT

The application of detection devices to components that are exposed to ambient is straightforward. Spot-type thermal detection devices are appropriate if the potential fire area can be defined clearly. These types of devices already are used as overheat detectors in many exposed components such as the resistor grid.

The use of extinguishing agents to suppress fires on exposed components is problematic. The most appropriate extinguishing agents for use on electrical fires are the halogenated agents. As noted in Section 4, carbon dioxide is less effective and the dry chemical extinguishing agents leave a residue which must be cleaned. Depending on the method used to apply the dry chemical, it may penetrate into spaces and areas that are very difficult and costly to clean.

A problem with halogenated agents is that since they are gaseous, their use is inappropriate in local application systems where air can flow rapidly past the protected components. Even Halon 1211 which is applied as a liquid stream, will evaporate quickly and be swept away if the train is moving.

For these reasons, it does not appear that an extinguishing system mounted under the transit car and directed at a specific exposed component for fire suppression purposes would work effectively on a reliable basis. One exception to this conclusion is the use of Halon 1211 in an on-board installation requiring operating personnel to release the agent only when the train is stationary. The Halon 1211 would be discharged as a liquid stream for a distance of up to 18 feet directly on to the affected component. Air flow past a stationary train in a tunnel due to the movement of other trains is not expected to have a significant effect on the Halon 1211 discharge stream. Therefore, the Halon 1211 would continue to contact the affected component for an extended period.

Application of Halon 1211 from a portable extinguisher can also be considered for situations in which operating personnel can position themselves where they can direct the extinguishing agent directly onto the affected component.

5.5 FIRE DETECTION AND SUPPRESSION IN ENCLOSED COMPARTMENTS

Fires within enclosed electrical compartments under the transit car are potentially the most dangerous from a passenger protection perspective. A fire initiating situation can persist in the enclosed compartment for a long time before smoke or fire becomes visible to passengers or operating personnel. By the time the fire causes visible smoke, even removal of power from the compartment may be insufficient to suppress further fire propagation. Insulation and jacketing around wires and cables typically are the major combustible material in the compartment. Once the insulation is ignited under high temperatures, it probably will continue to burn or smolder.

Fire detection devices that are most effective for use in enclosed compartments are spot-type and linear-type thermal detectors. The spot-type detector is more appropriate when the enclosed volume is small, e.g., battery box. A linear-type detector is more appropriate for larger enclosed volumes such as the propulsion motor control group compartment.

The most effective extinguishing agent for use in enclosed compartments is Halon 1301. The amount of Halon 1301 required to reach an extinguishing concentration of 5% for the propulsion motor control group compartment (the largest enclosed volume mounted under the transit car) is less than 2 pounds. This amount of Halon 1301 can easily be supplied by a small storage container mounted outside the compartment. For example, a commercially available spherical container designed for underfloor installation that contains 10 to 15 pounds of Halon 1301 measures less than 10 inches in diameter.

One further consideration in the application of detection and suppression systems to enclosed compartments is the situation where a forced (fan) cooling air flow is present. In this case provision must be made for shutting off the fan and restricting air flow out of the compartment prior to release of the Halon 1301. Otherwise the concentration of Halon 1301 cannot be maintained at an extinguishing level for a sufficient period of time.

5.6 SUMMARY OF RECOMMENDED FIRE DETECTION/SUPPRESSION SYSTEMS

Based on the evaluation of alternative fire detection/ suppression methods considered in this study, it is concluded that the most satisfactory approach is one which involves the use of thermal detection and one of the halogenated extinguishing agents - Halon 1211 for use on components exposed to the ambient and Halon 1301 for enclosed compartments.

Spot-type thermal detectors are recommended for detection of fires in exposed components where the area to be protected can be clearly defined and for small enclosed compartments (e.g., battery box). Linear-type thermal detectors are recommended for detection of fires in large enclosed compartments where it is difficult to pinpoint the location where a fire may occur.

The recommended detection and suppression system installation for components exposed to the ambient is an under car-mounted system with the extinguishing agent (Halon 1211) discharge nozzle(s) located no more than 10 feet from the area to be protected. The system should not provide for automatic release of the extinguishing agent upon transmission of an alarm signal from the detection device because the agent might be deployed while the train is moving. An automated release system is possible only if the system can be configured to also detect train motion. In that case, automated discharge would take place only when both the alarm and zero speed signals are received. The recommended approach is a manual discharge system controlled by operating personnel after indication of an alarm temperature. This recommendation is based upon considerations of simplicity and reliability.

The detection and suppression of fires in enclosed compartments can be handled with a coupled system of detection and suppression, but the decision to automate or to have operating personnel release the agent must be made based on local policy considerations at each transit system.

One additional recommendation which came out of the research for this project was the possibility of using an on-board nitrogen-enriched gas generating unit which could be used to flood and inert any enclosed equipment compartments where there was some concern regarding fire initiation.

The installation of a fire detection and suppression system on a rail transit car is a serious undertaking for any transit system because of additional cost, maintenance expense, and possible operational impacts if there are any reliability problems with the detection system. In order to provide additional information on the performance of the recommended detection and suppression system a laboratory test program was included as part of the overall project. The laboratory test program and results are presented in the next section.

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SECTION 6
LABORATORY TEST PROGRAM

6.1 INTRODUCTION

The laboratory test program represents the first step in establishing the practical applicability of fire detection and suppression systems to the operators of rail transit systems. The concerns of rail transit systems in the area of fire detection and suppression include safety, performance, reliability, and cost. The recommended extinguishing agents presented in Section 5 are expected to be safe because of the small amount of agent required and the large volume of air within the typical rail transit system tunnel. The dilution effects will be very large, particularly for an agent discharged into an enclosed compartment with subsequent leakage into the tunnel environment.

The issue of performance can be addressed in the laboratory setting whereas reliability can only be established through extensive field testing. The cost of the detection and suppression systems considered in this study are relatively nominal (on the order of several hundreds to several thousand dollars) when compared to the value of the rail transit vehicle and equipment being protected. The cost of an on-board nitrogen-enriched gas generating unit could not be defined because there were no commercial units available which were designed for transit or other similar applications.

A decision was made to select one undercar component for the laboratory testing of the recommended fire detection and suppression systems. The motor control group enclosure was selected because it was one component which had been identified in

Section 2 as being involved in numerous serious fires. Laboratory testing of detection and suppression for exposed components (e.g., resistor grids, current collectors, etc.) was not recommended due to the difficulty of setting up any type of simulated fire initiation conditions in a laboratory setting.

In order to develop a realistic test environment it was determined that the heat source for fire initiation would be an electric arc. Power arcing had been identified as the major source of fires within motor control groups. It was planned that the test apparatus could also yield some information on the specific nature of power arc-induced fires in cable insulation materials since there was no data available in the literature.

A total of twenty six laboratory tests were conducted by The Budd Company, under subcontract to KETRON, at their Technical Center in Fort Washington, PA. The New York City Transit Authority provided two motor control group enclosures, one of which was selected and used as the fire detection and suppression test bed. The following subsections present the objectives, test set-up, results and conclusions of the laboratory test program.

6.2 LABORATORY TEST OBJECTIVES

The principal objectives of the laboratory test of undercar fire detection and suppression systems were as follows:

1. Test the feasibility of using a linear thermal detection system inside a representative motor control group enclosure to detect overtemperature conditions caused by power arcing and to initiate cutoff of electrical power to prevent ignition or propagation of fires in cable insulation.

2. Test the effectiveness of a Halon 1301 extinguishing agent to control and suppress fires in cable insulation.

3. Test the effectiveness of a compact nitrogen-enriched gas generating unit to create an inert atmosphere in the motor control group enclosure which will control and suppress fires in cable insulation.

Each of the above test objectives address independent examinations of the feasibility and effectiveness of different concepts of undercar fire detection and suppression. However, the detection concept associated with Objective 1 can be combined readily with either suppression concept cited in Objectives 2 and 3.

6.3 DESCRIPTION OF TEST SETUP

The overall configuration and dimensions of the test motor control group enclosure are presented in Figure 6-1. The enclosure consisted of a steel-frame structure with two fiberglass doors running the full length. The doors were sealed with rubber molding and opened upwards to provide access to the electrical equipment inside. The enclosure also had two internal bulkheads as shown in Figure 6-1. These bulkheads also were equipped with rubber molding that sealed off the center compartment when the doors were closed. The fiberglass door shown toward the rear of the enclosure was equipped with an air vent consisting of several louvers located in the lefthand bulkhead area.

The motor control group enclosure was manufactured by the General Electric Company and had been in service for approximately 25 years. No history of parts replacement or refurbishment was available. When received, the enclosure was steam-cleaned and painted and one fiberglass door was repaired. The rubber molding on the doors and bulkheads, which were dry-rotted when received, were replaced.

The major modifications of the enclosure consisted of the installation of an inspection window in the front access door, carbon electrodes to create power arcs, and a fixture for holding cable samples, as shown in Figure 6-2. The inspection window was

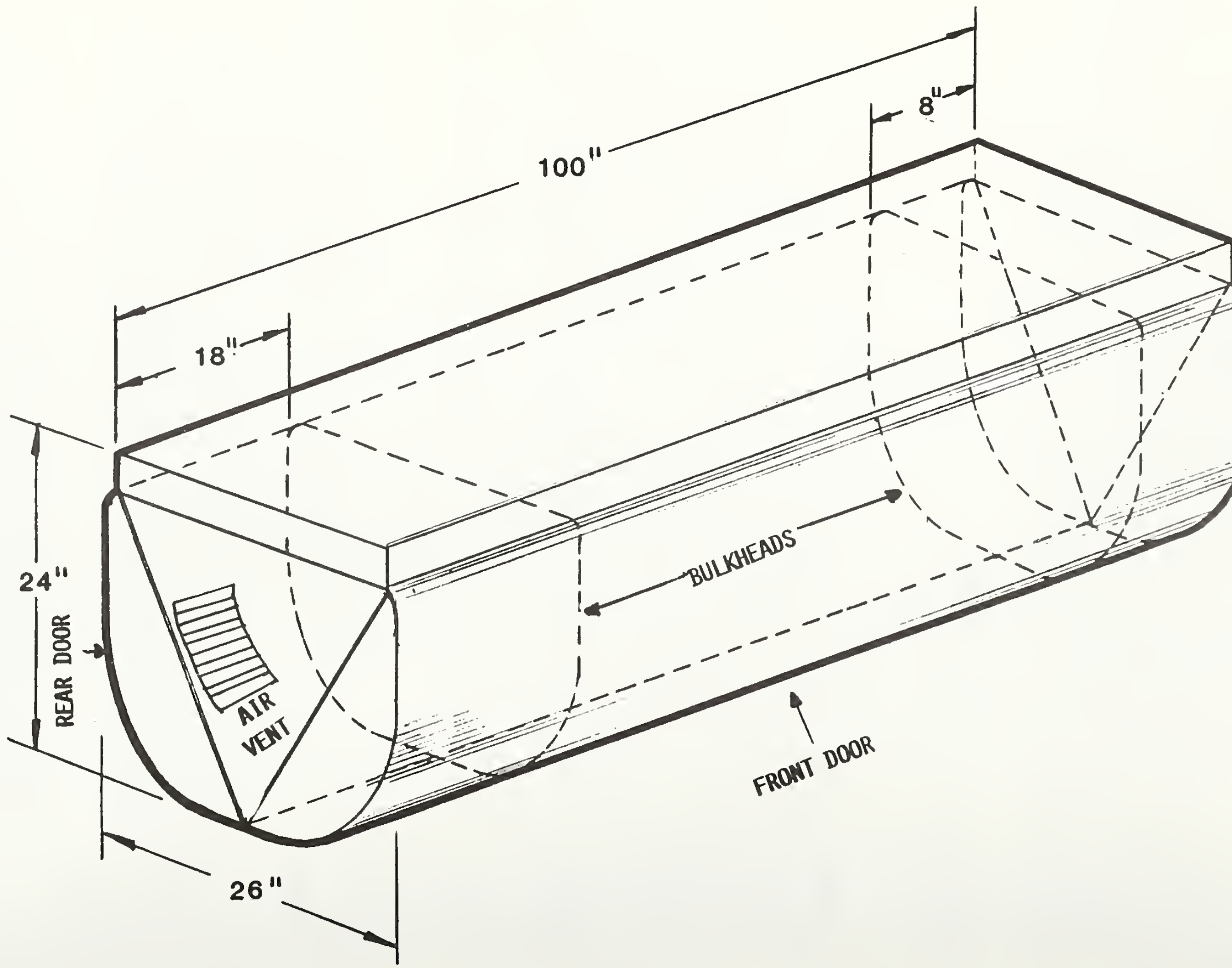

FIGURE 6-1. MOTOR CONTROL GROUP ENCLOSURE

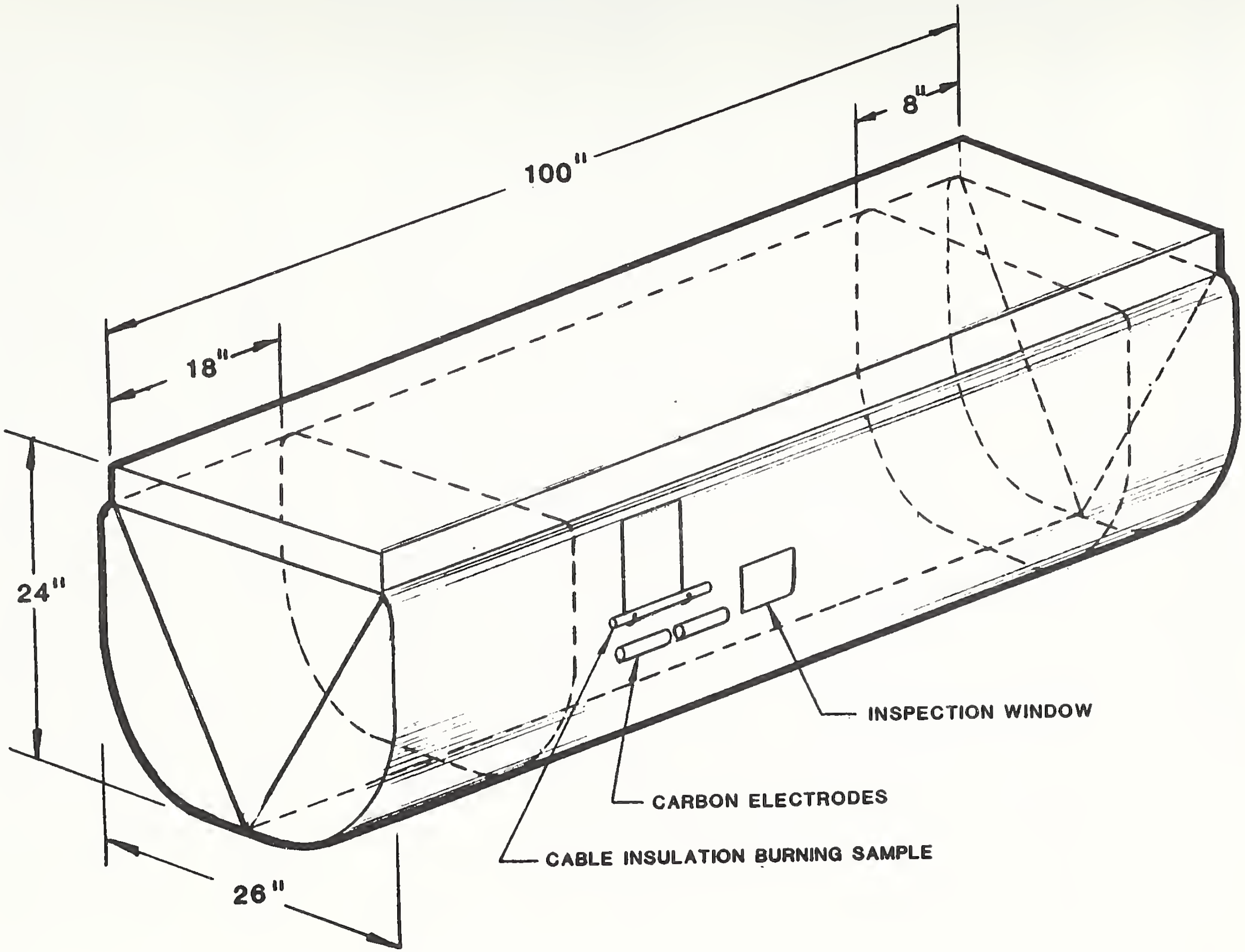

FIGURE 6-2. ELECTRICAL POWER ARC HEATING APPARATUS

used to monitor the carbon electrodes and the cable insulation samples during the burning tests.

All of the internal electrical and mechanical equipment was left intact to simulate the thermal mass characteristics of the motor control group enclosure.

The laboratory test was set up to evaluate the following detection and suppression equipment:

1. A linear thermal detector manufactured by Fenwal, Inc. The device is activated when any portion of the detection element (wire) reaches a pre-alarm temperature of 255 degrees F. The alarm temperature of this detection system was set at 400 degrees F.

2. A linear thermal detector manufactured by Alison Control, Inc. The device is activated when the integrated average temperature along the entire length of the sensor reaches a pre-alarm level of approximately 225 degrees F. and an alarm level of approximately 275 degrees F. The Alison system uses a more sophisticated control system which can be programmed to pre-alarm or alarm at different average temperature readings. The control system also has a programmable rate-of-rise indicator.

3. Spot thermal detectors manufactured by Fenwal placed at different locations around the upper portion of the enclosure. The spot detectors were set to alarm at 260 degrees F.

4. A Halon 1301 extinguishing system which was linked to the Fenwal linear thermal detector for automatic actuation when the alarm temperature of 400 degrees F. was reached.

5. A portable nitrogen-enriched gas generator manufactured by Clifton Precision. The unit is capable of reducing the oxygen concentration level in an enclosure from 20.9 percent (standard atmosphere) to approximately 5 percent, which is well below the oxygen concentration level needed to prevent combustion.

All of this equipment was tested extensively as part of the Laboratory Test Program.

Specific components of the test setup are described in the following subsections.

6.3.1 Electrical Power Arc Heating Apparatus

The power arc heating apparatus consisted of a pair of carbon electrodes connected to a welding power source. The carbon electrodes measured 3 inches in diameter and 12 inches in length. The gap between the electrodes was nominally 1/4 inch. This gap permitted the arc to start easily and remain stable. A very small flow of argon also was necessary to maintain arc stability. The argon was fed into the end of one electrode and flowed through the length of the electrode. The argon emerged into the arc-gap area through a small orifice in the electrode face.

The arc power source was capable of producing 300 amps DC at 100 volts. During most tests the voltage was somewhat lower and was primarily controlled by the electrode gap conditions. The arc would occasionally become unstable thus creating surges in voltage. Since the welding power source was a constant current device, under unstable arc conditions the net power was proportionately higher. These conditions are readily apparent in the power and temperature plots presented later.

There are no published data on the abnormal power arcing conditions associated with fire initiation in enclosed electrical equipment compartments such as the motor control group box. As discussed in Section 2, it is likely that the most common situation would involve multiple arcs which are subject to a great deal of instability involving rapid extinguishment and re-ignition. The maximum arc power level reached in the test program was approximately 15kw. With multiple arcs in an actual operating motor control group box it would be possible to have power levels which are 5 to 10 times higher than the test arc. Therefore, the arc heating apparatus does not simulate all of the thermal dynamic conditions which may exist but it does provide the overall thermal profile and basis for measurement and comparison of detector response.

During initial testing the arc heating power was sufficiently high to cause the wiring inside the box to ignite. The fiberglass enclosure itself also began to burn in an area adjacent to the arc. To prevent the enclosure from burning up prematurely, a water jacket was installed inside the fiberglass door adjacent to the arc. The water flow rate through the jacket was just enough to prevent the door from igniting.

Ceramic tiles were installed between the electrodes and existing wiring. These tiles prevented the wiring from igniting during subsequent tests. The ceramic tiles were removed before the final test.

6.3.2 Thermocouple Locations

Temperature measurements were taken at 14 thermocouple locations, shown schematically in Figure 6-3.

During certain tests, wire cable samples were suspended approximately one inch above the carbon electrodes. Thermocouples 15 and 16 measured the sample cable temperatures.

6.3.3 Fenwal Thermal Sensing System

The Fenwal Thermal Sensing System was installed by Fenwal representatives in the top of the motor control group enclosure as shown in Figure 6-4. This system consisted of a continuous wire loop that sensed local temperatures. The system was preset to respond to two different temperature levels (255 degrees F

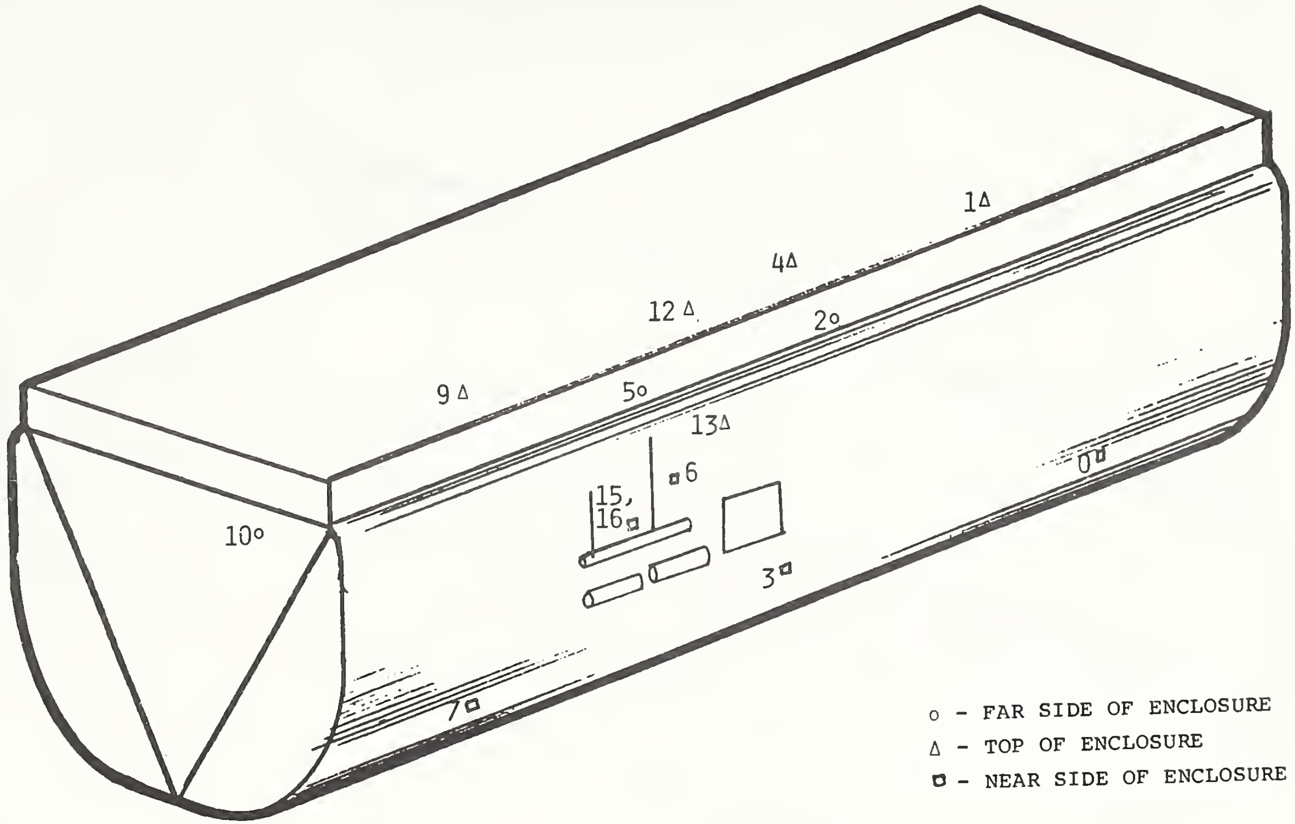

FIGURE 6-3. THERMOCOUPLE LOCATIONS

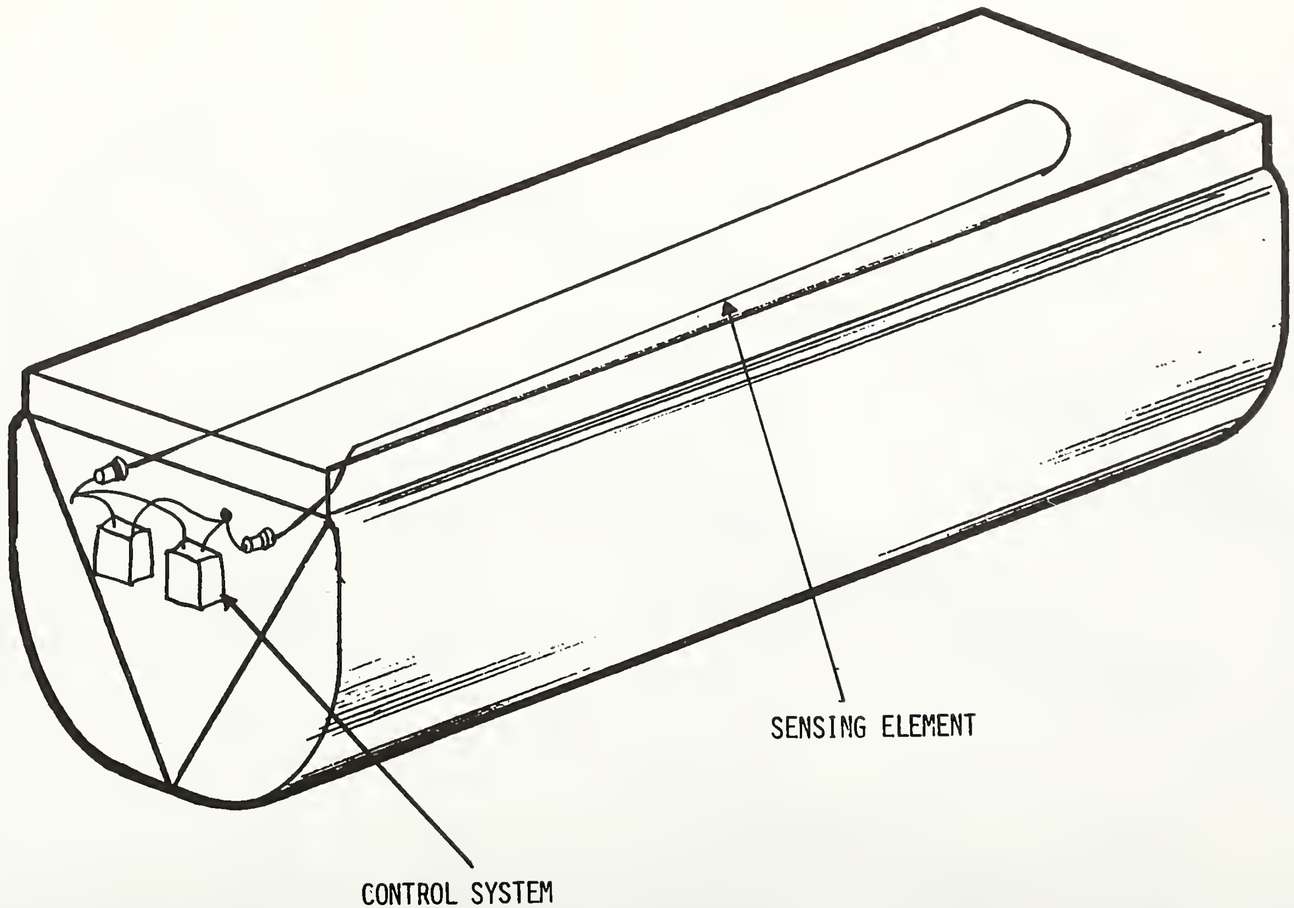

FIGURE 6-4. FENWAL THERMAL SENSING SYSTEM

pre-alarm and 400 degrees F alarm). The test setup included test lamps that indicated when the pre-alarm and alarm temperature levels were sensed. The time that each test lamp came on was recorded in the test log.

