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CABLE TRAY FIRE TESTS

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Abstract

Funds were authorized by the Nuclear Regulatory Commission to provide data needed for confirmation of the suitability of current design standards and regulatory guides for fire protection and control in water reactor power plants. This paper summarizes the activities of this program through March 1977. It describes a survey of industry in order to determine current design practices. The adequacy of cable tray spacing designated in Regulatory Guide 1.75 was chosen for evaluation. Using electrical cable types currently being selected for new nuclear power plant construction, a screening test was designed and completed to select two cable constructions which were used in subsequent full scale tests. Seven full scale tests were run and resulted in no functional damage to cables in trays adjacent to that cable tray in which a fire was electrically initiated. Characterization of these fires was made and reveal a margin of safety in the separation criteria of the regulatory guide for electrically initiated fires in IEEE-383 qualified cable.

DISCLAIMER

Introduction

The Office of Nuclear Regulatory Research of the United States Nuclear Regulatory Commission is conducting confirmatory research in areas considered important to protecting the health and safety of the public. Fire protection, as established by NUREG-0050, "Recommendations Related to Browns Ferry Fire," is one such critical area of research.

The objectives of the Fire Protection Research Project at Sandia Laboratories are (1) to provide data either to confirm the suitability of current design standards and regulatory guides for fire protection and control in light water reactor power plants or to indicate areas where they should be updated; (2) to obtain data that will provide improved technical basis either for modification of the standards and guides or for new standards and guides if necessary. Such changes are to be made where appropriate to decrease the vulnerability of the plant to fire; to provide for better control of fires; to mitigate the effects of fires on plant safety systems; and to remove unnecessary design restriction; (3) to obtain fire effects data for water reactor safety system equipment and to assess improved equipment, design concepts, and fire prevention data and methods that can be used to reduce vulnerability of plant safety to fire.

Background

When the project was initiated in July 1974, the only task assigned was to provide the experimental and analytical information to evaluate the adequacy of cable tray spacing designated in Regulatory Guide 1.75, "Physical Independence of Electrical Systems, Section 5.14, General Plant Areas." This section of the guide covers separation of protective systems in areas of the plant where power cables are included and the only source of fuel is that provided by the cable materials. All evaluations were to involve the testing of equipment and configurations representative of those going into new nuclear power plant designs.

It was decided that a survey of industry should be made to determine current design practices. The cooperation by members of the nuclear power industry was outstanding. Either personal visits or correspondence elicited responses from 13 leading architect-engineering firms, 13 utility companies, and 13 cable manufacturers. Three nuclear power plants were also visited, although design practices of existing nuclear power plants were not included for evaluation. Information obtained during this survey has proven very valuable in determining cable constructions, cable tray constructions, cable loading, and types of cable assignments in cable trays. The survey also solicited information about previous incidents and experiences including the cable tray fire at San Onofre 1 in 1968 and the subsequent investigation to determine the cause.[2]

A primary concern was to insure that the test facility truly represented the reactor plant area. The discussions with architectural and engineering firms were particularly valuable for improving the realism of the proposed tests.

Since we had been warned of the difficulties of electrically initiating a fire in power cable it was decided early in the project to conduct the test with 12 AWG, the smallest power cable normally used in nuclear power plants in order to minimize the amperage demands in the test setup. A preliminary heat transfer analysis was also performed at that early date. A rough analysis was all that was considered necessary to determine the approximate current required to raise cable insulation to a combustible temperature and to determine if the conductor temperature is at its melting point (1083°C) when the outside of the cable insulation is at its combustion temperature. The analysis showed that currents in the range of 100-120 amperes would raise the cable insulation to its combustible temperature. This agreed with subsequent testing.

With the results of the survey and the preliminary analysis as guidelines, a test facility was developed to perform full scale testing of cable fires of electrically initiated origin. Although it was originally intended to test all known types of cable currently specified and acceptable for use in nuclear power plant design and construction, the large number of cable types coupled with budget limitations precluded such broad testing. Therefore, screening was indicated that would lead to selection for testing of two typical cable types that would be most likely of propagating a fire and would present a conservative approach.

Cable Screening Tests

A survey of utility companies, architect-engineering firms, and cable manufactureres, ascertained their preferences of insulation and jacket materials. The inquiries stipulated that the cable types must be those currently being installed in or would be included in the design of nuclear power plants. As a result of this constraint, all cable types suggested were capable of passing IEEE Standard 383-74.[3]

There were thirty-nine replies from industry which cited 20 different cable types that were being considered for use in new construction. Screening was necessary to cut this list to manageable size and allow full scale testing to proceed. The first cut was made on the basis of popularity. The leading types were crosslinked polyethylene with or without some jacket material (34 percent), EPR with a Hypalon jacket (23 percent), and EPR with a Neoprene jacket (19 percent).