6.3.4 Fenwal Thermal Spot Detectors

Fenwal representatives also installed five thermal spot detectors in the approximate locations shown in Figure 6-5. These spot detectors were preset to sense 260 degrees F and also were connected to a test lamp that indicated when the set temperature was reached. Test lamp "on" times were recorded in the test log.

6.3.5 Alison Thermal Sensing System

A continuous-loop thermal sensing system provided by Alison Control also was evaluated. This system was installed by Alison representatives approximately as shown in Figure 6-6. This system had a self-contained electrical panel and warning lights. The lights indicated two different temperature levels. The pre-alarm level was activated when the average temperature along the length of the detector reached approximately 225 degrees F. The alarm level was reached at an average detector temperature of approximately 275 degrees F.

6.3.6 Halon System

Fenwal representatives also installed a Halon 1301 extinguishing system for evaluation. The system was installed approximately as shown in Figure 6-7. The system consisted of a pressurized tank containing the Halon 1301 and a remotely mounted control panel. The control panel was connected to the Fenwal Thermal Sensing System. The Halon system would normally be triggered automatically when the Fenwal system reaches the 400

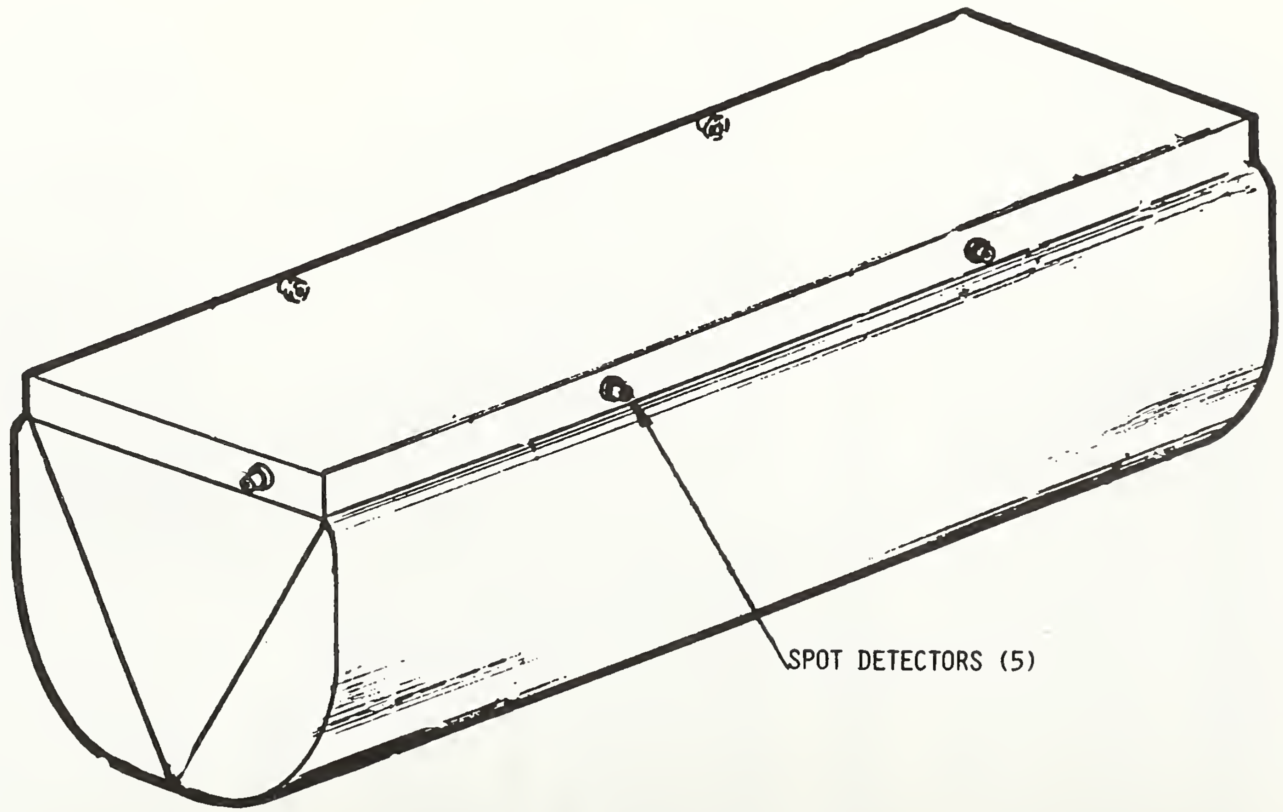

FIGURE 6-5. FENWAL THERMAL SPOT DETECTORS

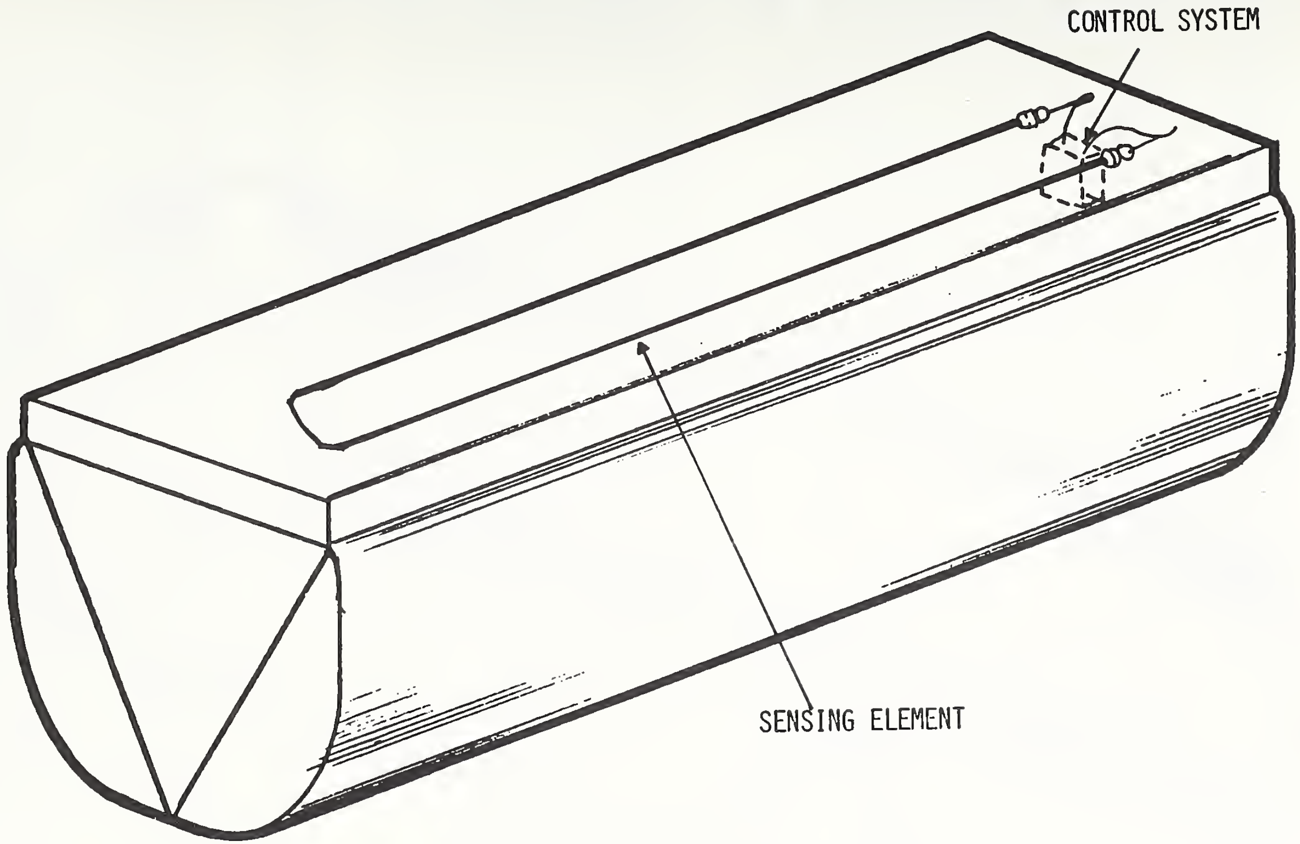

FIGURE 6-6. ALISON THERMAL SENSING SYSTEM

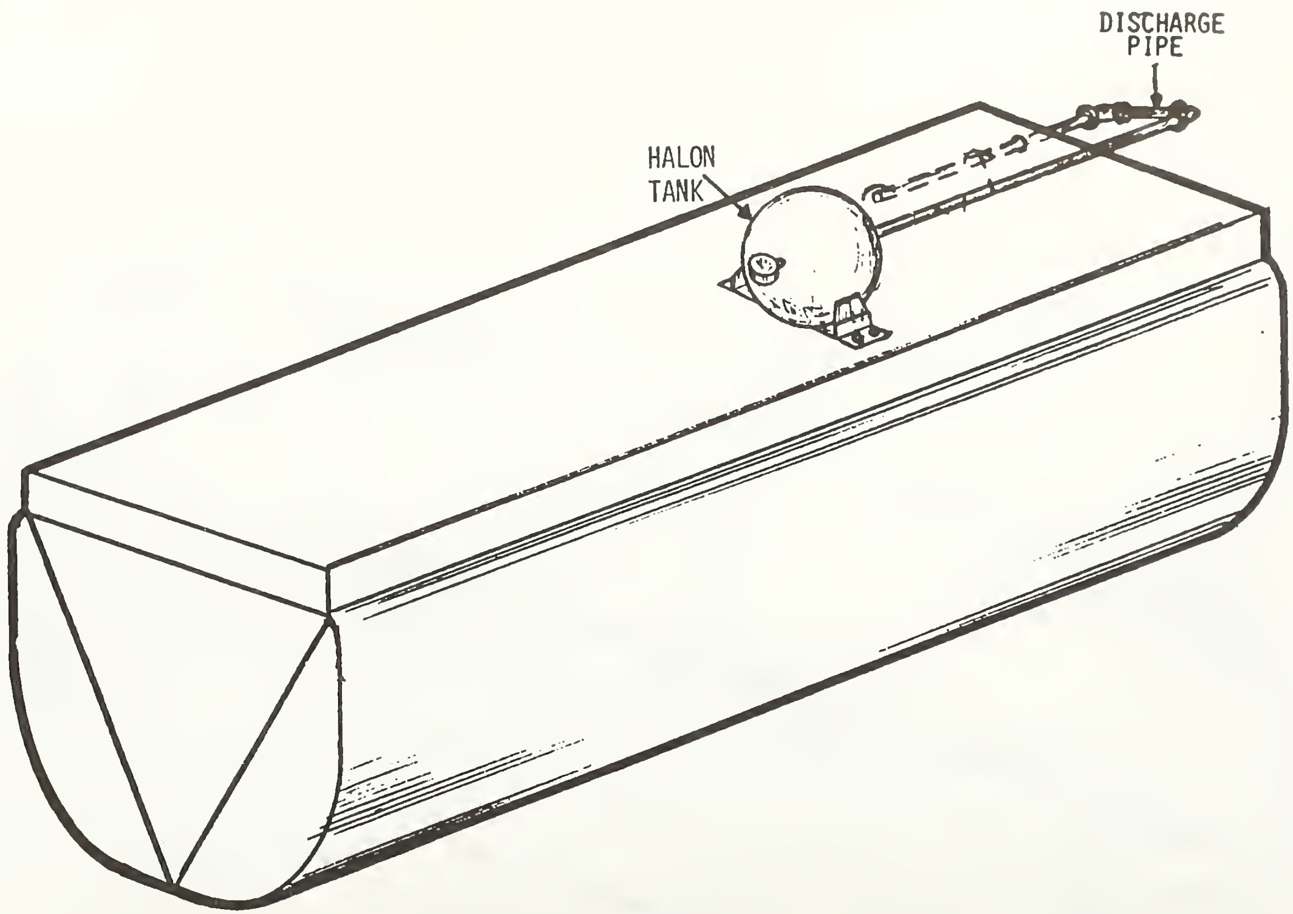

FIGURE 6-7. HALON SYSTEM

degree F. alarm point. However, because of radio frequency interference from the dc welding power supply and the arc, the Halon 1301 system could not be automatically released by the alarm level signal.

6.3.7 Nitrogen-enriched Gas Generator

A portable nitrogen-enriched gas generating unit was supplied by Clifton Precision. The inert (nitrogen-rich) gas generator utilizes a pressure swing adsorption process to produce oxygen-depleted product gas. In this process, some of the oxygen in pressurized air is adsorbed in a bed of synthetic zeolite (molecular sieve) while nitrogen passes through. The unit supplied contains two beds which are pressurized and flushed alternately to provide a continuous flow of nitrogen-enriched product gas.

The unit produced approximately one cubic foot per minute of a nitrogen-enriched gas which was piped into the motor control group enclosure. The oxygen concentration of the output gas was measured at approximately 5 percent, while standard air at amospheric conditions is approximately 20.9 percent oxygen. The unit was supplied with standard shop air for input gas and input power from a 400-cycle ac power supply.

6.4 TEST PROGRAM AND RESULTS

The laboratory test plan for the Motor Control Group Fire Detection and Suppression Test consisted of four test series:

- o Test Series A - Basic Flow and Thermal Tests: Eight tests were conducted to determine the leakage flow characteristics and the thermal response (temperature profile) of the motor control group enclosure with arc heating.

- o Test Series B - Wire/cable Fire Tests:
  Twelve tests were conducted to determine the performance of the detection systems when the arc heating apparatus was used to ignite the insulation on various wire/cable samples.

- o Test Series C - Nitrogen-enriched Gas Generator Tests:
  Four tests were conducted to determine the performance of the portable nitrogen-enriched gas generating unit as a means of creating an inert atmosphere within the motor control group enclosure.

- o Test Series D - Halon 1301 Extinguishing Tests:
  Two tests were conducted to determine the extinguishing effects of Halon 1301 on wire/cable insulation fires initiated by arc heating.

The test series are described in the following subsections, together with a discussion of the results from some representative tests.

6.4.1 Test Series A Basic Flow and Thermal Tests

The flow tests were set up to determine the leakage characteristics of the motor control group enclosure. This information is necessary to determine the amount of Halon 1301 required to maintain the concentrations at or above an extinguishing level. It is also important for the determination of the required flow rate for an on-board nitrogen-enriched gas generating system.

The motor control group enclosure contains vent holes, enclosure penetrations, and seals which are paths for leakage. A series of air flow tests was conducted to determine the leakage characteristics of the motor control group enclosure. The tests provided plots of internal pressure vs. air-flow rate. The leakage paths through the vent holes and other enclosure penetrations were left open for the first test runs and then blocked off for the second runs. The second series of runs provided a direct measurement of the leakage past the seals used on the access doors of the enclosure.

The enclosure leakage characteristics were determined using a standard shop air supply, flowmeter, and inclined manometer. The air supply was piped into the center compartment at the top of the enclosure. The internal static air pressure was measured in the center compartment. The air-flow rate was controlled with a large gate valve.

The internal static air pressure was measured for different flow rates. This data is plotted in Figure 6-8 for two different conditions. The short curve near the lower right-hand corner represents the leakage rate of the enclosure with the major, but not all, leakage paths blocked off (including the air louvres) and new door seals put in place.

The other curve, which starts at the origin on Figure 6-8, represents the leakage rate of the enclosure with all visible leakage paths closed off. This means that in addition to the blocked-off air louvres and the new door seals, all small holes and cracks in the enclosure were successfully sealed with duct tape.

The air flow tests demonstrated that the representative motor control group enclosure has a high leakage flow rate unless an extensive effort is made to reduce or eliminate all leakage paths. The effectiveness of a Halon 1301 extinguishing system or a nitrogen-enriched gas generator for compartment inerting would be severely degraded unless the enclosure was properly sealed.

The second part of Test Series A involved the thermal testing of the enclosure. These tests were conducted to determine the basic thermal response of the enclosure with internal arc heating. The results are presented in the form of temperature

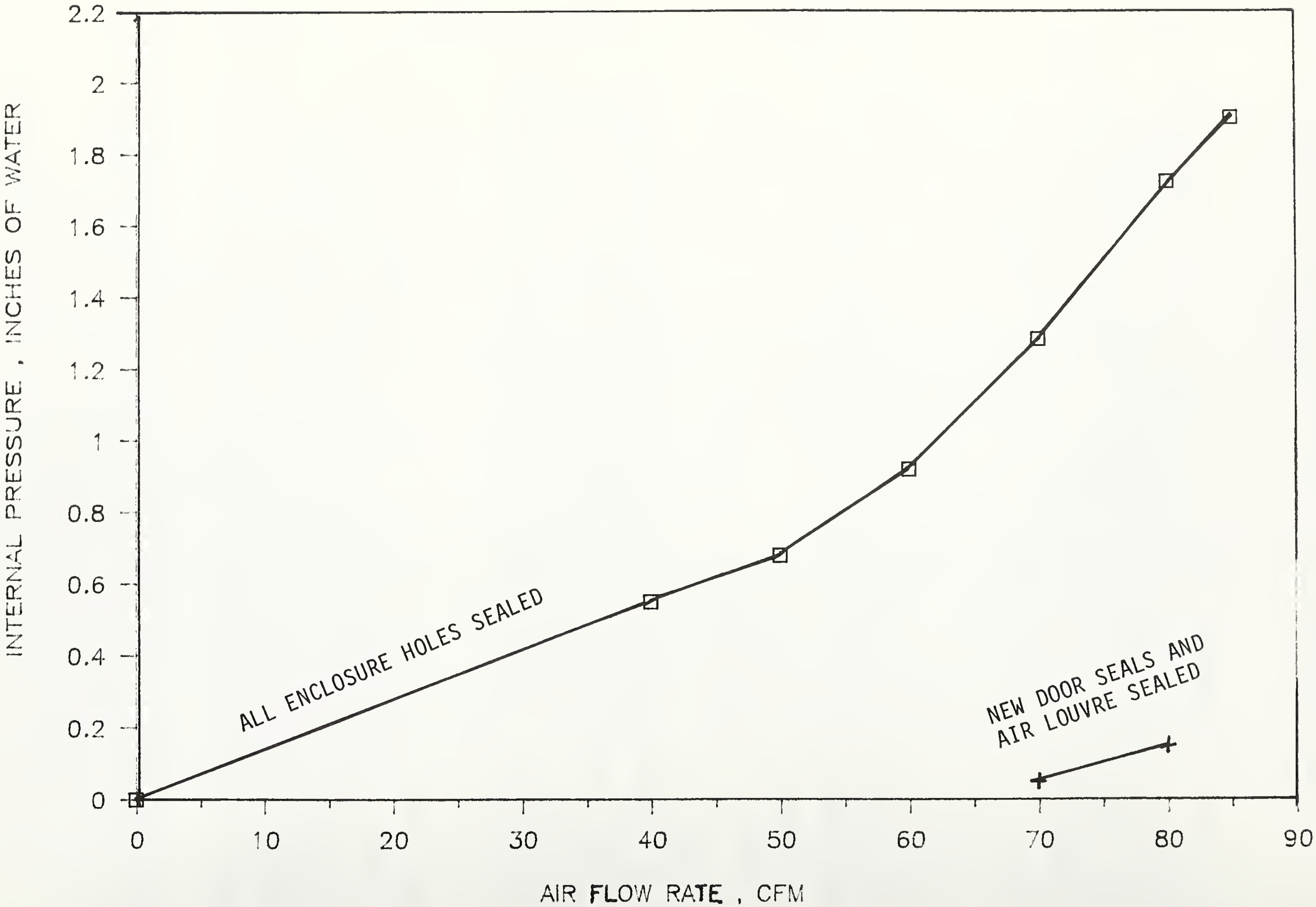

FIGURE 6-8. ENCLOSURE AIR FLOW LEAKAGE CHARACTERISTICS

versus time graphs. The amount of test data was voluminous, therefore, for clarity of presentation they are presented in Appendix A with references to particular figures described in the following text.

Six thermal tests of the enclosure were conducted after the air flow tests. The first two thermal tests were conducted with the leakage vents open, followed by six tests with the vents closed. The electrical power arc apparatus was the heating source for all tests. The enclosure was vented and cooled after each test so that it reached a condition of thermal equilibrium.

During all thermal testing, the carbon arc electrode power was kept on for 5-minute intervals, followed by a 30-second shutdown which was required to measure the thermocouple temperatures. The thermocouple temperatures could not be measured while the welding power supply was operating because radio frequency emissions interfered with the instrumentation. Thermocouple temperatures were measured and recorded using a Hewlett-Packard data logger. The data were then input to an IBM PC which was used to generate the temperature plots presented in this report. A similar procedure was used for the input power level plots.

The thermal detection systems were in place during the enclosure heating tests. Measurements of the temperatures detected by both systems were compared to the actual temperatures measured by the high response thermocouples. The times to reach pre-alarm and alarm temperatures for all thermal detectors were noted and recorded in the test log.

The results of some of the thermal tests conducted in Test Series A (Test Numbers 1, 3 and 4) which were considered to be representative are described in the following paragraphs. Test Numbers 2, 5, and 6 are not discussed in this document.

Test Number 1

The test conditions included arc heating at a power level of approximately six kilowatts for a period of 2 hours and 10 minutes. Measurements of temperature were conducted for a total time of 2 hours and 30 minutes. The input power level profile is shown in Appendix A as Figure A-1, followed by the thermal profiles in Figures A-2 through A-4. All thermocouples were installed in the large center compartment as previously shown in Figure 6-3. Figure A-2 illustrates the temperature profiles for Thermocouples 3 through 6, which are essentially located in a vertical plane to the right of the carbon-arc electrodes. Figure A-3 presents the temperature profiles for Thermocouples 7, 9, and 10, which are located in an equivalent vertical plane just inside the left bulkhead. Figure A-4 shows the temperature profiles for Thermocouples 0, 1, and 2, which also are located in an equivalent vertical plane just inside the right bulkhead.

In all cases the figures show that the temperature profiles are rising up to the point when the power arc was shut off, indicating that the enclosure temperature had not yet reached equilibrium. The Fenwal alarm light "on" times are noted in Figure A-2. Since Thermocouple numbers 4 and 6 are located near the linear detectors and the power arc, respectively, their output was used as a reference for comparison with the preset temperature levels for the pre-alarm and alarm detector test lights. For example, the average temperature for Thermocouples 4 and 6 is about 252 degrees F when alarm light no. 1 (Fenwal linear detector, pre-alarm) came on. The preset level for alarm light no. 1 was 255 degrees F. In this case the detector preset temperature corresponded very closely with the measured average temperature. When alarm light no. 3 (Fenwal spot detectors) came on, the average temperature for Thermocouples 4 and 6 was 290 degrees F, which is higher than the preset level of 260 degrees F. The difference between indicated detector temperature and the measured temperature can be explained by local temperature variations since the spot detectors are not in close proximity to Thermocouples 4 and 6.

The Alison Sensing System was not available for this test because radio-frequency emissions from the power source and arc interfered with operations of the Alison electronic control unit.

The thermocouple data indicates that there is a considerable thermal inertia in the motor control group due to the large mass of metal involved in the switch gear and cam drives. The alarm signals from the Fenwal linear and spot-type thermal detectors provide an indication of responsiveness and accuracy. The linear detector proved to be very responsive and accurate with the pre-alarm signal coming on when the measured average temperature was within 3 degrees F. of the preset level of 255 degrees F. This represents a very high level of accuracy. The accuracy of the spot detector cannot be determined directly due to local temperature variations. The response of the spot detector was considerably slower (approximately twenty five minutes later) due to the time it takes for the local air temperature near the detector to reach the 260 degree level.

Test Number 3

The input power level for Test Number 3 is presented in Figure A-5. During this test the carbon arc was unstable as can be seen in the power profile and temperature plots illustrated in Figures A-6 through A-8. During this test the input power level briefly reached 12 kw. The input power was on for 1 hour and 55 minutes. Temperature readings were taken for an additional 30 minutes during the cool-down in order to obtain further information on the thermal inertia of the motor control group enclosure.

The test results presented in Figure A-6 show a considerable variation between the measured temperatures (Thermocouples 4 and 6) and the preset temperatures of the detectors. For example, the Fenwal linear detector pre-alarm signal (#1) went on 31 minutes into the test which means that at some point along the detector wire the local temperature had reached the 255 degree F. set point. The manufacturer's estimated accuracy of the linear detector is $\pm$ 13 degree F. At that time the average of Thermocouple 4 and 6 was only 215 degrees F. Thermocouple 6 was at approximately 230 degrees while Thermocouple 4 was at approximately 200 degrees F.

Referring again to Figure A-6, the Fenwal spot detector alarm signal light (#3) came on 53 minutes into the test. This indicates that the spot detector closest to the arc heating source reached its set point temperature of 260 degrees F. The manufacturers estimated accuracy of the spot detector is $\pm$ 9 degrees F. The average temperature of the thermocouples at that time was approximately 240 degrees F with Thermocouple 4 at approximately 215 degrees F. and Thermocouple 6 at 265 degrees F.

The alarm light (#2) of the Fenwal linear detector came on at 82 minutes into the test indicating that some point along the detector had reached the set point temperature of 400 degrees F ($\pm$ 20 degrees F). At that time Thermocouple 4 was at approximately 278 degrees F and Thermocouple 6 was at 365 degrees F, resulting in an average temperature of 321 degrees F.

A number of conclusions can be drawn from these results. The first is that the unstable arcing patterns led to fluctuating temperatures within the enclosure as illustrated by the fact that the measured temperatures (see Figure A-6) did not continually increase. The unstable arcing also caused sharp temperature gradients within the enclosure as evidenced by the fact that the temperature difference between Thermocouples 4 and 6 reached approximately 100 degrees F. during the test. These thermocouples were mounted in essentially the same vertical plane with Thermocouple 4 mounted at the top of the enclosure (nearer the detectors) and Thermocouple 6 mounted on the side nearer to the electric arc. The vertical separation between these two thermocouples was approximately one foot.

These temperature gradients are important to understanding the fact that the detection signals appeared to be premature when compared to the results in Test No. 1, i.e., the alarms triggered when the measured average temperature near the arc and the detectors was below the set point value. In fact it appears that the detectors are quite accurate (within the manufacturer's specified limits) and that the actual local temperatures at some point along the linear detector and at the spot detector closest to the arc are higher than the average of the two thermocouple readings due to the existence of thermal gradients.

The spot detector response lags the pre-alarm signal of the linear detector by 22 minutes even though the set points are quite close (260 vs. 255 degrees F.). In Test No. 1 the time lag was approximately twenty five minutes. It is concluded that this lag is due to the fact that the linear detector senses a "hot spot" temperature well before the spot detectors. The spot detector appears to be accurate since the temperature of Thermocouple 6 has reached 270 degrees F at the time the detector senses a temperature of 260 degrees F. It is clear that the temperatures in the vicinity of the spot detector could have reached the preset level at that time.

The balance of the results from Test No. 3 are presented in Figures A-7 and A-8. These figures show that the temperature fluctuations and gradients at the ends of the compartment (within the bulkheads) are significantly smaller. The maximum temperature at the left end of the compartment (Thermocouples 7, 9, 10) reached a maximum temperature of approximately 300 degrees F., which is 150 degrees F. lower than the area near the arc. The right end (Thermocouples 0, 1, 2) reached a maximum temperature of approximately 180 degrees. These temperature differences demonstrate a very substantial thermal gradient along the length of the compartment even after a very long period of arc heating. This observation provides further evidence of the advantage of a linear detection system that can sense an overtemperature condition anywhere along the length of the compartment.

Test Number 4

An attempt was made in Test Number 4 to reduce arc instability by beginning at a lower power level and gradually increasing input power. The input power plot is presented in Figure A-9, which shows that the arc was relatively stable for the first 55 minutes but became unstable for the last 50 minutes. The maximum power level reached was about 14 kw. Cool-down temperatures were measured for 35 minutes after power shutdown. The total test period was 2 hours and 20 minutes.

The thermocouple plots are shown in Figures A-10 through A-12. A maximum temperature of about 450 degrees F was measured at Thermocouple 6.

During this test the Fenwal sensing systems were not functioning correctly. Test data was limited to thermocouple readings to collect more information about the thermal inertia characteristics of the enclosure.

The conclusion of the test was that the temperature buildup in the enclosure during the period when the arc was relatively stable (the first 55 minutes of the test) was fairly smooth as evidenced by the Thermocouple 4 and Thermocouple 6 temperature plots which track together. Once the arc becomes unstable (the next 50 minutes of the test) the two temperature readings begin to diverge demonstrating that significant temperature fluctuations are associated with the arc instabilities. This test verified the results obtained in Test Numbers 1 and 3.

6.4.2 Test Series B Wire/Cable Fire Tests

The purpose of this test series was to test the performance of the thermal detection systems after a fire was initiated in a typical section of insulated wire/cable. The power arc was used as the ignition source. The proximity of the wire/cable sample to the arc was adjusted until it was close enough that the insulation ignited. The burning wire/cable insulation was expected to provide an additional heat input to the enclosure, resulting in an additional temperature rise.

The wire/cable samples were obtained from two different manufacturers who are currently suppliers to the transit industry. ITT Surprenant provided representative EXANE cable samples and BIW provided representative LO-SMOKE cable samples. The samples from each manufacturer were of two different sizes--12 awg and 4/0 awg. These sizes are representative of the range of wire/cable sizes found in the motor control group. The proximity required between the arc and the cable sample for ignition of the insulation necessitated using a single cable rather than an array or series of parallel cables as originally planned. For the smaller-diameter wire a cluster of three or four size-12 wires was placed adjacent to the arc.

It should be noted that the observations regarding the ignition of insulation cable reported in the following test results should not be considered as an evaluation of the performance of these materials in a fire situation involving the motor control group. There are standard tests as defined in Reference 10 which are typically used to evaluate cable insulation properties.

Twelve wire/cable tests were conducted, of which Test Number 5 is considered to be representative. This test is discussed in the following paragraphs.

Test Number 5

The primary objective of Test Number 5 was to test the performance of the detection systems under conditions where a fire was initiated in the sample cable insulation by means of the power arc. The test also provided the opportunity to observe the ignition of the cable insulation and to examine its condition afterwards. Samples of each cable type (EXANE and BIW) were suspended approximately one inch above the carbon-arc electrodes as previously shown schematically in Figure 6-2. Thermocouples (No. 15 and No. 16) were attached to the cables as illustrated in Figure 6-3.

The input power level was increased gradually from 2 to 6 kw during the first 10 minutes of testing and remained at about 6 kw for an additional 115 minutes, bringing the total" on" time to 125 minutes as shown in Figure A-13. The arc was reasonably stable throughout this test. Temperature measurements were continued for another 55 minutes leading to a total test time of three hours.

Temperature plots for Test Number 5 are presented in Figures A-14 through A-16. The alarm light-on times are noted in Figure A-14. The temperatures reached in the enclosure were not high enough to set off the spot detectors or the alarm levels of the linear detectors.

Referring to Figure A-14 the Fenwal linear detector pre-alarm light (# 1) came on at 92 minutes when the average temperature of Thermocouples 4 and 6 was 247 degrees F, as compared to the pre-alarm point of 255 degrees F. The Alison pre-alarm light came on when the average temperature of Thermocouples 4 and 6 was 255 degrees F. These measurements indicate that both sensing systems performed as predicted. The Alison system response is based on the integrated effect of the temperature along the full length of the sensor.

Measurements of cable sample temperatures are presented in Figure A-17. Note that Thermocouple number 15 was attached to the BIW (LO-SMOKE) sample and Number 16 was attached to the EXANE sample. Figure A-17 shows about a 40 degree F temperature differential between the two cable samples. The maximum recorded temperatures were 580 degrees F for BIW and 540 degrees F for EXANE.

Both cable samples began to emit a small amount of smoke after approximately 20 to 25 minutes of testing. Neither cable showed any signs of burning with a visible flame throughout the test. Examination of the cable samples showed damage (charring) to the insulation was limited to a distance of approximately three to four inches on either side of the arc.

There were a number of conclusions from the results of Test Number 5. The effect of the cable insulation ignition of the heating of the enclosure was negligible, due to the very small amount of insulation which was burned during the test. There was no adverse effect on the performance of the detection systems from the burning of the insulation. The Fenwal linear detector pre-alarm came on at a temperature which corresponded to the expected range of 242 to 268 degrees F. based on the estimated accuracy of $\pm$ 5 percent.

The Alison Control linear detector came on approximately 12 minutes later. The set point for the Alison Control pre-alarm was approximately 225 degrees F. The pre-alarm signal is initiated when the entire detector reaches a uniform temperature of 225 degrees F. or any other combination of higher and lower temperatures which causes the resistance characteristics to be the same. In the case of this test the portion of the detector element near the power arc was sensing temperatures in the range of 260 degrees F. while the portion of the element further away sensed much lower temperatures. It is not possible to discuss these results in the context of the accuracy since there is no direct measurement of the actual temperature distribution along the detector element. It is clear, however, that the temperature set point of the Alison Control (temperature averaging) type of linear detector must be set lower (30 degrees F. in this case) than the Fenwal (point sensing) type in order to have it respond in the same time frame.

6.4.3 Test Series C. Nitrogen-enriched Gas Generator Tests

The nitrogen-enriched gas generator was tested to determine the effectiveness of the nitrogen-rich environment for controlling the initiation and propagation of cable insulation fires in the motor control group compartment. The ability of the unit to inert the motor control box interior volume was assessed by measuring the relative concentrations of oxygen and nitrogen as a function of time.

The nitrogen-enriched gas generator was initially operated to establish its performance in reducing the oxygen concentration level in the motor control group enclosure. The gas generator performance is presented in Figure 6-9 where the percent oxygen concentration in the enclosure is shown as a function of time.

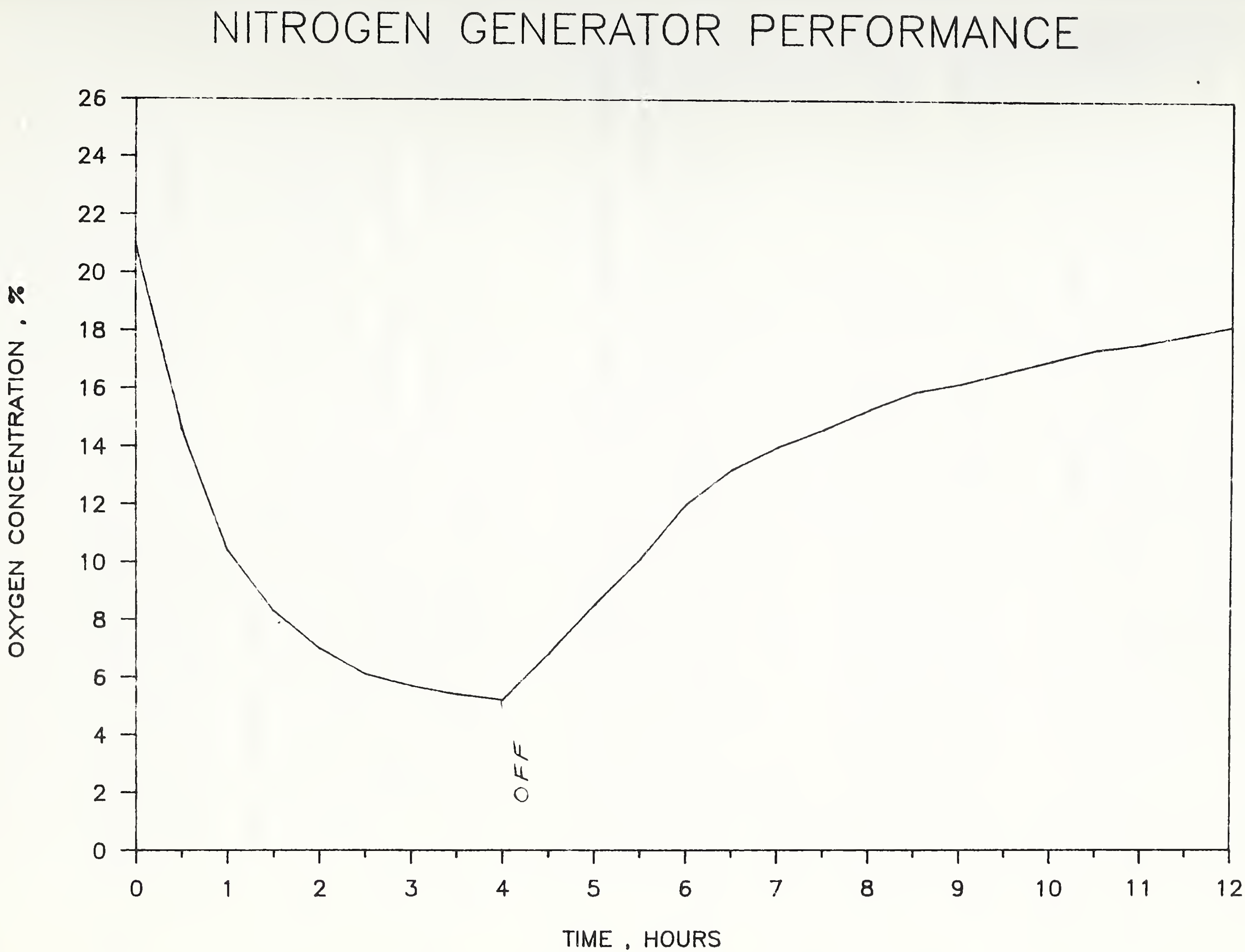

FIGURE 6-9. NITROGEN GENERATOR PERFORMANCE

Standard atmosphere is typically 20.9 percent oxygen. The tests showed that nitrogen-enriched gas generator lowered the oxygen concentration level to 8 percent in only 1.5 hours; this level is sufficiently low to prevent combustion. The oxygen concentration level inside the enclosure reached a steady state of approximately 5 percent in 4 hours. The unit then was turned off and the oxygen concentration monitored for an additional 12 hours as shown in Figure 6-9.

Four tests of detection and suppression system performance were conducted using the gas generator to create an inert (nitrogen-enriched) environment in the enclosure. Test Number 6 is considered to be representative of this test series.

Test Number 6

The primary objective of Test Number 6 was to test the performance of the detection systems and to determine whether there were any substantial differences when cable insulation fires were initiated in a nitrogen-rich atmosphere. The cable samples were suspended approximately one inch above the carbon-arc electrodes.

The nitrogen-enriched gas generator was operated for 2 hours before starting the carbon arc and remained operational throughout the test. The gas generator reduced the oxygen concentration within the enclosure from 20.9 percent oxygen to 6 to 7 percent oxygen. The lower oxygen concentrations also are referred to as a nitrogen-enriched atmosphere. Oxygen concentration levels below 8 percent cannot support combustion.

The input power level of the arc was increased gradually from 2 to 6 kw during the first 10 minutes of testing and remained at about 6 kw for the remainder of the test. Figure A-18 shows that the input power level was reasonably stable for the 2-hour heating period. Temperature measurements were continued for another hour resulting in a total test period of 3 hours.

Temperature plots for Test No. 6 are presented in Figures A-19 through A-21. The alarm light-on times are noted in Figure A-19. The temperatures were only high enough to activate the pre-alarm settings of the linear detectors. Both of the pre-alarm signals corresponded very closely with the measured temperature and time results from Test No. 5 which had a very similar power input.

Figure A-22 shows the temperatures measured directly on the cable samples. The maximum temperatures measured are 604 degrees F. for the BIW sample and 508 degrees F for the EXANE sample. The nitrogen flow rate inside the enclosure acted to retard the cable sample heating rate as shown in Figure A-22. The sample cables emitted very little smoke and neither cable showed any signs of burning or visible flame throughout the test. Examination of the cable samples showed damage (charring) to the insulation was limited to a distance of approximately three to four inches on either side of the arc.

The results of Test No. 6 showed that the presence of nitrogen-enriched gas had no measurable effect on the arc or the heating effect within the enclosure. Those results were expected because arcing in a nitrogen-enriched atmosphere is very similar to that in standard air. It was expected that the nitrogen-enriched atmosphere would have acted to retard the ignition and burning of the cable insulation samples but there was no significant difference in damage to the sample between tests in standard vs. nitrogen-enriched air. It appears that the cable insulation damage is caused by the intense radiant heating associated with direct exposure and proximity to the arc. The radiant heating is not affected by the presence of nitrogen-enriched gas. The nitrogen flow rate did have some effect on the temperature buildup in the cables.

The similarity of detector responses between Test Nos. 5 and 6 shows that there is a high level of consistency in the detector response. Therefore, the presence of the nitrogen-enriched gas did not have any adverse effect on detector performance.

6.4.4 Test Series D Halon Extinguishing Tests

The purpose of this test series was to determine the effectiveness of Halon 1301 as an extinguishing agent for motor control group fires.

The test setup used for the Halon 1301 extinguishing system is illustrated in Figure 6-7. Approximately 10 pounds of Halon were held in a spherical container with an outside diameter of approximately 10 inches. A single piece of tubing was placed between the Halon tank and the nozzle which projected directly into the center portion of the enclosure. The nozzle area was selected to ensure a rapid discharge rate of Halon during the initial stage discharge. The estimated weight of Halon 1301 required to reach an extinguishing concentration of 5 percent within the enclosure is approximately 1.25 lbs.; therefore, at the design flow rate the extinguishing concentration was reached in less than 10 seconds. The 10 second period is consistent with the National Fire Protection Association (NFPA) Standard 12A-1980 for Halon 1301 Fire Extinguishing Systems.

A total of 4 Halon 1301 extinguishing tests were planned; however, due to difficulty in establishing a significant fire in the cable insulation or other parts of the enclosure only two tests were conducted. The Halon test discharge which was conducted during Test Number 7 is considered to be representative.

Test Number 7

The objective of Test Number 7 was to demonstrate the Halon 1301 extinguishing system performance by heating the enclosure sufficiently high to start an internal fire. The input power level was maintained at approximately 7 kw for the first 2 hours, then gradually increased during the last 1.5 hours to a maximum level of 15 kw. The carbon arc remained relatively stable for the first 3 hours of the test as shown in Figure A-23. The arc was on for a total of 215 minutes with temperature measurements continued for another 85 minutes leading to a total test time of 5 hours.

The ceramic tiles that were installed at the beginning of the test program to prevent the internal wiring from igniting were removed for this test. However, the motor group enclosure was previously heated or baked for so long that all of the volatiles were driven from the existing wiring and harnesses. Therefore, although the temperatures were sufficiently high to cause ignition under normal circumstances such as those encountered in the initial Test Number 1, no combustible products were left. In an attempt to start a fire, the input power level was increased to a maximum level of 15 kw for the final 25 minutes. During this time a portion of the fiberglass door began to burn with a visible flame but extinguished in less than 2 minutes.

Temperature plots are presented in Figures A-24 through A-26. All five sensing system alarm lights eventually came on as noted in Figure A-24. A review of the Thermocouple No. 6 data presented in Figure A-24 indicated a malfunction starting approximately 30 minutes into the test.

The measurements of cable insulation temperature are presented in Figure A-27. The maximum temperatures measured directly on the cable samples were 1,040 degrees F for the BIW sample and 804 degrees F for the EXANE sample. The sample cables emitted a relatively small amount of smoke after approximately 20 to 25 minutes. However, as in previous tests, neither cable sample showed any signs of burning or visible flame.

The Halon 1301 system was actuated at approximately 200 minutes into the test when the maximum temperatures were reached on the cable sample. The explosive valve located on the Halon supply tank responded to manual operation and the motor group enclosure rapidly filled with Halon as expected.

The result of the Halon 1301 discharge was a very rapid cooling of the temperature of the cable samples and other high temperature areas near the arc. If there had been any flaming fires within the enclosure at the time of the discharge it is highly likely that they would have been quickly extinguished. The rapid reduction in cable insulation temperature demonstrated that the effect of any glowing insulation fire was quickly counteracted by the Halon 1301.

The test was also used to evaluate detection system performance. There was a considerable difference in the temperature buildup in the enclosure for this test and other tests which were conducted at approximately similar power input levels. For example, Test No. 6 was conducted with approximately 6kw power input for the first two hours while Test No. 7 was at approximately 7kw for the first two hours. Comparing Figures A-19 and A-24 it can be seen that there was more fluctuation in the Test No. 7 temperature readings. This indicates that there was more arc instability in Test No. 7 which resulted in greater temperature fluctuations and gradients throughout the enclosure. The removal of the ceramic tiles that were used to shield the internal wiring from arc heating may have also affected the temperature distribution.

The Fenwal linear detector pre-alarm light went on at 38 minutes into the test. The highest measured temperature at that time was approximately 240 degrees F. at Thermocouple 4. The Alison Control pre-alarm light came on at 65 minutes when Thermocouple 4 had a measured temperature of approximately 255 degrees F. The response time difference between these two detector types increased from approximately 10 minutes in earlier tests to 27 minutes in this test. This change is attributable to the temperature fluctuations associated with arc instability.

The alarm signals from the Alison Control and the Fenwal spot detectors came on at 96 and 103 minutes, respectively. The set point for the Alison Control was an average sensor length temperature of 275 degrees or approximately 50 degrees F. above the pre-alarm. The set point of the spot detector was 260 degrees F. Based on these results it appears that the spot detectors were in locations which were exposed to lower temperatures due to gradients.

The conclusion from Test Number 7 was that the Halon 1301 proved to be effective in extinguishing any glowing fire in the cable insulation. In addition, the Fenwal linear detector was able to respond more quickly than the spot detectors or the Alison Control linear detector to the temperature conditions caused by arc instability.

6.5 SUMMARY RESULTS AND CONCLUSIONS OF THE LABORATORY TEST PROGRAM

This subsection provides a summary of the test results and conclusions derived from the laboratory test program. Emphasis has been placed on the test results which demonstrate the feasibility of using thermal detection and Halon 1301 for the detection and suppression of fires within enclosed compartments. Recommendations for further testing of the detection/suppression concepts are presented at the end of this subsection.

1. <u>A thermal detection system is feasible for detection of fires within the motor control group enclosure of a typical cam-controlled transit car propulsion system.</u>

Both the spot-type and the two linear-type thermal detection systems tested worked reliably on a repeated basis once they were correctly installed.

2. <u>The linear or continuous type thermal detection system is better suited to the motor control group enclosure application than the spot-type detector.</u>

The results of repeated thermal testing showed that the measured air temperature at the top of the enclosure varied widely. In some tests the average temperature of the air at the top of the enclosure was approximately 200 degrees F, but the maximum differential was approximately 100 degrees F between two thermocouple locations. These temperature differences suggest that relatively little internal air circulation is caused by the localized arc heating. The continuous thermal detector will be much more effective than spot detectors in identifying local thermal hot spots associated with power arc-induced fires or localized heating.

3. <u>The linear detection system which uses a sensor that alarms when the local temperature at any point reaches the preset level is more suitable for the motor control group enclosure application than the type that responds to the integrated average temperature along the whole sensor length.</u>

This conclusion is also based on the fact that power arcing is likely to result in localized heating of the air. The test results showed that the Fenwal sensor (point sensing) responded more quickly than the Alison Control sensor (length sensing), although the difference in response times were only significant when there were temperature fluctuations caused by arc instabilities. At the higher arc power levels that are likely in an actual transit car motor control group enclosure (under abnormal conditions) the localized heating effect and temperature differentials can be expected to be much larger. In general, it is concluded that the point response sensor will provide a faster response to a preset pre-alarm temperature under the abnormal arcing conditions that may lead to initiation of a fire.

4. <u>The electrical environment within the motor control group enclosure creates a very high level of electromagnetic interference, particularly under conditions of abnormal power arcing; therefore, any electronics associated with detection and suppression systems must be heavily shielded.</u>

The laboratory testing experience showed that normal electronic control units used in testing the detection and suppression systems did not work correctly when the power arc was on. After the electronic control units were appropriately shielded, no problem was experienced maintaining continuous reliable performance from the detection and suppression system control units.

5. <u>The thermal mass (inertia) of the representative motor control group enclosure tested was substantial, resulting in a significant time lag in the buildup of air temperature and large temperature differentials throughout the enclosure.</u>

The arc power input was generally in the range of 6 kw to approximately 15 kw At the 6-kw level, air temperatures in the enclosure were still rising after more than 2 hours (130 minutes) of virtually continuous arcing with a maximum measured temperature of about 300 degrees F. At higher power levels (averaging about 10 kw), the same trend of increasing air temperature was found after 2 hours but the maximum temperature had reached about 450 degrees F.

No experimental or other data are available on the power input associated with abnormal arcing in the motor control group enclosure under typical transit operating conditions. Such a measurement would be extremely difficult because the arc would be unstable and its position and length unpredictable. If the power level were approximately 10 times higher in the abnormal arcing situation than it was in the laboratory test program, the thermal inertia of the enclosure still would leave adequate time (on the order of several minutes) to take some action before the average enclosure temperature reached a critical level. It is expected that unstable arcs will create hot spots that could be detected rapidly by a continuous thermal detection system.

6. <u>The combined results of the slow buildup of temperature within the enclosure and the fire-resistant qualities of the newer cable insulation samples used suggest that an effective means of suppressing a fire or thermal incident is to use the detector pre-alarm signal as a means of removing electrical power from the motor control group box. This will remove the ignition source and rapidly decrease internal temperature.</u>

Examination of motor control boxes that have been damaged by fires when the car was in operational service showed substantial damage from the extremely high temperatures associated with abnormal arcing. A linear thermal detector could detect an overtemperature condition anywhere in the enclosure. Immediate removal or shutdown of power to the enclosure would extinguish the arc before substantial damage could result.

Although the purpose of the laboratory tests was directed at fire detection and suppression, the tests conducted clearly indicate that the cable insulation on the new cable samples tested are very resistant to burning and that very little smoke was visible, even after extreme heating. Placing the cable insulation very close to the arc resulted only in charring the insulation that was directly exposed to the radiant heat flux. Older cable taken from the NYCTA motor control box that was not used for testing began smoking after about 5 to 10 minutes of exposure to the arc with visible flaming occurring after another 5 minutes. The laboratory results clearly indicate the fire suppression advantage associated with use of modern formulations of cable insulation.

7. The Halon 1301 extinguishing system tested provided a complete suppression of the fire initiated within the enclosure.

The Halon 1301 system was far more effective than required to suppress the small fires that could be initiated at the end of the laboratory test series. The Halon 1301 system provides a useful backup to the proposed method of fire suppression based on removing power to the motor control group upon detection of a pre-alarm temperature.

8. The nitrogen-enriched gas generator test demonstrated that it is possible in a reasonably short time (less than two hours) to reduce the oxygen content of the air in the motor control compartment to a level which will not support combustion (less than 8 percent oxygen).

The results of the gas generator tests indicate that it is definitely feasible to develop and maintain an inerting atmosphere within the motor control group enclosure or other sealed compartment. The relatively short time period required to develop an inert atmosphere means that it would be possible to consider an operational mode where the unit is restarted whenever the transit car is to be placed in service.

An additional benefit of the nitrogen-enriched gas generator is that it maintains a constant positive pressure within the enclosure, therefore, contaminants and dirt from the ambient environment would be kept out. This factor, along with the fact that the gas supplied is filtered, dried, and very low in oxygen should help to create an environment which is conducive to low maintenance and long life for many of the electrical switches/ contacts and electronic components located within the enclosure.

The cable fire tests conducted with the lower oxygen levels produced by the nitrogen-enriched gas generator did not demonstrate any significant improvement in the damage effects on the cable insulation. This is attributed to the fact that most of the charring of the cable results from the close proximity to the intense radiation energy from the arc. It is certain that the nitrogen-enriched atmosphere would prevent propagation of any arc-induced fire beyond the immediate vicinity of the arc.

6.6 RECOMMENDATIONS

The overall results of the laboratory tests indicate that the application of a linear thermal detection system and a Halon 1301 extinguishing system will provide very satisfactory performance for fire detection and suppression within enclosed compartments such as the motor control group enclosure. The reliability of these devices should be further evaluated in field tests on transit cars.