Considerations of the cost of filling cable trays in a full scale test prompted a further screening test to obtain two different cable types that were "most likely to propagate a fire." The screening tests were performed merely to rank the various cable types in some manner. The relative differences between results were small thereby subjecting the conclusions to dispute, especially if proprietary interests were involved. When burn length differences are measured in millimeters, as they were in one of the tests, it is difficult to attach true significance to those differences.

The relative ranking of the cable types was based on three different evaluations. They were chosen to complement other evaluations, not to duplicate them. The oxygen index test which has been done on all of the cable insulation types under consideration is a case in point. The three types reported here are a small scale electrically initiated cable insulation fire test, Underwriter Laboratories FR-1 flame test,[4] and a pyrolyzer and thermal chromatograph test (measure of insulation outgassing as a function of temperature).

Electrically Initiated Cable Insulation Fire Test

To determine the amount of current needed to produce a flame, five small scale tests were performed on five different electrical cables. The cable types were:

Cable #1 - Single conductor #12 AWG, 45 mil (1.14 mm) EPR, 30 mil (0.76 mm) Hypalon jacket, 600 V.

Cable #2 - Single conductor #12 AWG, 47 mil (1.19 mm) chlorinated rubber (proprietary), 47 mil (1.19 mm) chlorinated polymer (proprietary) jacket, 600 V.

Cable #3 - Single conductor #12 AWG, 47 mil (1.19 mm) EPR, 15 mil (0.38 mm) Neoprene jacket, 600 V.

Cable #4 - Single conductor #12 AWG, 30 mil (0.76 mm) crosslinked PE, no jacket, 600 V (Supplier B).

Cable #5 - Three conductor #12 AWG, 30 mil (0.76 mm) crosslinked PE, silicon glass tape, 65 mil (1.65 mm) crosslinked PE jacket, 600 V (Supplier A).

Figure 1 shows how the cables were arranged in a cable tray for each test. Current was increased in increments of 5 amperes every 10 minutes until a flame was observed. Cable #1 flamed at 130 amps, Cable #2 flamed at 130 amps, Cable #3 flamed at 124 amps (while increasing to 125), Cable #4 at 120 amps, and Cable #5 at 120 amps. The spread of currents measured and observations of flame extent (flames extinguished shortly after the conductor open circuited) make all results appear close, but relative positions were assigned with the better cables being the ones with the highest current for flaming to occur.

FR-1 Flame Test

Underwriter Laboratories FR-1 Flame Test was chosen as another screening test. It was not intended to be used as a pass-fail test (for which the test was devised) but to establish a rank based on length of burn and burn damage. It was expected that all cables tested would pass this test, and they did. In order to fail, the paper flag 10 inches (254 mm) above the flame impact point must burn. See Figure 2.

The test was conducted in a three-sided metal enclosure under an exhaust hood. The metal enclosure was 12 inches (305 mm) wide, 14 inches (356 mm) deep, 24 inches (610 mm) high, and the top and front were open. An 18-inch (457 mm) specimen cut from a sample length of each cable was secured with its longitudinal axis vertical in the center of the enclosure. Figure 2 shows the test configuration.