The concept of an on-board nitrogen-enriched gas generator should be studied further. The unit used in the laboratory test was developed for aircraft application and was, therefore, relatively costly. The next step in the study of the on-board nitrogen-enriched gas generator should be a careful evaluation of the estimated acquisition and maintenance costs of a unit specifically designed for transit car installation. Once these costs are established it would be possible to conduct a cost-benefit analysis considering both fire suppression considerations and the possibility of reduced maintenance and longer life for the motor control group and other electrical/electronic equipment enclosures.

SECTION 7
PROPOSED FIELD TEST PROGRAM

7.1 INTRODUCTION

This section presents a proposed field test program for evaluation of the recommended rail transit undercar fire detection and suppression system. The specific equipment proposed for field testing includes a linear point sensing-type thermal detector coupled with a Halon 1301 suppression system. The detection and suppression system will be installed to protect the motor control group compartment using a configuration similar to the laboratory test setup. The objective of the field test program is to determine the reliability, maintainability, operational impacts, and overall cost of the proposed system based on actual transit service. The field program results, although specific to the motor control group enclosure, will also be generally applicable to other electrical equipment compartments mounted under a transit car.

The following subsections present the proposed field test program approach, selection of test fleet, installation of detection and suppression systems, test procedures, and reporting.

7.2 FIELD TEST PROGRAM APPROACH

Initially, the field test program will emphasize the performance of the linear thermal detection units. Once the reliability of the detection system has been demonstrated, field testing will concentrate on deployment of the Halon 1301 suppression system.

The following approach to the proposed field test program is presented in order of scheduled performance of test activities:

1. Run a thermal validation test on at least two motor control group enclosures to establish typical temperature profiles which can be used as a baseline for determining pre-alarm and alarm-point settings. Two cars will be equipped with thermocouples and recording devices.

2. Complete pilot testing of the recommended linear thermal detection systems before installing them on a larger scale to ensure that no basic problems exist.

3. Conduct a full-scale deployment of the recommended detection system for approximately 6 months to obtain sufficient data to predict long-term reliability and estimate the rate of false alarms.

4. Conduct a test of a combined detection/suppression concept for an additional 6 months after the detection system testing phase is completed. The recommended suppression concept is based on removal of electric power from the motor control group enclosure upon detection of a pre-alarm signal and the deployment of Halon 1301 upon sensing of an alarm signal.

7.3 SELECTION OF TEST FLEET

The proposed field test program must be described in the context of a specific transit system. This subsection provides an example of the selection of a test fleet for a motor control group fire detection and suppression test program. The example transit system is assumed to be the New York City Transit Authority (NYCTA). The example helps to illustrate some of the specific decisions which must be made in the test program development process.

The NYCTA rail transit car fleet is very large--more than 6,000 cars. The fleet contain cars of varying age, some of which are more than 25 years old. Propulsion motor control equipment also varies, but two manufacturers of those systems are dominant--General Electric and Westinghouse.

The NYCTA System Safety Department has conducted extensive statistical studies on the history of fires that originate in the motor control group enclosure. These fires are classified as Propulsion Control Equipment Fires (PCEF). The earlier studies have indicated that on a mileage-normalized basis the older cars were more prone to PCEF. Since NYCTA is continuing an extensive transit car overhaul program, many older cars are receiving completely upgraded propulsion control systems. The continuing analysis of PCEF by the System Safety Department should demonstrate the effectiveness of the overhaul program. In addition, NYCTA is devoting a substantial amount of effort to improved car maintenance, which also is expected to have a significant positive impact on PCEF.

The diversity of car designs and equipment at the NYCTA makes statistical analysis of the effects of any test program on the transit car fleet as a whole very difficult. To be effective the field test program must concentrate on the specific car classes and motor control group configurations (combination of master controller and control group) that have the poorest record of PCEF, based on the most recent statistical data.

Approximately 30 separate motor control group configurations exist; therefore, on average, approximately 200 transit cars with a particular configuration exist. Testing the detection system with three of the most PCEF-prone configurations would amount to an estimated total of 600 transit cars. A minimum sample size of 5 percent of the total, or approximately 30 detection units, is recommended for long-term testing. The field test results from 30 sample units will provide reasonable predictions of the expected reliability and performance if the entire fleet were equipped with the same units. The sample size within each motor control group category (approximately 10 units on average) will enable comparisons of performance for the same detection system in different operating environments and motor control group configurations.

Under normal operating conditions the false-alarm rate is the appropriate performance measure for the detection system. The earlier NYCTA statistical data indicated a range of 0.02 to 6.0 PCEF incidents per million miles (IPMM). For the motor control group combinations with the most serious PCEF problems, the range was approximately 2.5 to 6.0 IPMM. Assuming that this is representative of the most recent conditions, an average PCEF incidence rate of 4 per million miles can be expected. If 30 units are being tested and the transit cars are accumulating approximately 45,000 miles per year, the estimated mileage after 6 months of operation is 675,000 miles. Thus, we could expect two or three PCEFs to occur on the field-test fleet if the random sampling selection procedure yielded a representative sample.

It would be useful to increase the expected number of PCEFs by selecting those cars whose individual histories showed them to be more trouble-prone. NYCTA maintains a computerized record of the maintenance history on each car from which it should be relatively easy to identify cars with an above-average PCEF record.

The cars selected for field testing on either a random or targeted basis should not include any car class scheduled to be retired within the next three to four years. Although such cars are likely to be at the top of the list in PCEFs, the results of the detection-system tests in such an operating environment may not be applicable to the other transit cars which will remain in service.

7.4 INSTALLATION OF DETECTION AND SUPPRESSION SYSTEMS

The initial installation will consist of two pilot cars that are selected for thermal validation and initial installation of the recommended detection system. The motor control group enclosures of the two pilot cars will be equipped with thermocouples and recording devices to establish the typical temperature profiles within the enclosure. Temperature measurements will be augmented by the placement of temperature monitoring patches, which permanently change color upon reaching certain preset temperature levels, within the enclosure.

The pilot testing phase of the field test program will last for a period of approximately one month. The data to be collected during this period include the thermocouple readings and periodic inspection of the linear thermal detection system to ensure that it is functioning properly.

After the pilot test has proven successful, full scale field test deployment of the recommended detection system will take place. This will involve installation of linear detection systems on an additional 28 cars. The pre-alarm and alarm temperature settings for these linear detection systems will be established from the temperature profile data collected during the pilot testing phase.

Setting the pre-alarm and alarm temperatures correctly for the detection system is very important. As noted earlier, the pilot tests will determine the normal operating temperature profile within the enclosure during revenue service. Based on the results of data from other research programs, such as the PATH Motor Controller Investigation (Reference 7), normal operating temperatures are expected to be approximately 50 degrees F above ambient temperature. It is recommended that the initial pre-alarm setting tested be approximately 100 degrees F. above the expected maximum normal temperature, based on the expected maximum ambient temperature during a 1-year test. Assuming that the maximum ambient temperature is 100 degrees F, the normal operating temperature would be 150 degrees F and the pre-alarm setting would be 250 degrees F. The alarm setting should be approximately 100 to 150 degrees F higher than the pre-alarm setting.

After the 6 month reliability test period for the detection system has been completed, a test of the recommended suppression concept will begin for another 6 month period. It is recommended that all 30 test cars be equipped to remove electrical power to the motor control group automatically when a pre-alarm signal is received from the detection system. The test car then should function as a neutral or "free wheeling" car within the train, with all auxiliary power and control signal functions available for normal operating service. The Halon 1301 suppression system will be installed at the same time with provision for deployment upon sensing of an alarm temperature signal from the detection system. It is recommended that the release of the Halon 1301 be triggered automatically from the alarm signal.

7.5 INSPECTION AND REPORTING

For the detection-only system tests, it is recommended that a visual display of both the pre-alarm and the alarm signals be provided on the motorman's control panel, if feasible, or on the exterior side of the transit car so that it is readily visible to the conductor. A means should be provided to count the number of times the pre-alarm and alarm signals are activated as an independent means of checking on the observations of the operating personnel. No recommendation is made that any action be taken when the pre-alarm signal is activated unless it is accompanied by other visible evidence of a serious problem with the test car.

The frequency of any thermal incident that would activate the pre-alarm signal is expected to be very small as noted earlier. Therefore, at least initially, it is recommended that any car that gives a pre-alarm signal be visually inspected at the earliest practical opportunity to determine whether any evidence of overheating or severe arcing is apparent. If the car gives repeated pre-alarm signals for no apparent reason, it should be removed from service as early as possible to determine the cause.

If the pre-alarm sensor provides numerous indications of an over temperature condition but no evidence of damage is apparent on inspection, it may be necessary to increase the pre-alarm temperature by 50 degrees F. If subsequent testing demonstrates that a problem with the pre-alarm indication still exists, the detection unit probably is providing false alarm signals. This conclusion could be verified by maintaining the two instrumented cars (with thermocouples in the motor control group) in a status where additional tests could be conducted to verify any potential problems with false alarms.

The detection system will be tested in combination with the power cutoff/Halon 1301 suppression system using the same 30 test cars. The display setup will remain the same with visible indicators for both the pre-alarm and the alarm sensor signals. It is proposed that this test will be conducted over a 6-month period. At least three PCEF incidents during that time period can be expected, based on a random sampling approach and the assumed PCEF incidence rate noted in earlier NYCTA statistical reports.

7.6 FIELD TEST PROCEDURES

The most important parts of the field test program are the measurement of reliability and maintainability. The development of procedures to measure these factors must be incorporated into the test plan. The procedure for measuring reliability of the detection/suppression system will involve a means for counting the number of false alarms (pre-alarms or full alarms). A false alarm is defined as the actuation of a pre-alarm or alarm signal in the absence of any thermal incidents. The only means of detecting a false alarm condition is to conduct an inspection of the motor control group unit that has alarmed. Temperature monitoring patches placed within the enclosure will help to verify the existence of pre-alarm or alarm temperatures.

The specific criteria used to measure reliability will be false alarm incidents per million car miles. The maximum acceptable range of false alarm incidents will depend upon the specific requirements of the transit system. For a typical transit car which accumulates approximately 50,000 miles per year, a rate of one incident per million miles would average out to one false alarm every twenty years. In the very largest transit systems, such as in New York City, this rate would result in one false alarm per day because the fleet mileage each day is on the order of one million miles. The reliability calculated from the detection/suppression tests must be used by individual transit systems to make their own judgements of an acceptable rate of false alarms.

The maintainability of the detection/suppression system will be measured in terms of labor hours of maintenance personnel required for inspection and servicing. The linear thermal detection and Halon 1301 suppression system units do not have any moving parts, therefore, minimal conventional maintenance required. The electronic control systems on the detection/suppression units also have their own "problem" indicator lights which simplify the inspection process. There is no reason to expect that there will be a significant maintenance effort for the recommended detection/ suppression system. A record should be kept of the maintenance actions and level of efforts associated with each unit. The maintainability measure will be the level of maintenance effort per unit per year. Transit systems can then apply their own judgement regarding the balance between maintenance labor costs and the value of an on-board fire detection and suppression system.

APPENDIX A

POWER-LEVEL AND TEMPERATURE-READING GRAPHS OF LABORATORY TEST RESULTS

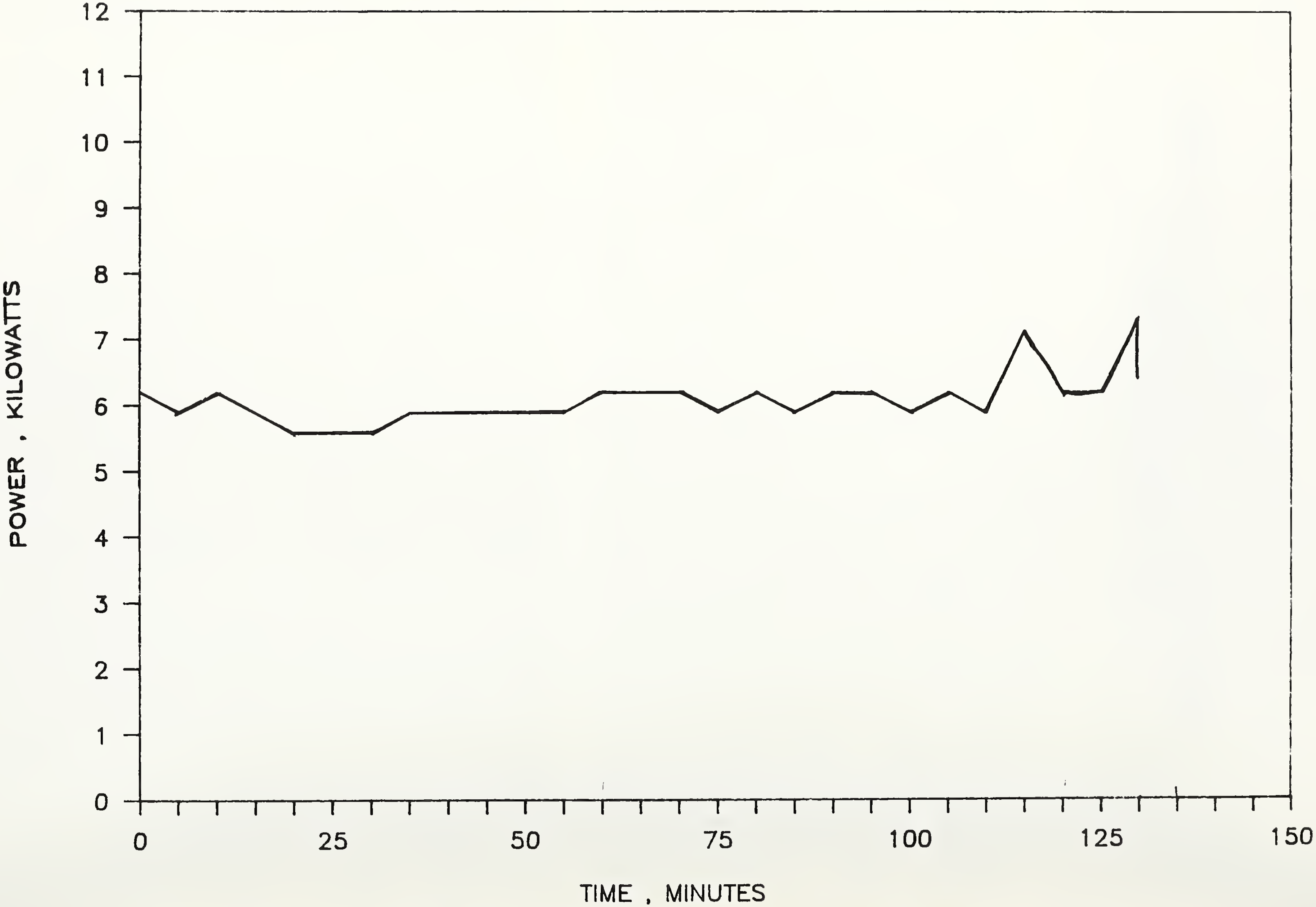

FIGURE A-1. TEST NUMBER 1, POWER LEVEL

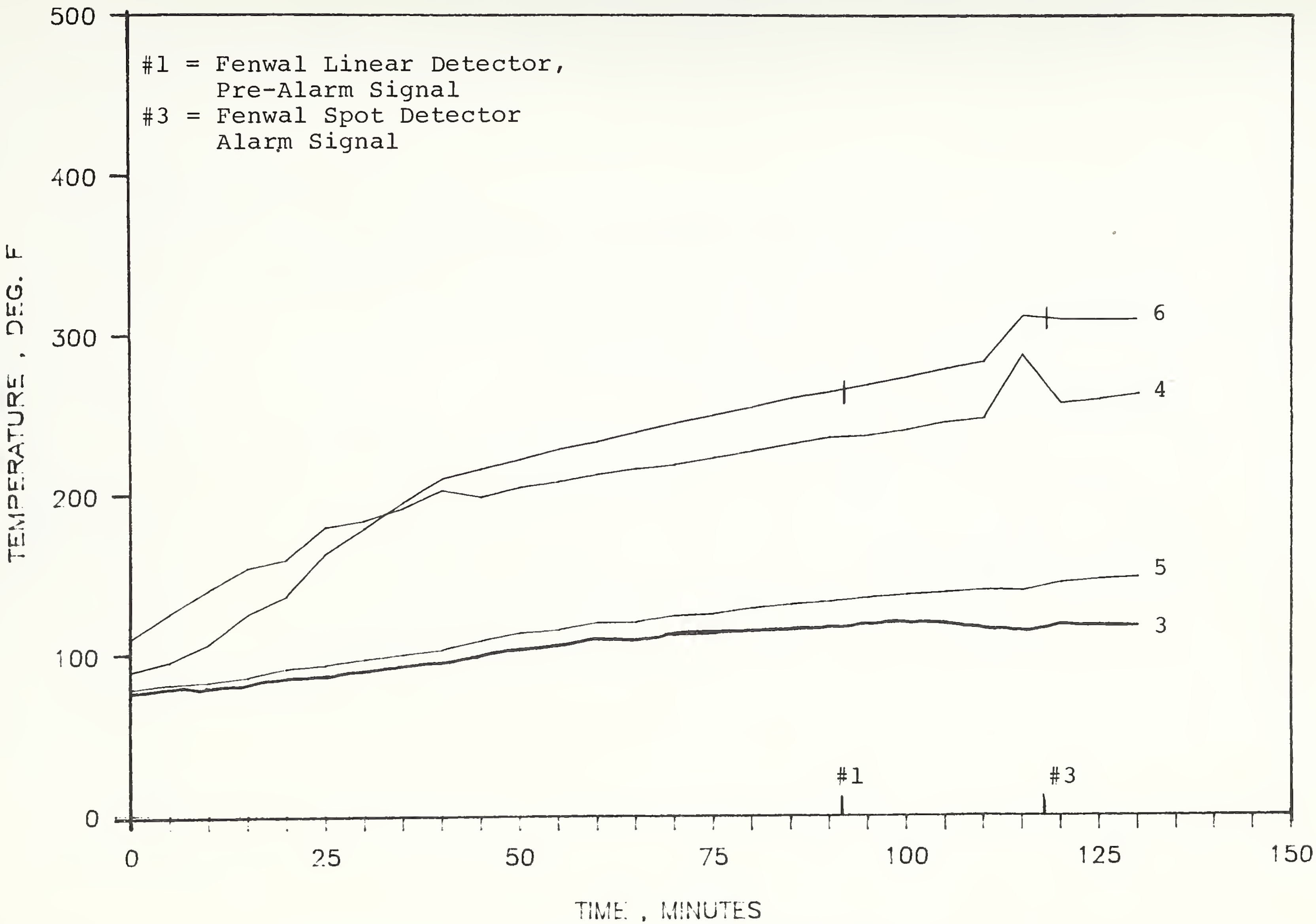

FIGURE A-2. TEST NUMBER 1, THERMOCOUPLES 3, 4, 5, 6

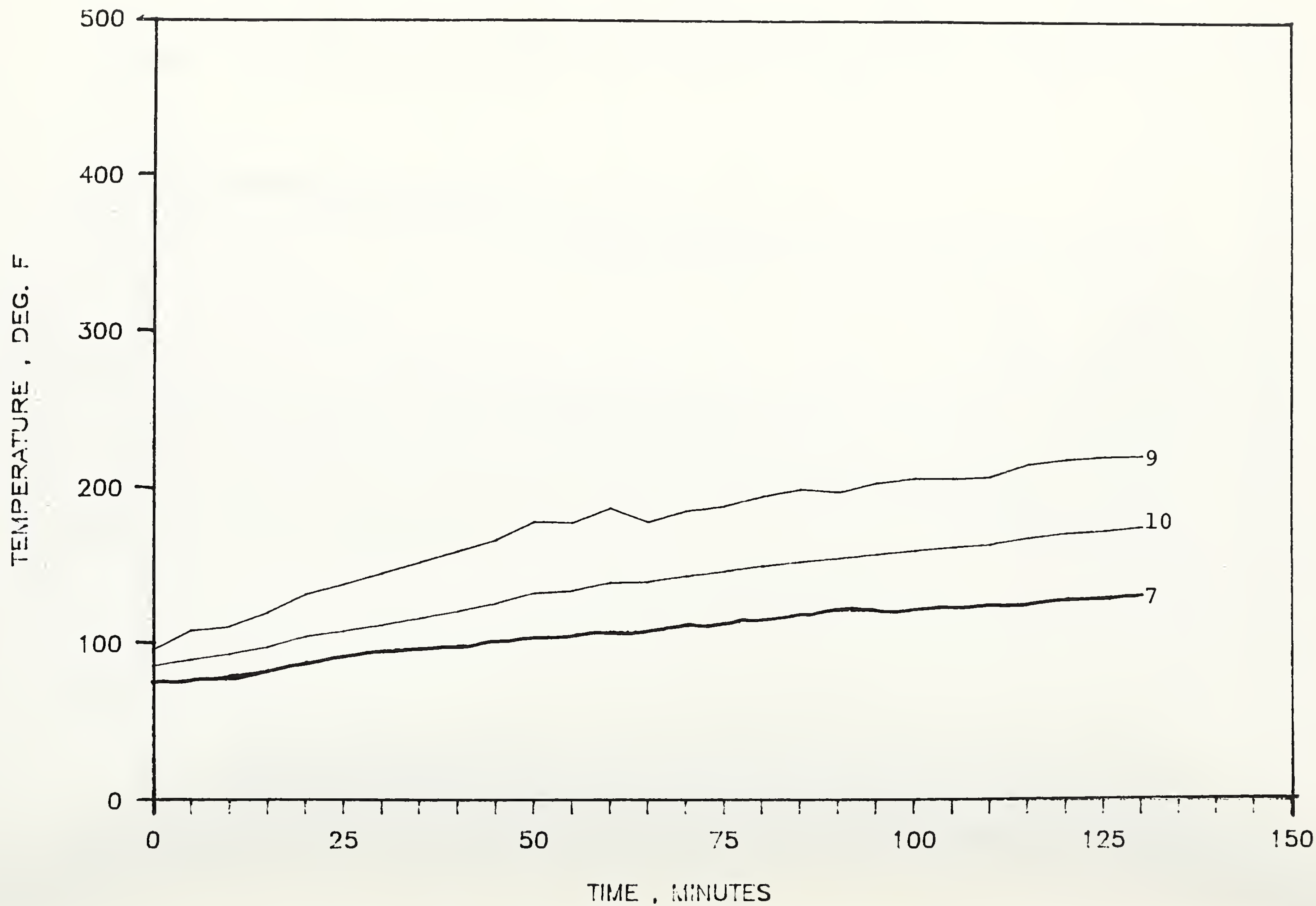

FIGURE A-3. TEST NUMBER 1, THERMOCOUPLES 7, 9, 10

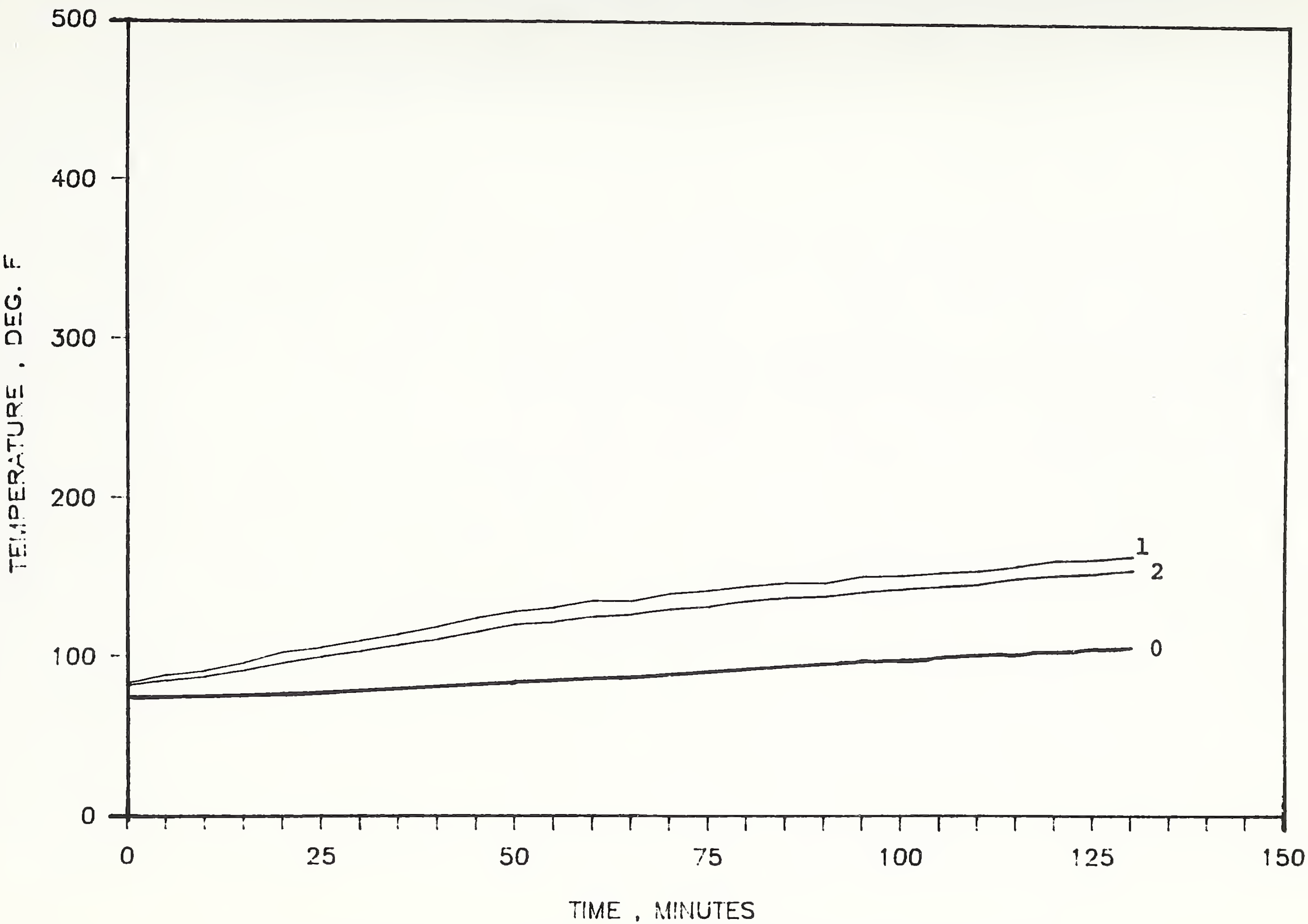

FIGURE A-4. TEST NUMBER 1, THERMOCOUPLES 0, 1, 2

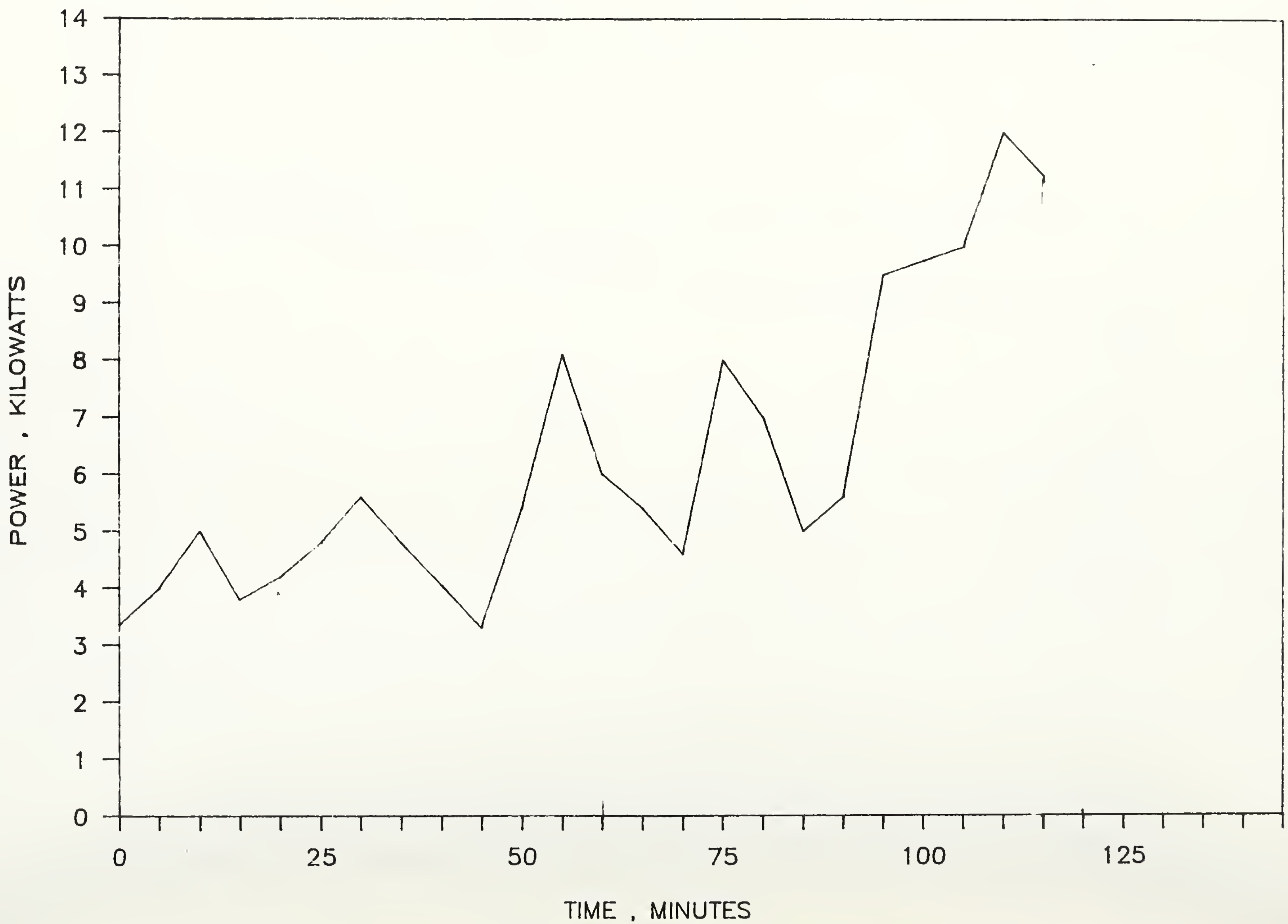

FIGURE A-5. TEST NUMBER 3, POWER LEVEL

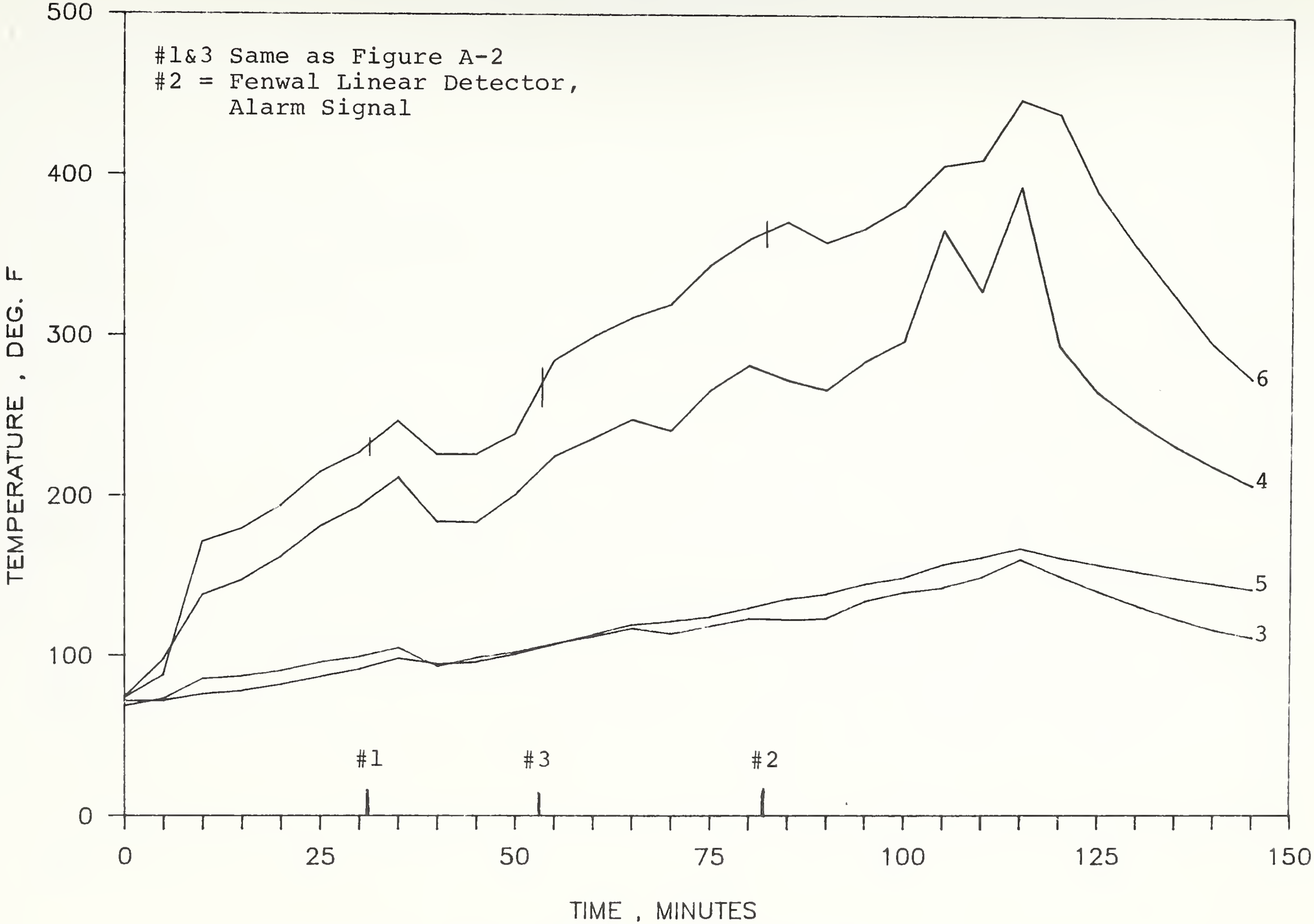

FIGURE A-6. TEST NUMBER 3, THERMOCOUPLES 3, 4, 5,6

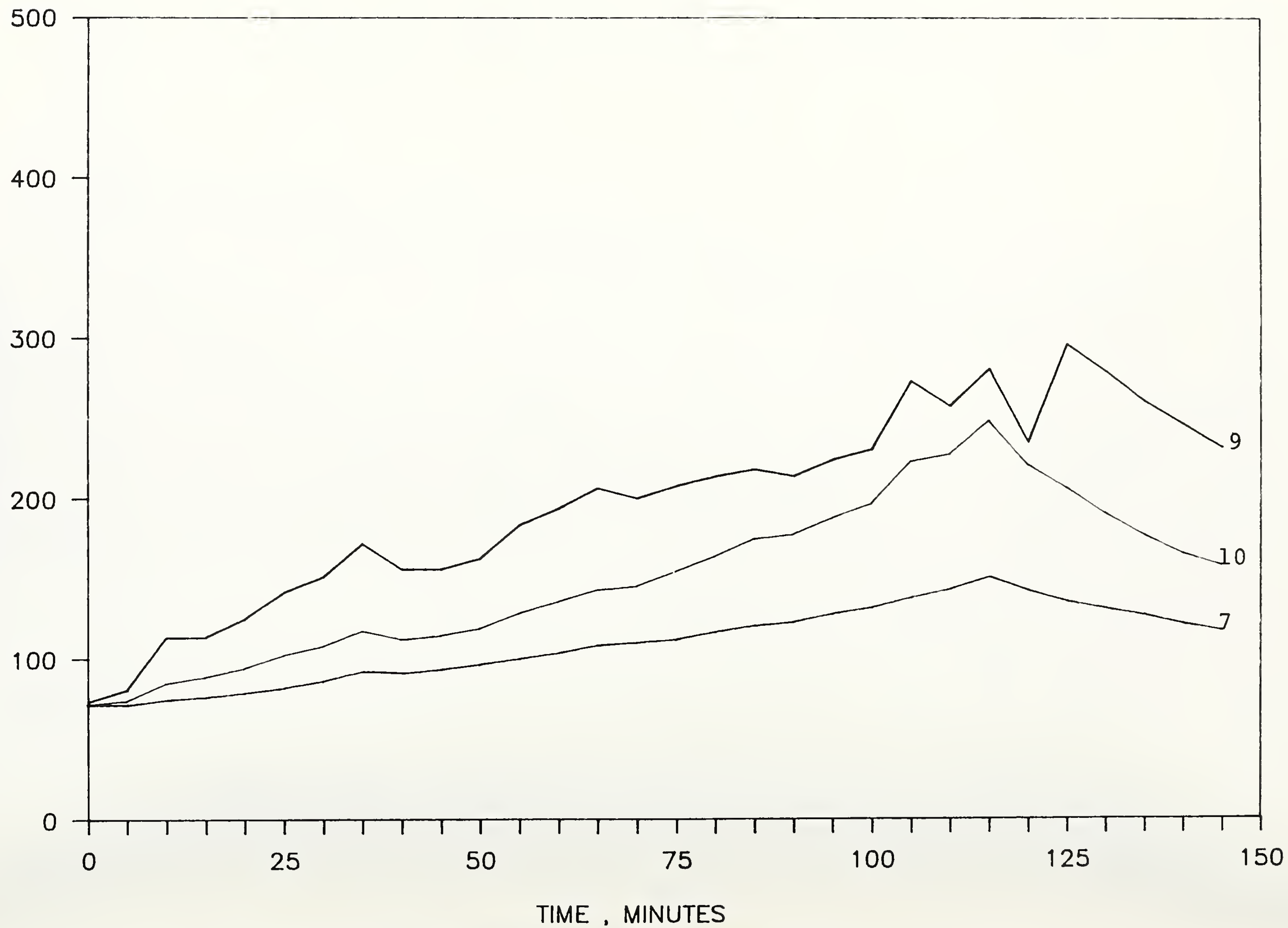

FIGURE A-7. TEST NUMBER 3, THERMOCOUPLES 7, 9, 10

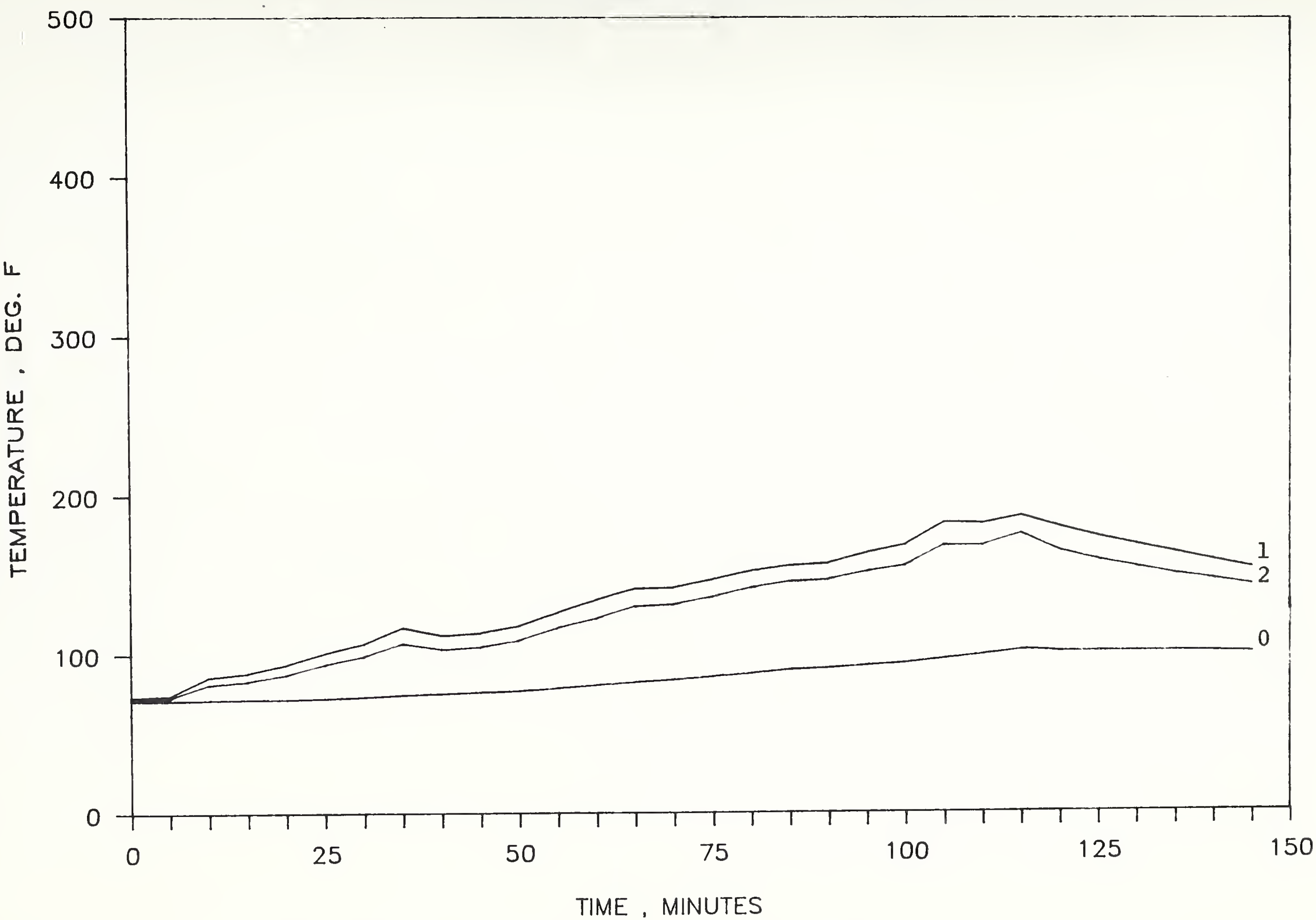

FIGURE A-8. TEST NUMBER 3, THERMOCOUPLES 0, 1, 2

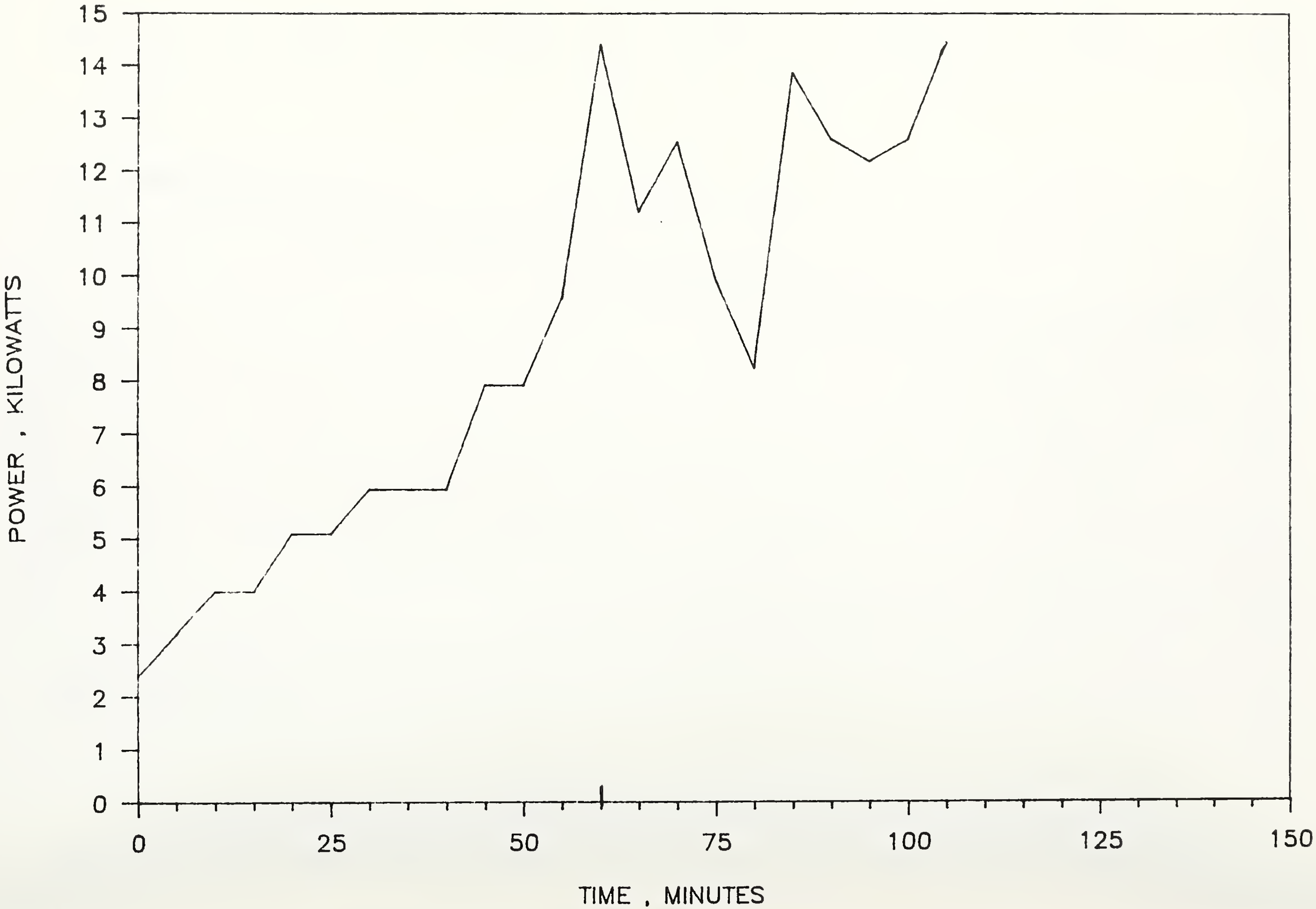

FIGURE A-9. TEST NUMBER 4, POWER LEVEL

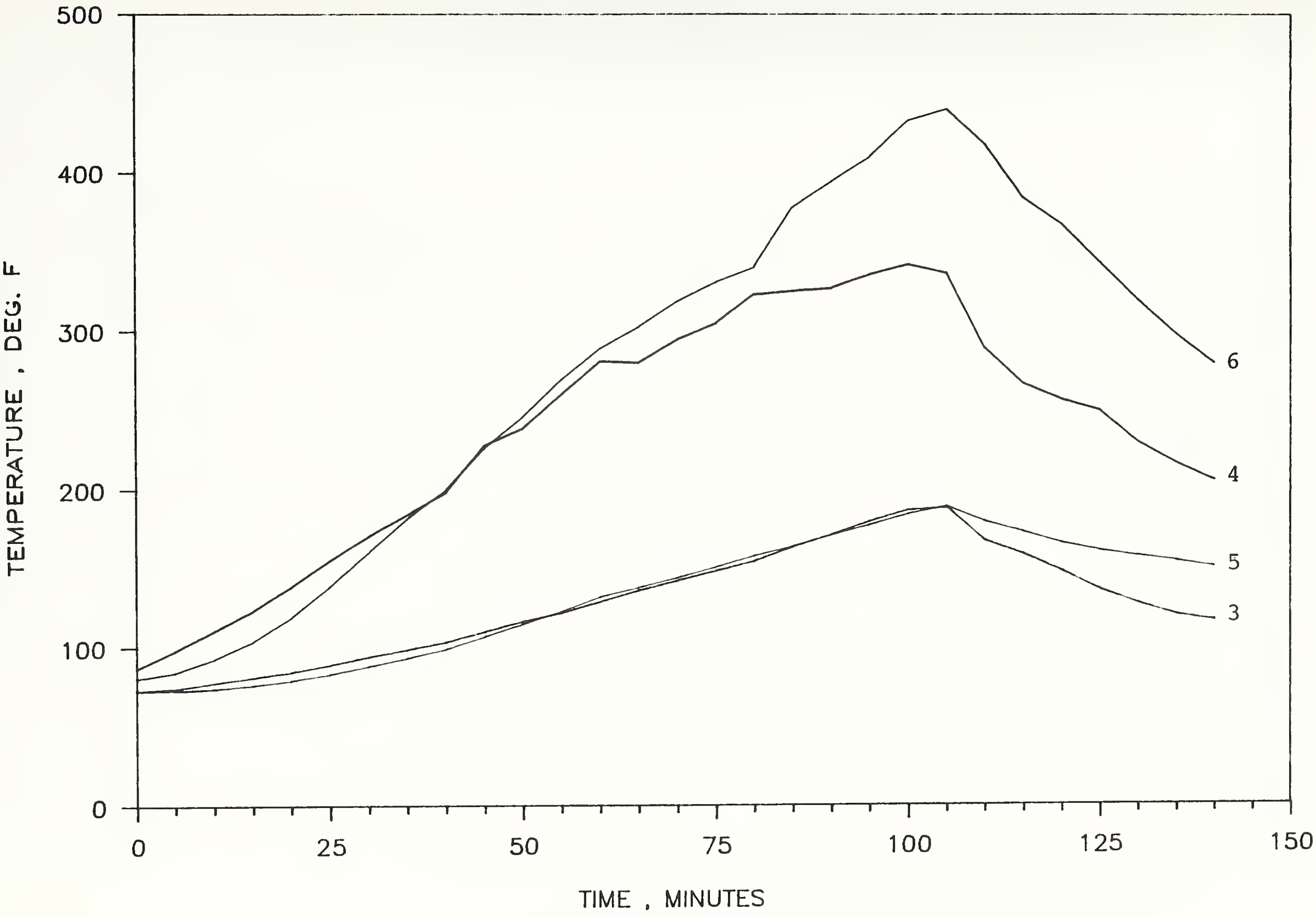

FIGURE A-10. TEST NUMBER 4, THERMOCOUPLES 3, 4, 5, 6

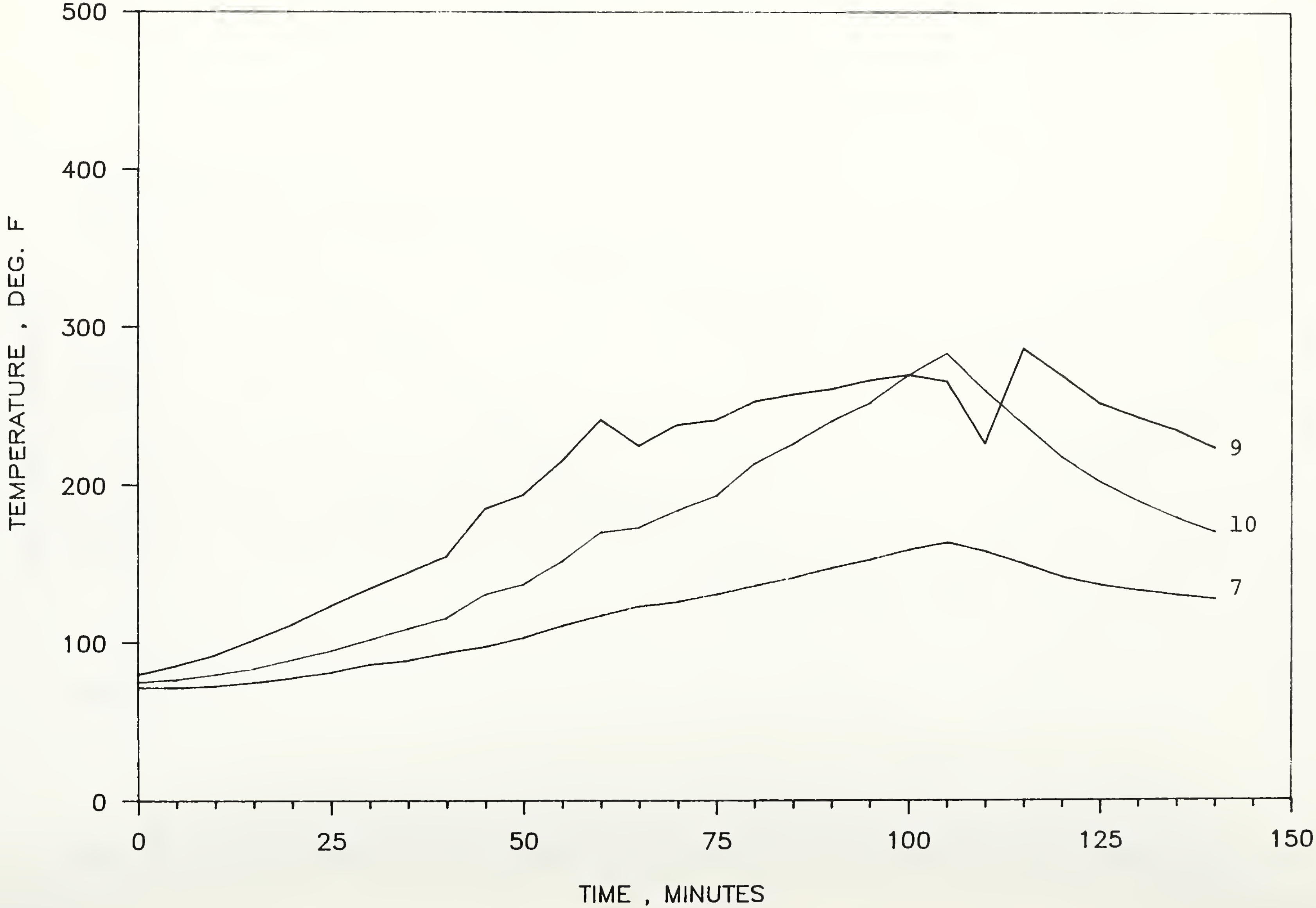

FIGURE A-11. TEST NUMBER 4, THERMOCOUPLES 7, 9, 10

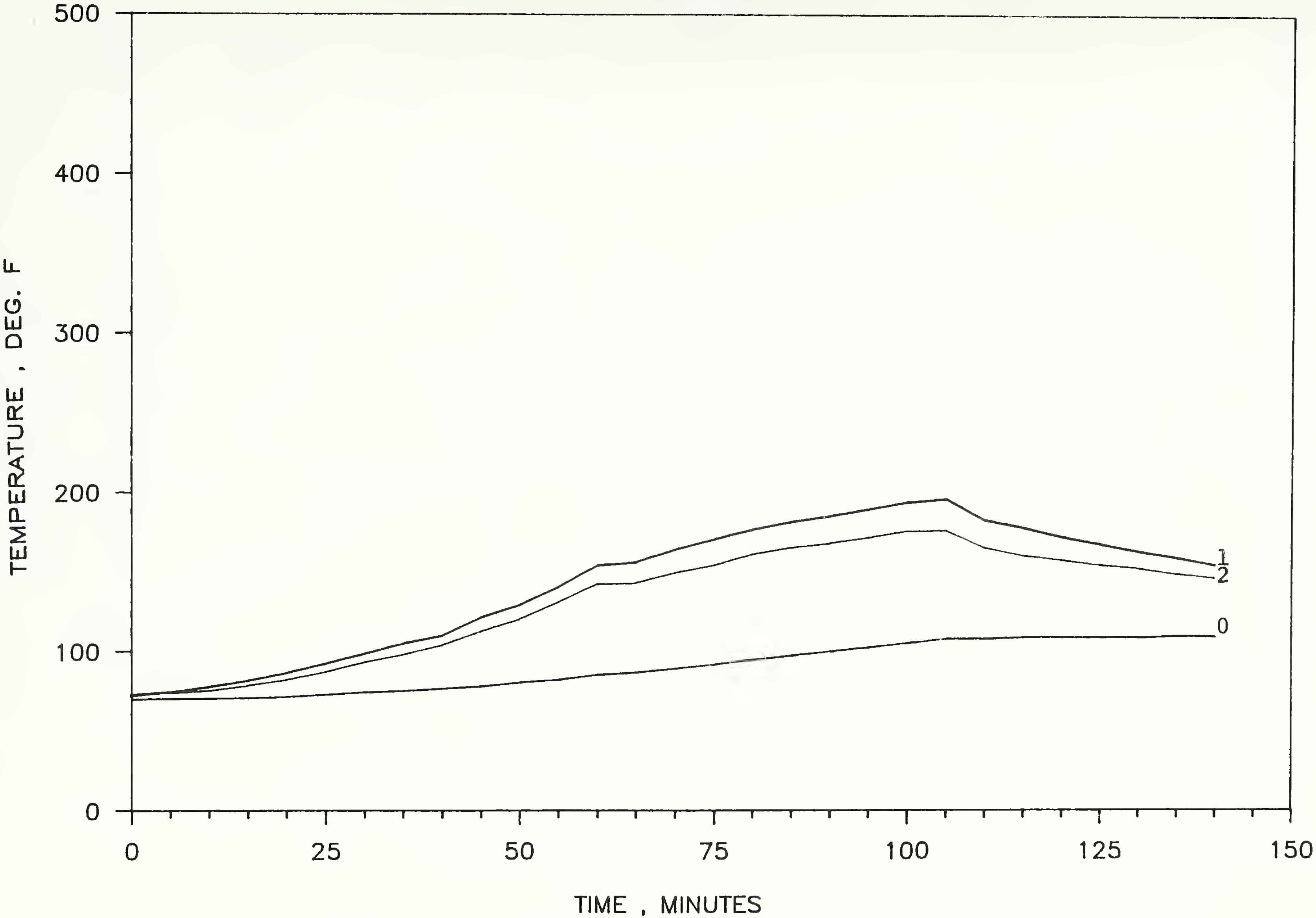

FIGURE A-12. TEST NUMBER 4, THERMOCOUPLES 0, 1, 2

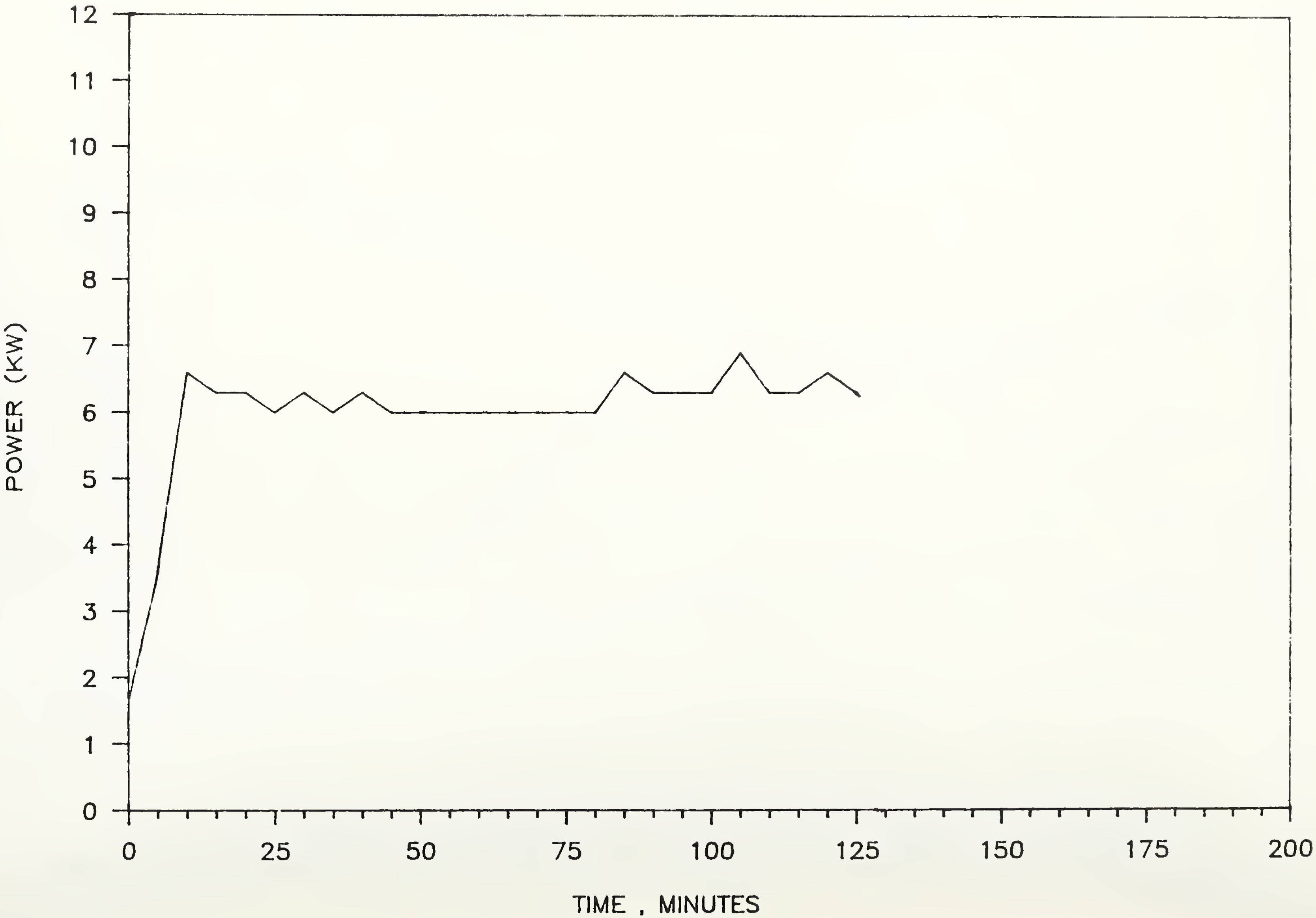

FIGURE A-13. TEST NUMBER 5, POWER LEVEL

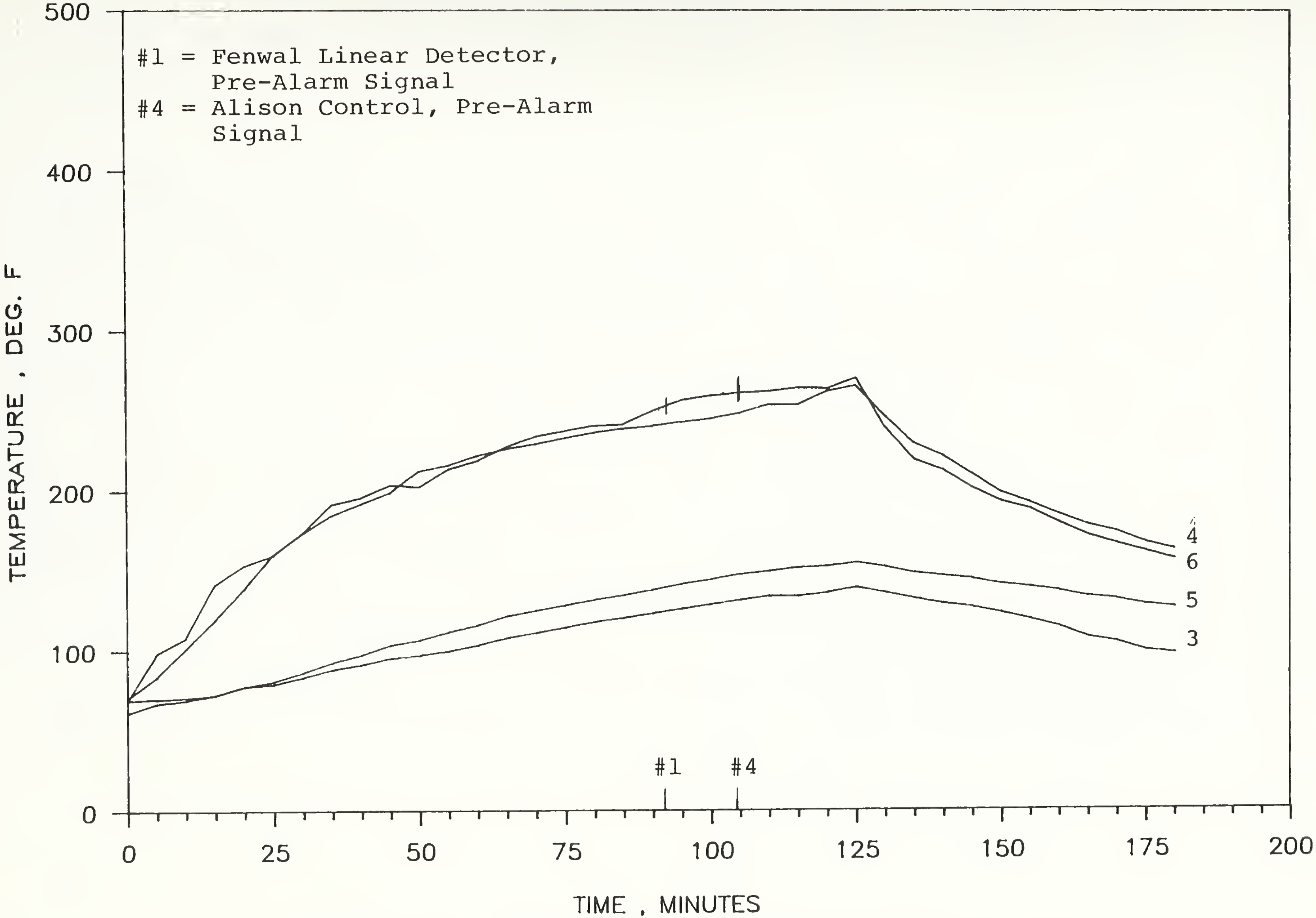

FIGURE A-14. TEST NUMBER 5, THERMOCOUPLES 3, 4, 5, 6

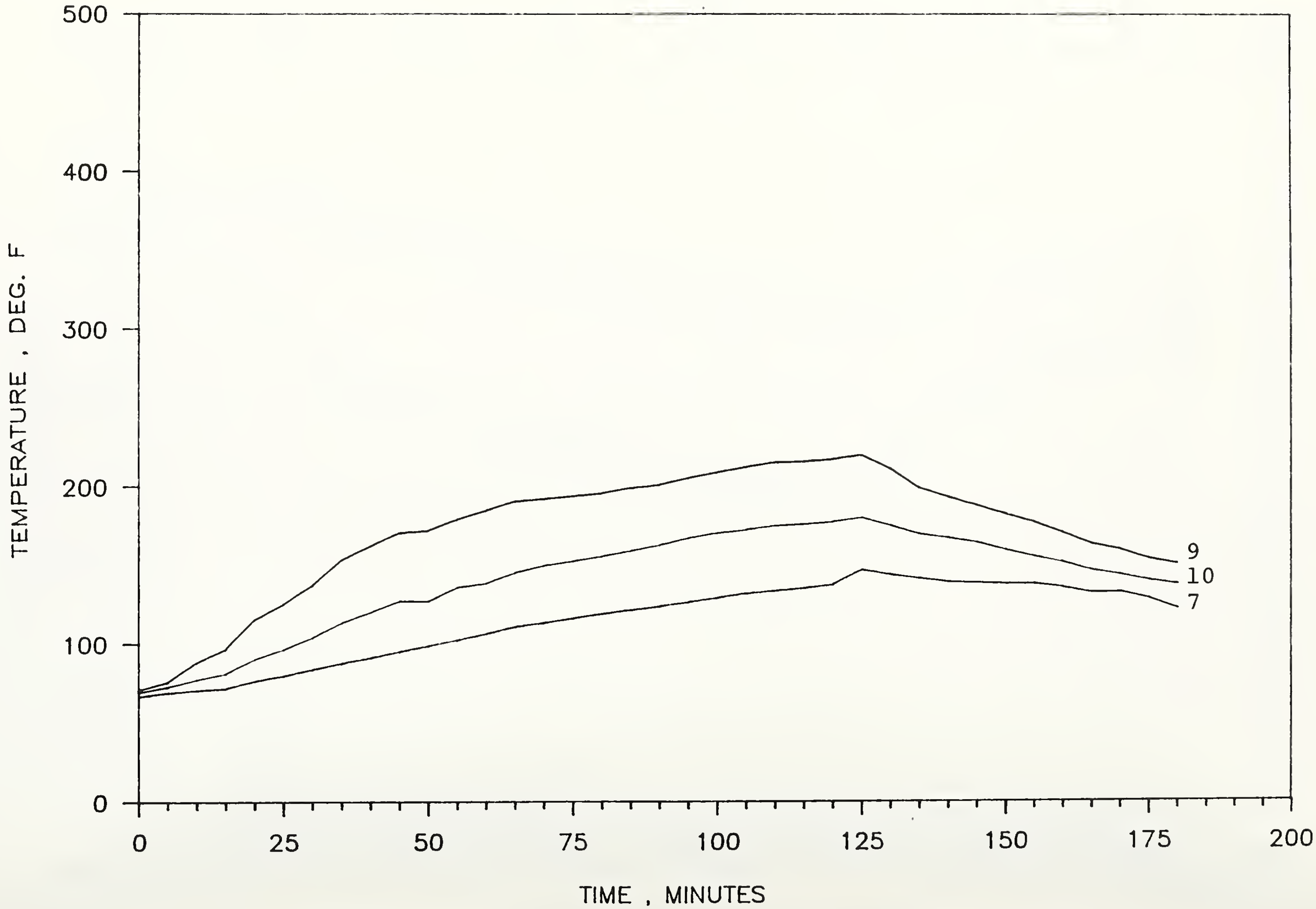

FIGURE A-15. TEST NUMBER 5, THERMOCOUPLES 7, 9, 10

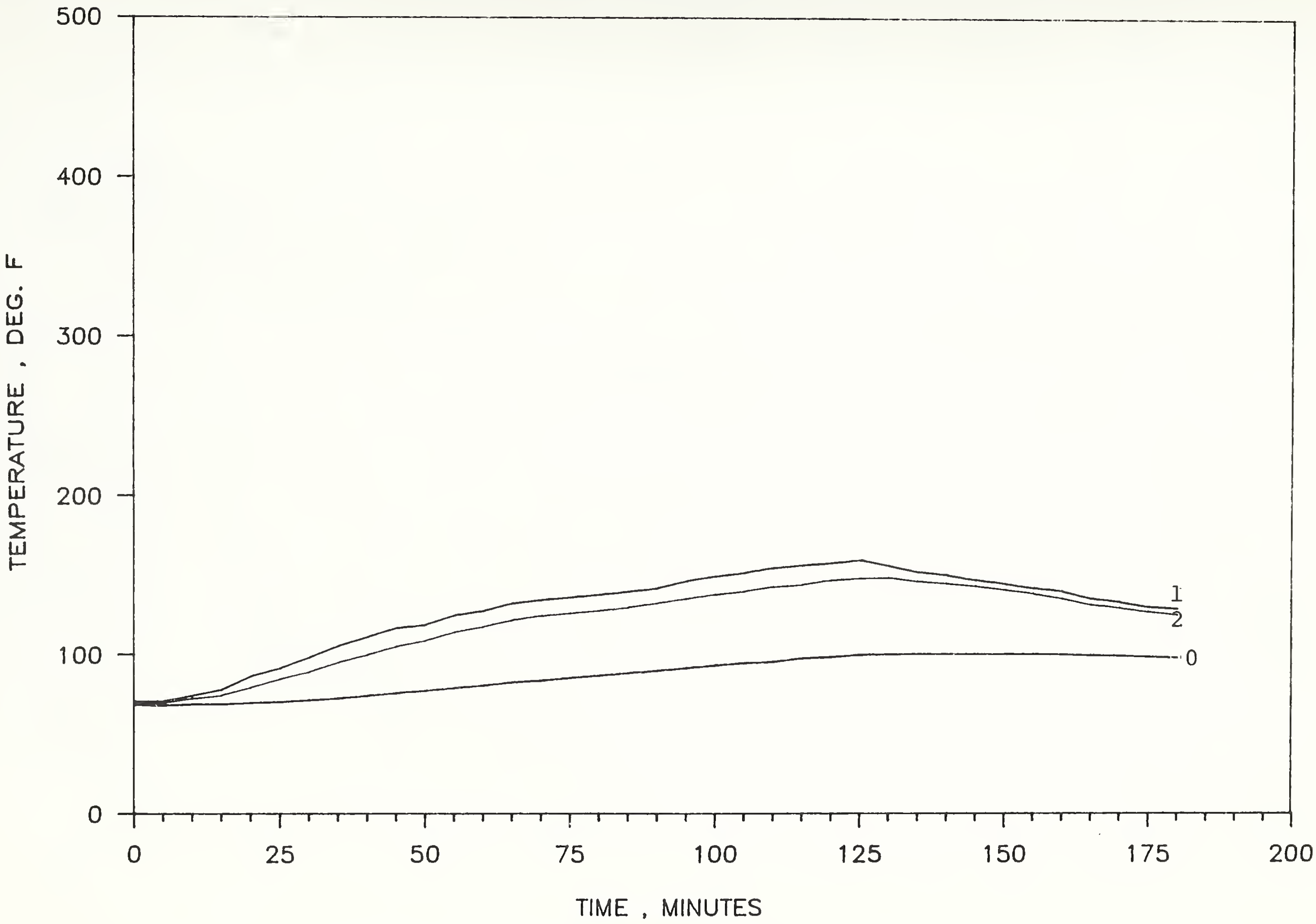

FIGURE A-16. TEST NUMBER 5, THERMOCOUPLES 0, 1, 2

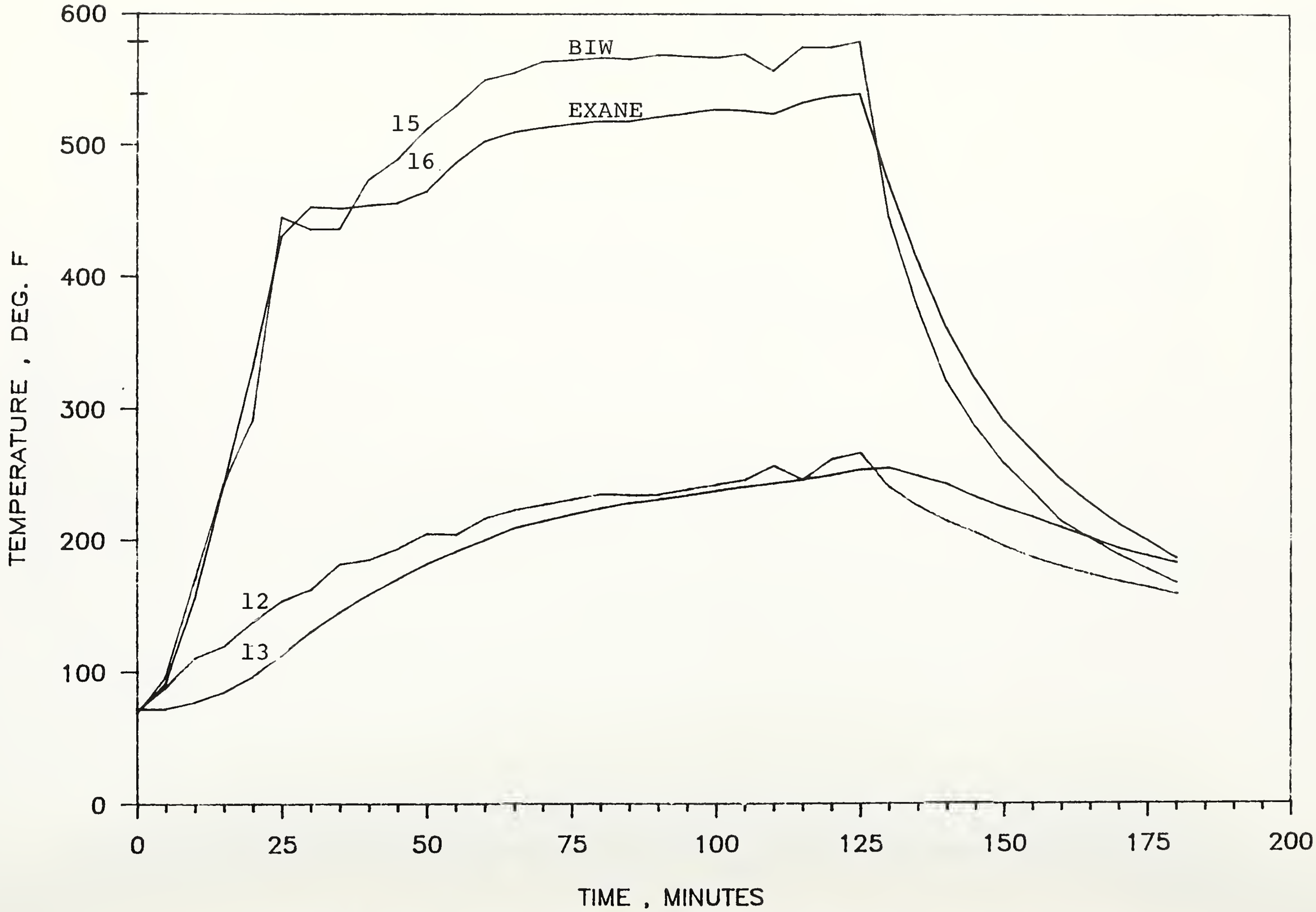

FIGURE A-17. TEST NUMBER 5, THERMOCOUPLES 12, 13, 15, 16

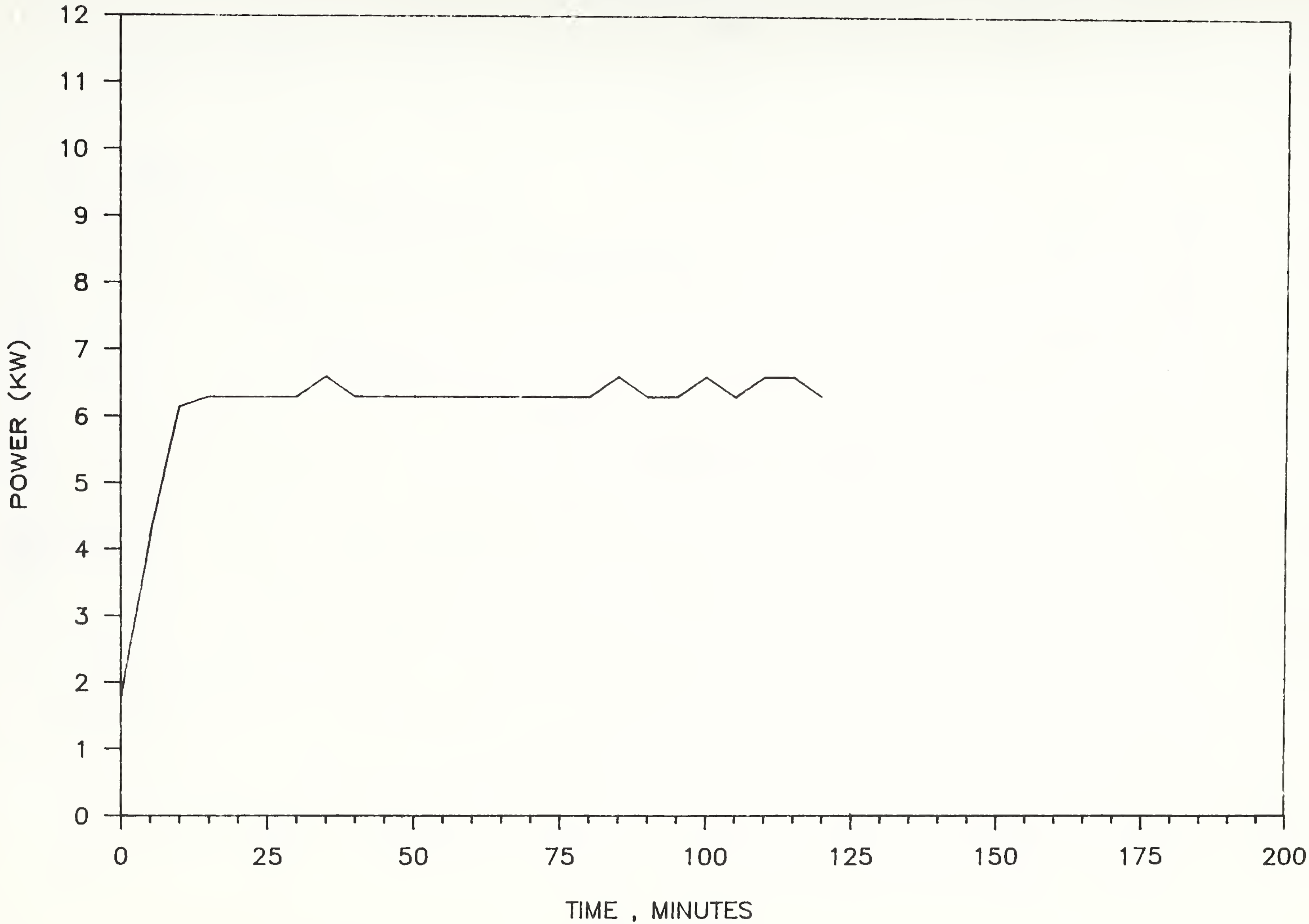

FIGURE A-18. TEST NUMBER 6, POWER LEVEL

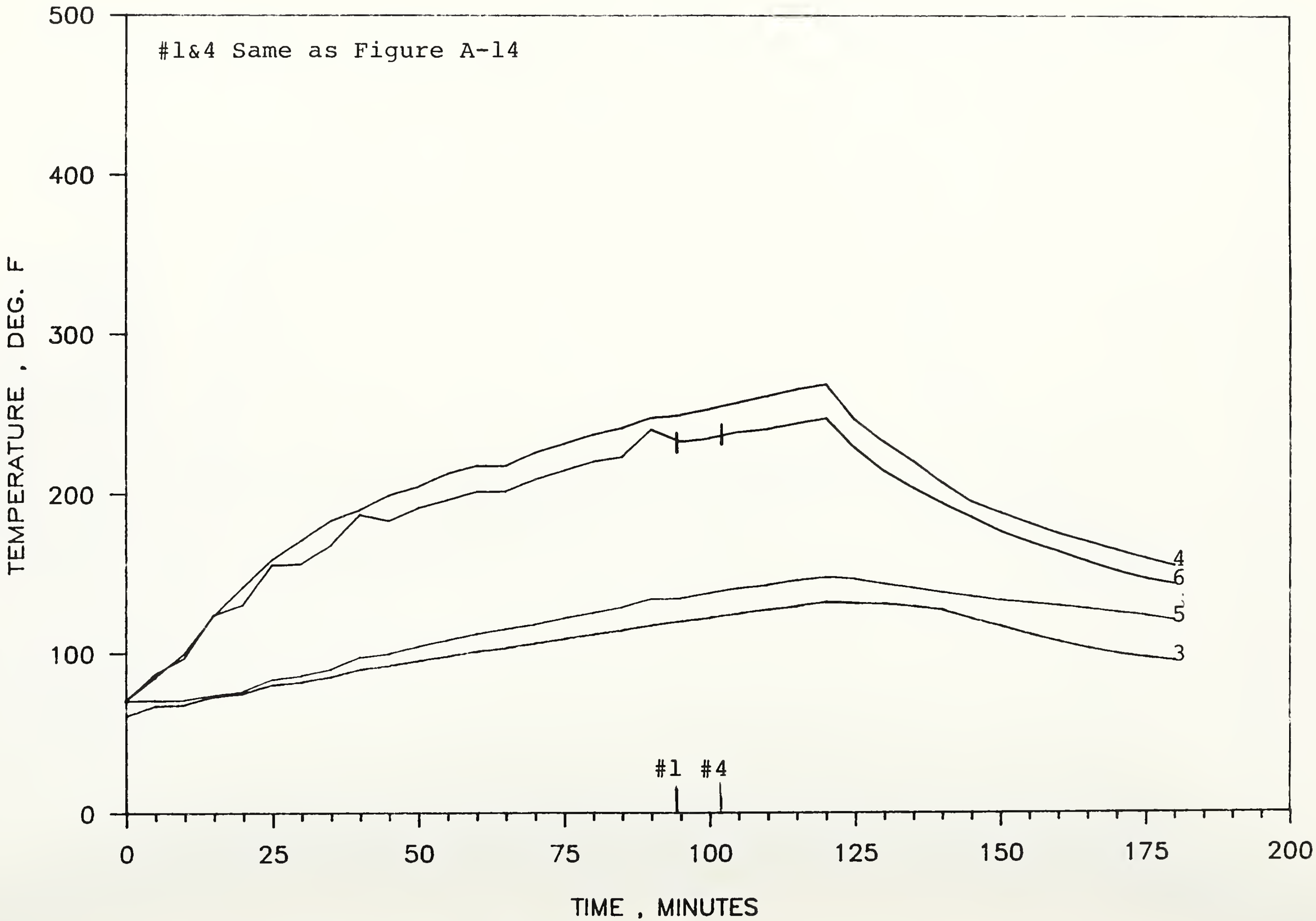

FIGURE A-19. TEST NUMBER 6, THERMOCOUPLES 3, 4, 5, 6

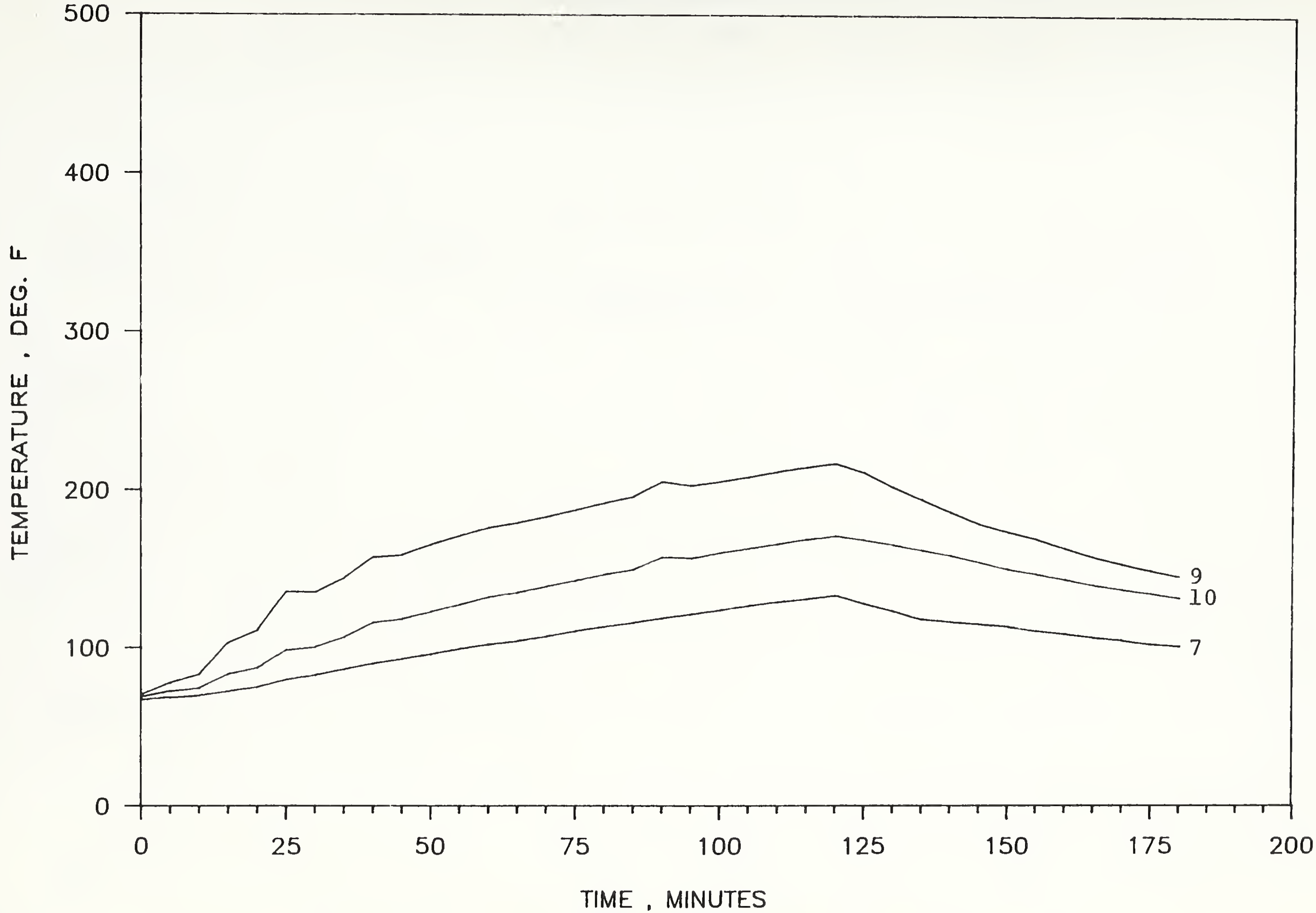

FIGURE A-20. TEST NUMBER 6, THERMOCOUPLES 7, 9, 10

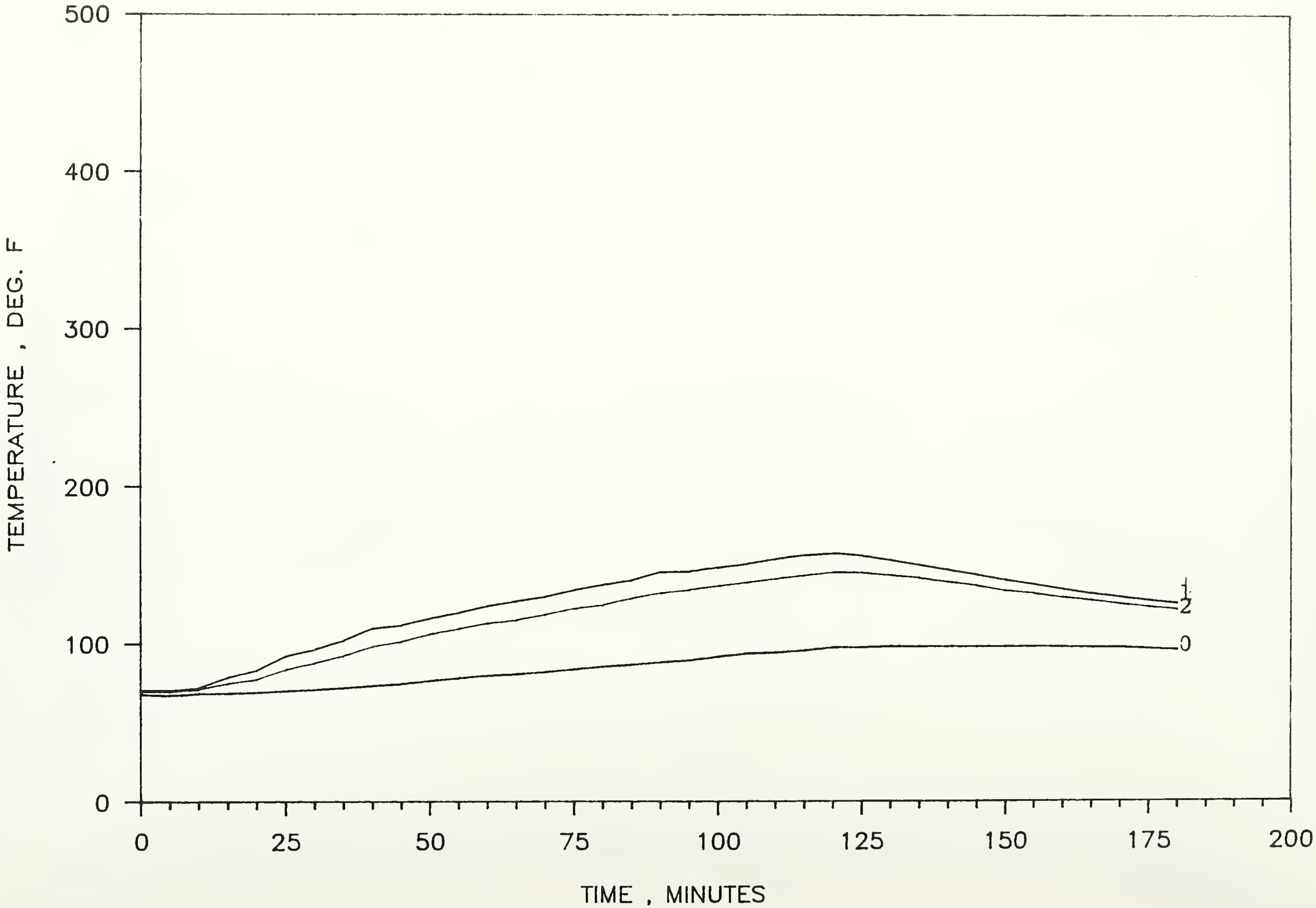

FIGURE A-21. TEST NUMBER 6, THERMOCOUPLES 0, 1, 2

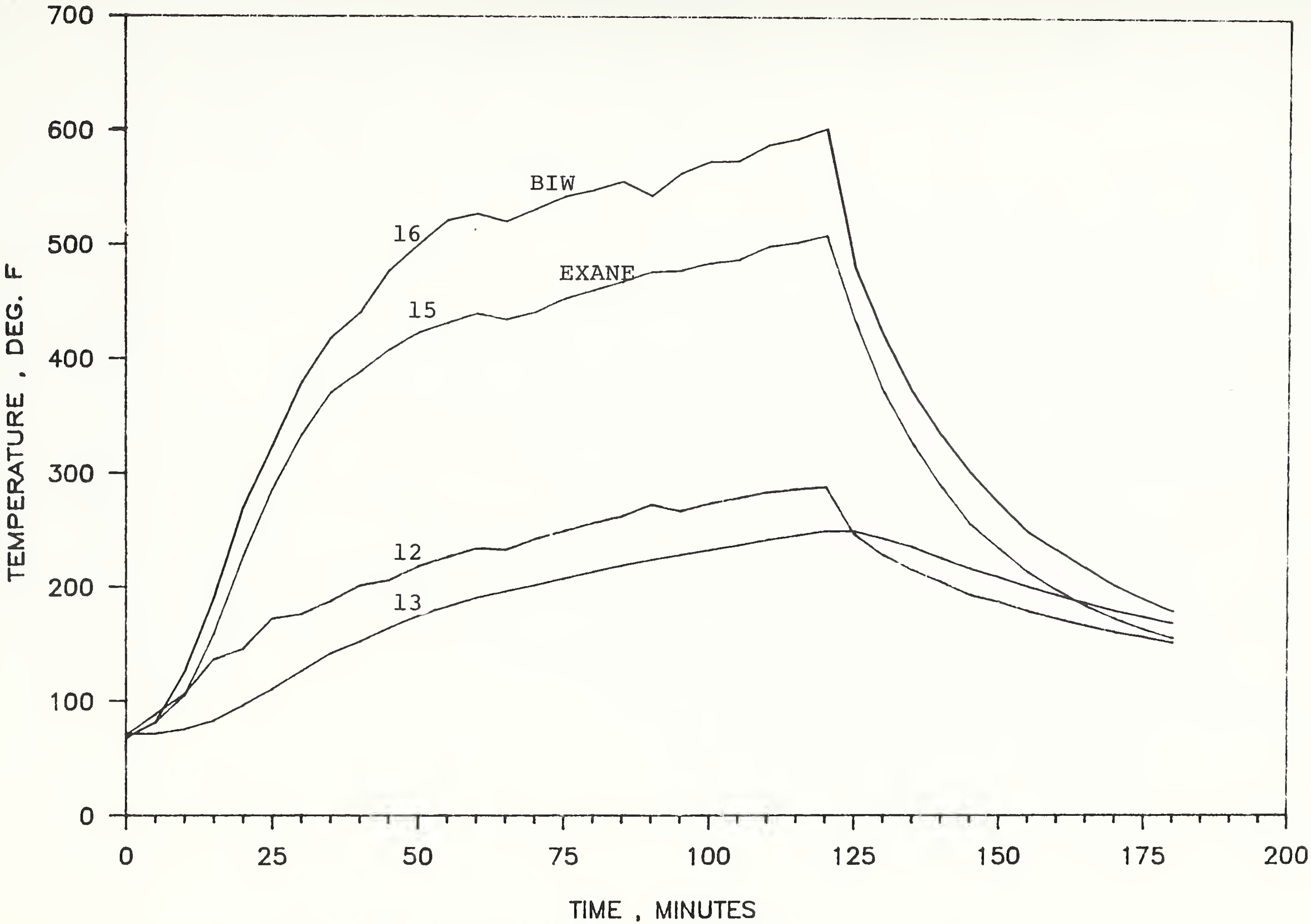

FIGURE A-22. TEST NUMBER 6, THERMOCOUPLES 12, 13, 15, 16

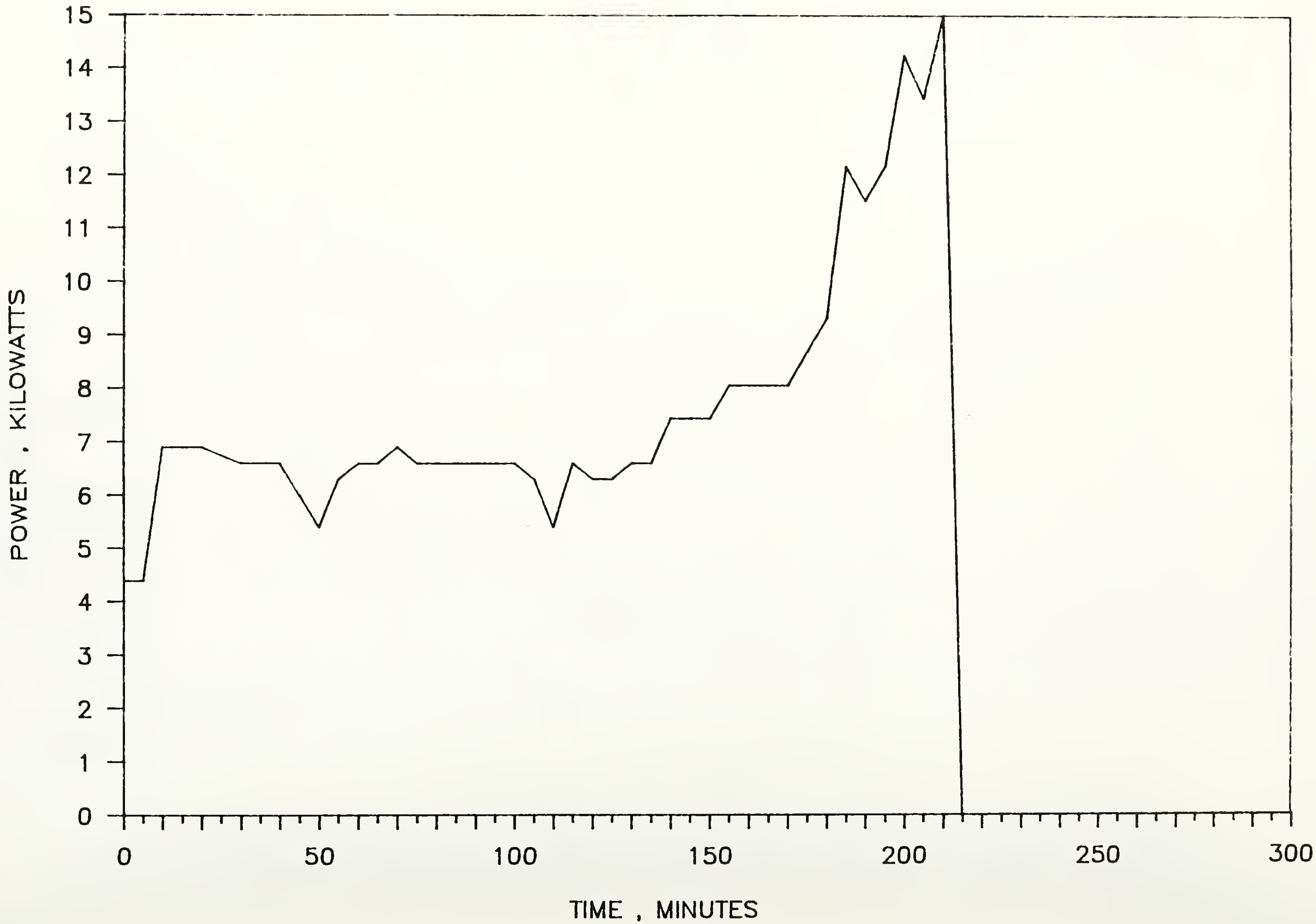

FIGURE A-23. TEST NUMBER 7, POWER LEVEL

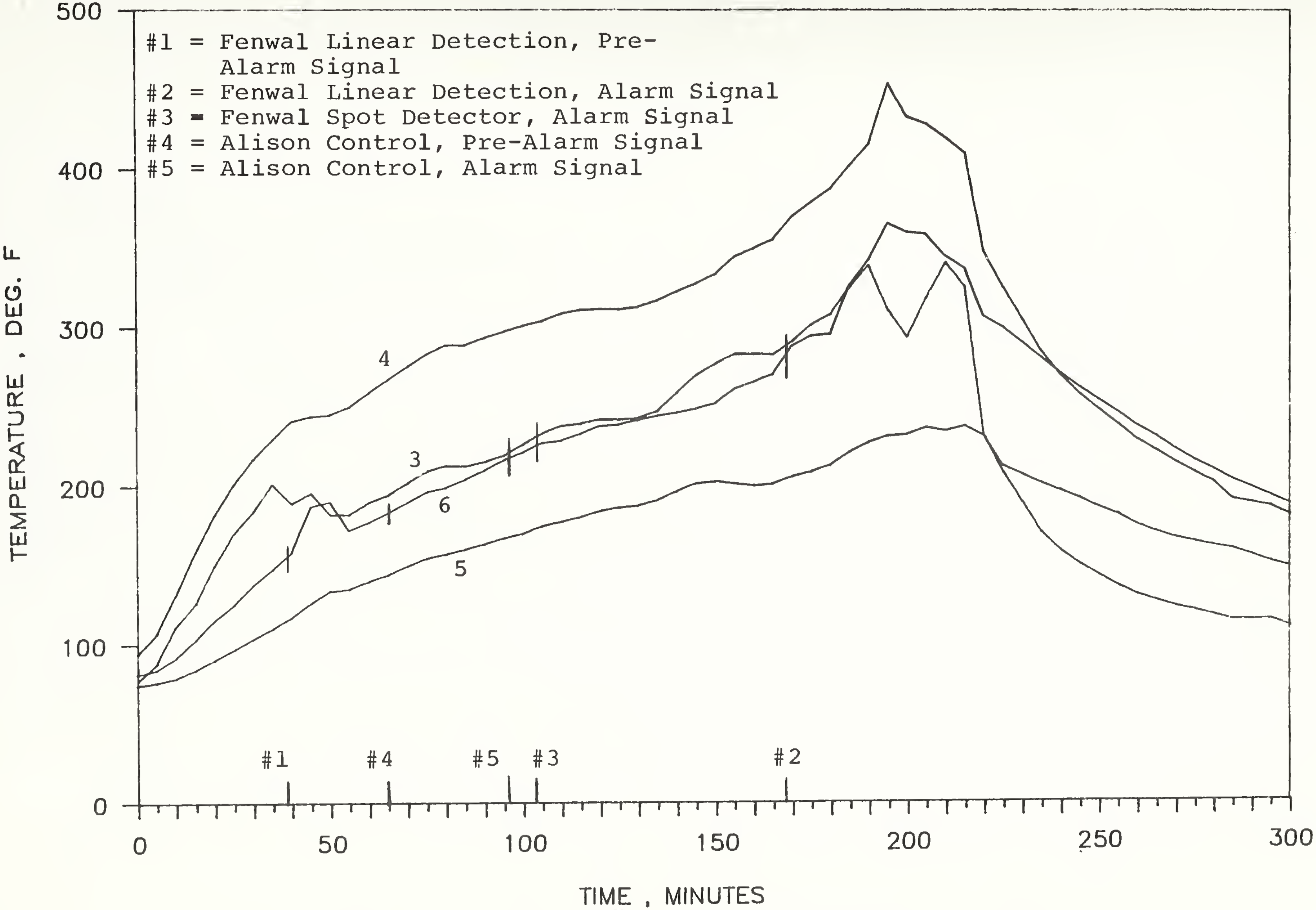

FIGURE A-24. TEST NUMBER 7, THERMOCOUPLES 3, 4, 5, 6

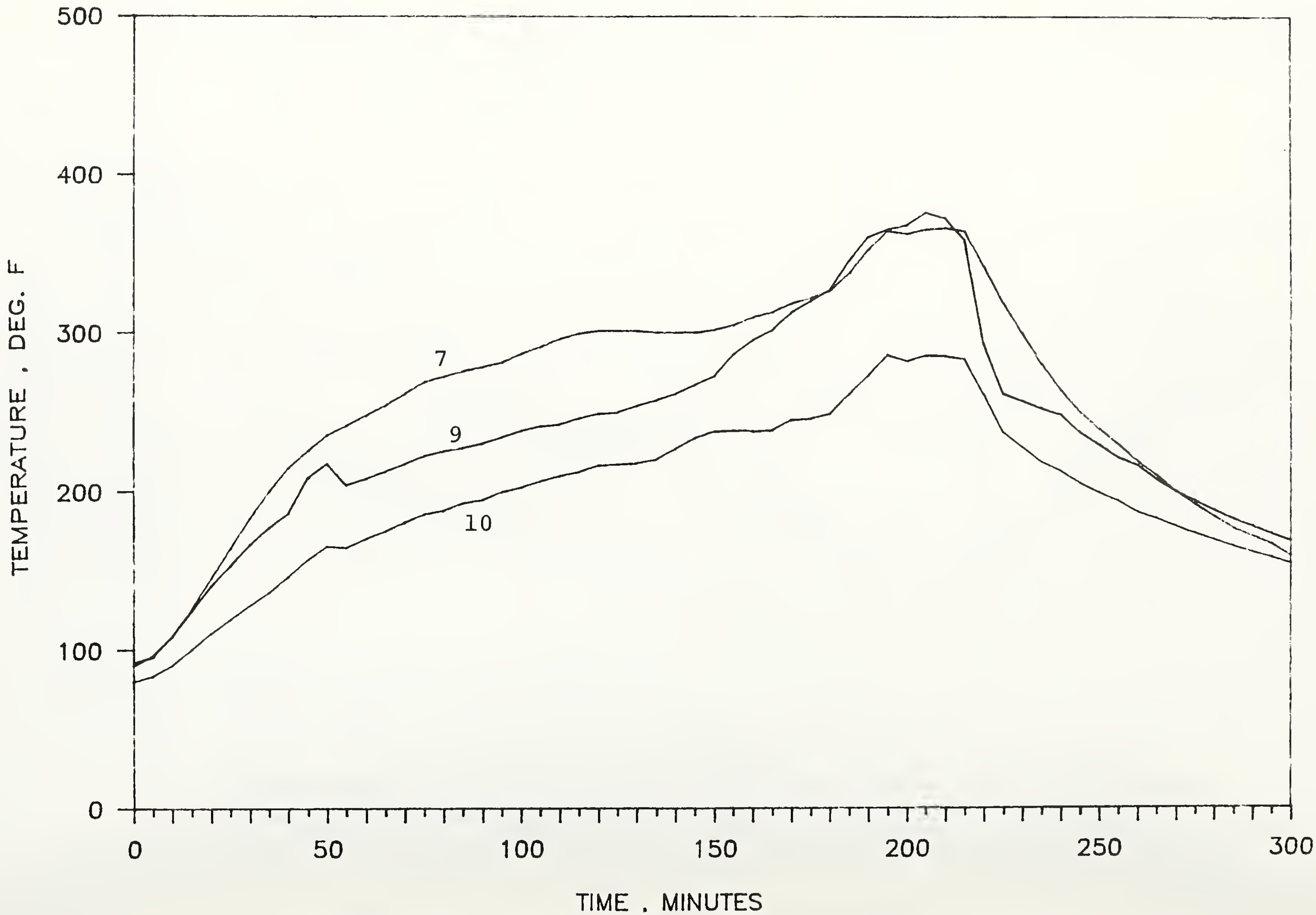

FIGURE A-25. TEST NUMBER 7, THERMOCOUPLES 7, 9, 10

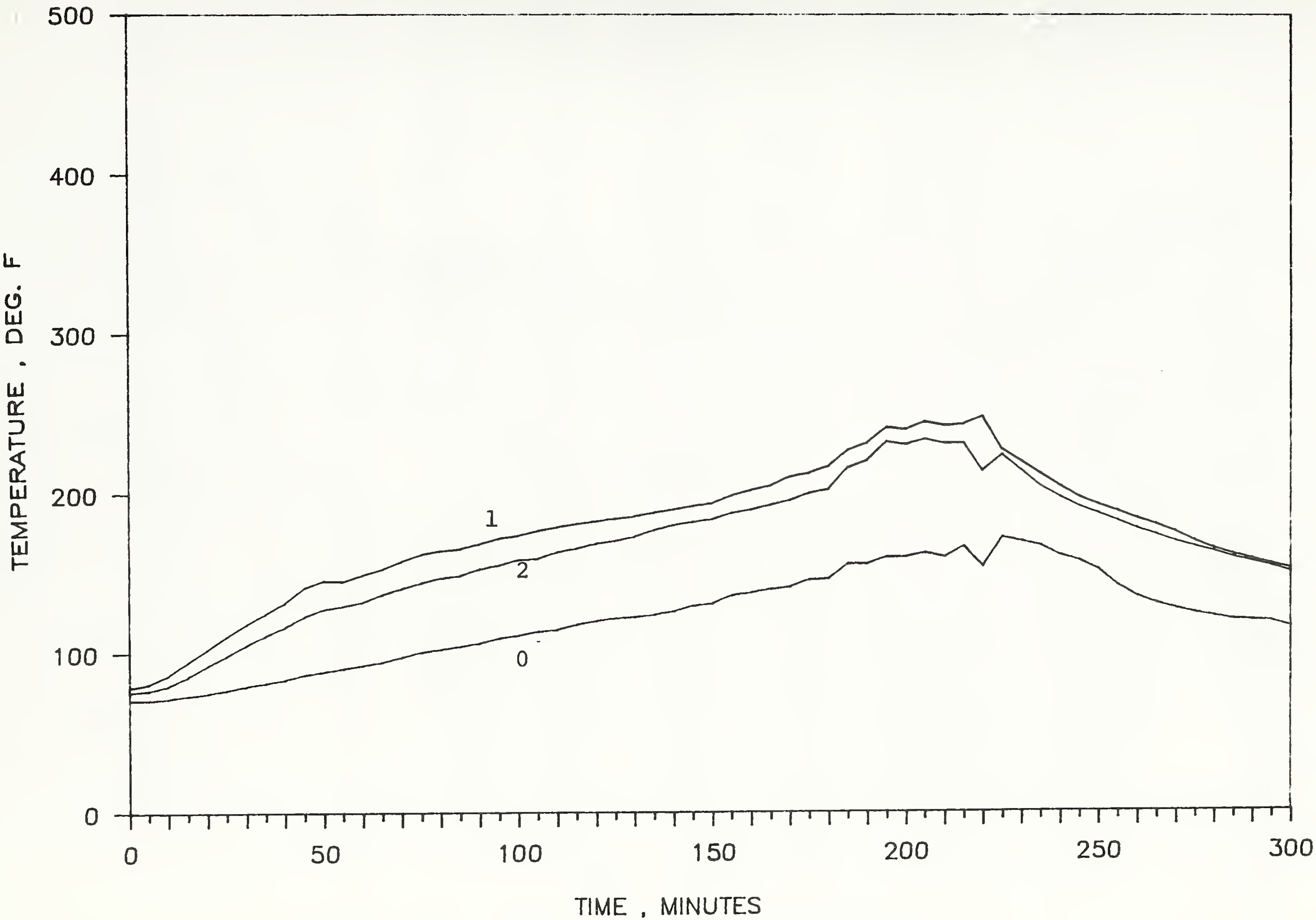

FIGURE A-26. TEST NUMBER 7, THERMOCOUPLES 0, 1, 2

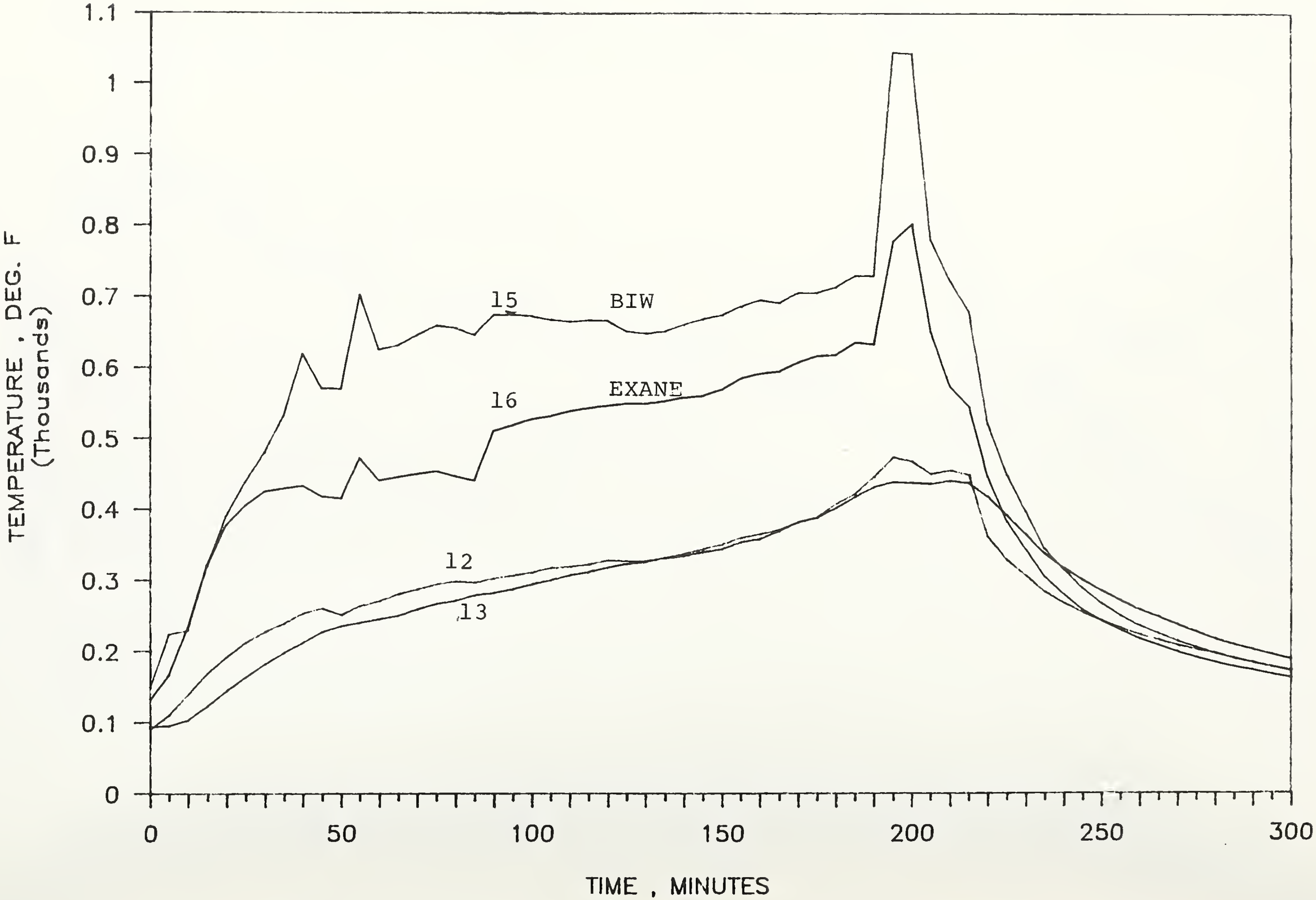

FIGURE A-27. TEST NUMBER 7, THERMOCOUPLES 12, 13, 15, 16

REFERENCES

1. Hathaway, William T., and Flores, A.L., Identification of the Fire Threat in Urban Transit Vehicles, Washington, DC: Urban Mass Transportation Administration, Report No. UMTA-MA-06-00051-79-4, July, 1979

2. National Transportation Board, Bureau of Accident Investigation, Special Investigation - Eight Subway Train Fires on New York City Transit Authority with Evacuation of Passengers, Washington, DC: National Transportation Safety Board, Report No. NTSB-SIR-81-5, September 22, 1981

3. National Transportation Safety Board, Bureau of Accident Investigation, Railroad Accident Report Bay Area Rapid Transit District Fire on Train No. 117 and Evacuation of Passengers While in the Transbay Tube, San Francisco, CA, January 17, 1979, Washington, DC: National Transportation Safety Board, Report No. NTSB-RAR-79-5, July, 1979

4. Port Authority Trans-Hudson Corporation, Special Investigation Report: PATH Car No. 725 Fire, March 16, 1982, The Authority, Jersey City, May 25, 1982

5. Mniszewski, K., Campbell, J., Waterman, T., and Wakely, H., Study of Smoke Detection and Fire Extinguishment for Rail Transit Vehicles, IIT Research Institute, Report No. UMTA-MA-06-053-83-3, August 1983

6. Hathaway, W.T., Markos, S.H., and Baker, J.B., Review of BART "C" Car Fire Safety Characteristics, USDOT Transportation Systems Center, Report No. UMTA-MA-06-0178-87-1, September 1987

7. Port Authority Trans-Hudson Corporation (PATH) and Parsons, Brinckerhoff, Quade and Douglas, Inc., PATH Car Motor Controller Unit Investigation, Report No. UMTA NY-06-0117-86-1, February 1985

8. Beland, B., "Examination of Electrical Conductors Following a Fire", Fire Technology, Vol. 16, No.4, November 1980, pp 252-258

9. Beland, B., "Arcing Phenomenon as Related to Fire Investigation", Fire Technology, Vol. 17, No. 3, pp 189-201

10. Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems, Volume I--Flammability, Factory Mutual Research Corp., May 1983

11. Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems, Volume II--Toxicity, Civil AeroMedical Institute, May 1983

12. American Public Transit Association, Report of The Propulsion Control Group Fires Task Force Meeting of January 5-6, 1983

13. Grabowski, G.J., "Fire Detection and Actuation Devices for Halon Extinguishing Systems," Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, Washington, DC: National Academy of Sciences, 1972

14. Energy Audit Corp., Infrared Thermographic Inspection on Various Model Subway Cars for the New York City Transit Authority, July 1985

15. NFPA 10, Portable Fire Extinguishers, 1981

16. NFPA 12, Carbon Dioxide Extinguishing Systems, 1980

17. NFPA 12A, Halon 1301 Fire Extinguishing Systems, 1980

18. NFPA 12B, Halon 1211 Fire Extinguishing Systems, 1980

19. NFPA 17, Dry Chemical Extinguishing Systems, 1980

20. Bryan, John L., Fire Suppression and Dectection Systems - Second Edition, University of Maryland, 1982

21. Woolhouse, R.A., and Sayers, D.R., "Monnex Compared with Other Potassium-based Dry Chemicals," Fire Journal, 1973

22. Thorne, P.F., and Tucker, D.M., The Development of an Improved Dry Powder--Field Trials, Fire Research Note 1042, Borhamwood: Department of the Environment. 1975

23. Geyer, G.B., 1972, Evaluation of Aircraft Ground Fire Fighting Agents and Techniques, Technical Report AGFSRS 71-1, Wright Patterson AFB, Ohio: AFLC-WPAFB

24. Ford, C.L., "Extinguishment of Surface and Deep Seated Fires with Halon 1301", Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, 158-172, Washington, DC: National Academy of Sciences, 1972

BIBLIOGRAPHY

Alexander, G.H., Conrad, R.E., and Neale, M.R., Determination of the Tradeoffs Between Safety, Weight, and Cost of Possible Improvement to Vehicle Structure and Restraints. Columbus, Ohio: Battelle Laboratories, December, 1974.

American Pubic Transit Association, Moving People Safely, Third Edition, 1978.

American Public Transit Association, Report of The Propulsion Control Group Fires Task Force Meeting of January 5-6, 1983

Anderson, P.B., A Review of the Literature Concerning the Toxicity of Bromotrifluormethane and its Decomposition Products, NRTS Health and Safety Information, No. 55, Idaho Falls, Atomic Energy Commission, Idaho Operations Office, 1969.

"Another Rail Fire," The Star Ledger, March 17, 1982.

APTA 1981 Rapid Transit Conference; Emergency Preparedness Workshop, PATH's Emergency Simulation Exercies. June 10, 1981.

"APTA Panel Investigates D.C. Crash," Passenger Transport, N.4, January 22, 1982.

Baehr, Guy T. "Authorities Report 19-Minute Delay in Receiving Alarm on PATH Blaze," The Star Ledger, March 17, 1982.

"BART Prepares for Emergencies," Passenger Transport, N.4, January 22, 1982.

BART (Bay Area Rapid Transit District) Fire/Life Safety Capability Profile.

Bay Area Rapid Transit, San Francisco Bay Area Rapid Transit District Emergency Plan, December 1, 1981.

Beland, B., "Arcing Phenomenon as Related to Fire Investigation", Fire Technology, Vol. 17, No. 3, pp 189-201

Beland, B., "Examination of Electrical Conductors Following a Fire", Fire Technology, Vol. 16, No.4, November 1980, pp 252-258

Bergeron, J. David, First Responder, Bowie, MD: Robert J. Brady Co., 1982.

Blair, William G, "Hundreds Trapped by Fire in PATH Train," The New York Times, March 17, 1982.

"Blame Electrical Fault for PATH Terror," New York Post, March 17, 1982.

Boeing Vertol Co. Act-1: Urban Rapid Rail Vehicle and Systems Program: Engineering Test of Act-1 Vehicle at Transportation Test Center, Washington, DC: Urban Mass Transportation Administration, December, 1979.

Booz, Allen Applied Research, and Simpson & Curtin, Fire Accident Report Rohr Transbus Prototype Model R45-WTA102 Urban Coach on Interstate Route I-17, North of Phoenix, Arizona May 13, 1975, Washington, DC, Urban Mass Transportation Administration, Contract No. DOT-UT-10008, August, 1975.

Braun, E., Fire Hazard Evaluation of BART Vehicles, National Bureau of Standards, March, 1978.

Braun, E., Fire Hazard Evaluation of BART Vehicles, Washington, DC: National Bureau of Standards, Center for Fire Research, Report No. NBSIR-75-971, December, 1975.

Braun E., A Fire Hazard Evaluation of the Interior of WMATA Metrorail Cars, Washington, DC: National Bureau of Standards, Center for Fire Research, Report No. NBSIR-75-971, December, 1975.

Bright, Richard G., A New Test Method for Automatic Fire Detection Devices, Washington, DC, Center for Fire Research, National Bureau of Standards, 1976.

Bryan, John L., Fire Suppression and Dectection Systems - Second Edition, University of Maryland, 1982.

Bryan, J.L., Human Behaviour in Fire--A Bibliography, Washington, DC, National Bureau of Standards, Center for Fire Research, Report No. NBS-GCR078-138, August, 1978.

Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems, Volume I--Flammability, Factory Mutual Research Corp., May 1983

Combustibility of Electrical Wire and Cable for Rail Rapid Transit Systems, Volume II--Toxicity, Civil AeroMedical Institute, May 1983

Connell, W.M., Safety Priorities in Rail Rapid Transit, Volume 1 - Report, Washington, DC: Transit Development Corporation, Report No. UMTA-OC-06-0091-75-1, March, 1975.

Connel, W.M., Safety Priorities in Rail Rapid Transit, Volume 2 - Exhibits, Washington, DC: Transit Development Corporation, Report No. UMTA-OC-06-0091-75-1, March, 1975.

Conrad, R.E., Alexander, G.H., and Neagle, M.R., Determination of the Tradeoffs Between Safety, Weight, and Cost of Possible Improvements to Vehicle Structure and Restraints, Final Report, Ohio: Battelle Columbus Laboratory, 1974.

Donato, George, Montreal Metro: Fire Safety, Paper Prepared for Presentation at the National Transportation Safety Board, July 28-29, Washington, DC.

Duca, Kathleen, "700 PATH Riders Escape Fiery Trap," The News World, March 17, 1982.

Edmonds, Richard Green, Mel and Sutton, Larry, "Blaze Closes PATH," Daily News, March 17, 1982.

Energy Audit Corp., Infrared Thermographic Inspection on Various Model Subway Cars for the New York City Transit Authority, July 1985

Factory Mutual Engineering Corporation, Factory Mutual Approval Guide, Norwood: Factory Mutual Engineering Corporation, 1978.

Federal Emergency Management Agency and U.S. Department of Transportation, On Track to Fire and Life Safety in Rail Rapid Transit: Workshop Handbook, Washington, DC, August, 1982.

Federal Register, Vol. 49, No. 158, "Recommended Fire Safety Practices for Rail Transit Materials Selection", Urban Mass Transportation Administration, August 1984

"Fire Study Shows Rail Transit Safe," Passenger Transport, December 18, 1981.

Ford, C.L., "Extinguishment of Surface and Deep Seated Fires with Halon 1301", Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, 158-172, Washington, DC: National Academy of Sciences, 1972

Ford, C.L., "Halon 1301 Fire Extinguishing Agent: Properties and Application," Fire Journal, 1970.

Ford, C.L., "Halon 1301 Fire Extinguishing Agent: Properties and Application," Fire Journal, 1970.

Ford, Charles, "Winterhur Revisited (A History of a Fire Extinguishant Halon 1301 System)," Fire Journal, 1975.

Ford, Charles B., "Why Not Halon 1301?" Fire Journal, 1975.

Geyer, G.B., 1972, Evaluation of Aircraft Ground Fire Fighting Agents and Techniques, Technical Report AGFSRS 71-1, Wright Patterson AFB, Ohio: AFLC-WPAFB.

Gordon, Larry, "Terror in a Fiery Tunnel", The Record, March 17, 1982.

Grabowski, G.J., "Fire Detection and Actuation Devices for Halon Extinguishing Systems," Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, Washington, DC: National Academy of Sciences, 1972.

Guise, A.B., "The Chemical Aspects of Fire Extinguishment," N.F.P.A. Quarterly, 1960.

Hammack, J.M., "The Halons, What Are They?" Fire Journal, 1970.

Harpur, W.W., "Monnex: A New Dry Chemical Agent," Fire Journal, 43:38-40, 43, 1969.

Hathaway, William T., Commonalities in Transportation Fire Safety: Regulations, Research and Development, and Data Bases, November, 1980, Final Report, Transportation Systems Center, U.S. Department of Transportation.

Hathaway, William T., Fire Safety in Transit Systems, Presented at Fifth International System Safety Conference, Denver, CO, July 27-31, 1981, Transportation Systems Center, U.S. Department of Transportation.

Hathaway, William T., Survey of Fire Modeling Efforts with application to Transportation Vehicles, July, 1981, Transportation Systems Center, U.S. Department of Transportation.

Hathaway, William T., et. al., Fire Safety in Transit Systems Fault Tree Analysis, September, 1981, Project Memorandum, Transportation Systems Center, U.S. Department of Transportation.

Hathaway, William T., and Flores, A.L., Identification of the Fire Threat in Urban Transit Vehicles, Washington, DC: Urban Mass Transportation Administration, Report No. UMTA-MA-06-00051-79-4, July, 1979.

Hathaway, William T., and Litant I., Assessment of Current U.S. Department of Transportation Fire Safety Efforts, Washington, DC: Urban Mass Transportation Administration, Report No. UMTA-MA-06-00051-79-4, July, 1979.

Hathaway, W.T., Markos, S.H., and Baker, J.B., Review of BART "C" Car Fire Safety Characteristics, USDOT Transportation Systems Center, Report No. UMTA-MA-06-0178-87-1, September 1987

Heckstead, G., and C. Yao, A New Approach to Development of Installation Standards for Fire Detectors, Technical Proposal FMRC 19574, Norwood: R.M. Research Corporation, 1971.

Hill, Richard, G., George R. Johnson, Fire Detection, Extinguishment, and Material Tests for an Automated Guideway Transit Vehicle, U.S. Department of Transportation/Urban Mass Transportation Administration, Final Report, May, 1978.

Jensen, R., "Halogenated Extinguishing Agent Systems," Fire Journal, 1972.

Lay, D., A New Concept for Automatic Detection and Extinction of Fires, Washington, DC: Center for Fire Research, National Bureau of Standards, NBSIR 76-1028, 1976.

Litant, I., "Fire Safety Problems in Ground Mass Transportation," Journal of Fire and Flammability, Volume 8, July, 1977.

Luck, I.H., "Economics of Fire Protection with Fire Detectors," Fire Technology, 1973.

Mniszewski, K., Campbell, J., Waterman, T., and Wakely, H., Study of Smoke Detection and Fire Extinguishment for Rail Transit Vehicles, IIT Research Institute, Report No. UMTA-MA-06-053-83-3, August 1983

"Moorgate Tube Train Disaster," British Medical Journal, Volume 3, No. 5986, September, 1975.

Morgan, Earl and Larkins, Robert, "Third Fire Hits PATH," The Jersey Journal, March 17, 1982.

National Fire Protection Association, 1975, Dry Chemical Extinguishing Systems, No. 17, Quincy, MA.

National Fire Protection Agency, Fire Protection Reference Directory 1982, December, 1981, 7th Edition.

National Fire Protection Association, Inc. Life Safety Code, NFPA 101, 1981, The Association, Quincy, MA, 1981.

National Transportation Board, Bureau of Accident Investigation, Special Investigation - Eight Subway Train Fires on New York City Transit Authority with Evacuation of Passengers, Washington, DC: National Transportation Safety Board, Report No. NTSB-SIR-81-5, September 22, 1981.

National Transportation Board, Bureau of Accident Investigation, Special Investigation - Eight Subway Train Fires on New York City Transit Authority with Evacuation of Passengers, Washington, DC: National Transportation Safety Board, Report No. NTSB-SIR-81-5, September 22, 1982.

National Transportation Safety Board, Bureau of Accident Investigation, Railroad Accident Report Bay Area Rapid Transit District Fire on Train No. 117 and Evacuation of Passengers While in the Transbay Tube, San Francisco, CA, January 17, 1979, Washington, DC: National Transportation Safety Board, Report No. NTSB-RAR-79-5, July, 1979.

NFPA 10, Portable Fire Extinguishers, 1981

NFPA 12, Carbon Dioxide Extinguishing Systems, 1980

NFPA 12A, Halon 1301 Fire Extinguishing Systems, 1980

NFPA 12B, Halon 1211 Fire Extinguishing Systems, 1980

NFPA 17, Dry Chemical Extinguishing Systems, 1980

Peacock, R.D., Fire Safety Guidelines for Vehicles in a Downtown People Mover System, Washington, DC: National Bureau of Standards, January, 1979.

Port Authority Trans-Hudson Corporation, Special Investigation Report: PATH Car No. 725 Fire, March 16, 1982, The Authority, Jersey City, May 25, 1982.

Port Authority Trans-Hudson Corporation, Special Investigation Report: PATH Car No. 725 Fire, March 16, 1982, Appendix, The Authority, Jersey City, May 25, 1982.

Port Authority Trans-Hudson Corporation (PATH) and Parsons, Brinckerhoff, Quade and Douglas, Inc., PATH Car Motor Controller Unit Investigation, Report No. UMTA NY-06-0117-86-1, February 1985

Rajan, K.S., Snelson, Alan, Schetcher, H.R., Mniszewski, K.R., Waterman, T.E., and Yamate, George, IIT Research Institute, and Harpe, S.W., Underwriters' Laboratories, Inc., New Concepts of Fire Detection, Washington, DC, 1978.

Ruegger, H. "The Fire-Extinguishing and Rescue Trains of the Swiss Federal Railways," Glasser Annelen, ZEV, Volume 10, No. 2, February, 1977.

Schirmer Engineering Corporation, and Rolf Jensen and Associates, Inc., Fire Experience and Exposure in Fixed-Guideway Transit Systems, December, 1980.

Smith, E.E., Transit Vehicle Material Specification Using Release Rate Tests for Flammability and Smoke, Phase I Report, Columbus, Ohio: Ohio State University, October, 1976.

Takita, T. "Research on Prevention of Train Fire," Rail International, Volume 8, No., 7/8, July, 1977.

Tanaka, H., and Takaoka, S., "Lighting Effect in the Smoke of Tunnel Fire," Railway Technical Research Institute, Volume 15, No., 2, Quarterly Report, 1974.

Teiber, Eli; Matlick, Maralyn and Weingrad, Jeff, "The PATH in Tunnel Fire Drama Hundreds Felled," New York Post, March 16, 1982.

Thorne, P.R., "The Toxicity of Halon Extinguishing Agents - A New Appraisal," Fire Research Note 1073, Borehamwood: Department of the Environment, Fire Research Station, Building Research Establishment, 1977.

Thorne, P.F., and Tucker, D.M., The Development of an Improved Dry Powder--Field Trials, Fire Research Note 1042, Borhamwood: Department of the Environment. 1975

Underwriters' Laboratories, Inc., Fire Protection Equipment Directory, Northbrook: Underwriters' Laboratories, Inc., 1979.

Weissman, Dan, "PATH Fire Probed on Response," The Star Ledger, March 18, 1982.

White, David, Evaluation of Multi-Purpose Dry Powder Extinguishing Agent, Juneau: Alaska Department of Education, Fire Service Training Program, 1971.

Wickham, R.T., "Engineering and Economic Aspects of Halon Extinguishing Equipment," Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, Washington, DC, National Academy of Sciences, 1972.

Wiersma, Steve J., "Flow Characteristics of Halon 1301 in Pipelines," _Fire Technology_, 1978.

Williamson, H.V., "Halon 1301-Minimum Concentrations for Extinguishing Deep Seated Fires," _Fire Technology_, 1972.

Woolhouse, R.A., and D.R., Sayers, "Monnex Compared with Other Pottassium-based Dry Chemicals," _Fire Journal_, 1973.

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