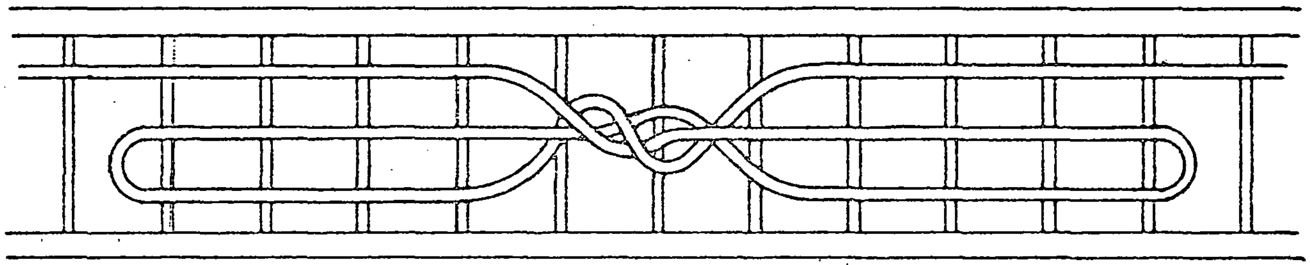

Figure 1. Cable Configuration for Electrical Ignition

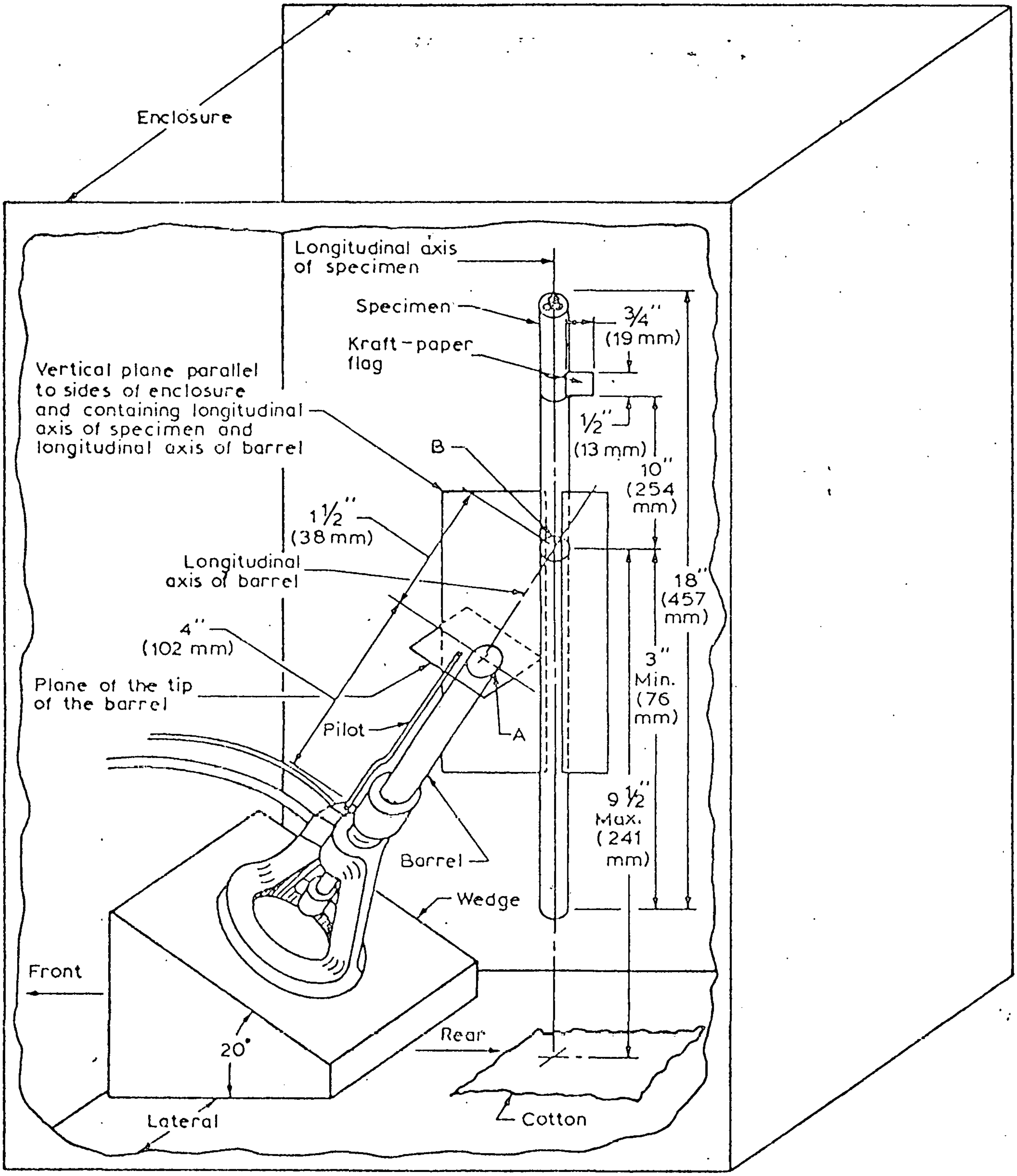

Figure 2. Essential Dimensions of Apparatus and Specimen of Vertical Flame Test

A Tirrell gas burner (which differs from a Bunsen burner in that the air flow as well as the flow of gas is adjustable) supplied the flame. The barrel of the burner extended 4 inches (102 mm) above the air inlets and its inside diameter was 3/8 inch (9.5 mm). While the barrel was vertical, the overall height of the flame was adjusted to 5 inches (127 mm). The blue inner core was 1-1/2 inches (38 mm) high and the temperature at its tip was approximately 815 °C (1500 °F).

A wedge was secured to the base of the burner to provide a sloping surface of 20 degrees from the vertical. This wedge was positioned to place the point A 1-1/2 inches (38 mm) from the point B, Figure 2. Point B is the point at which the tip of the blue inner core touched the center of the front of the specimen. A half-inch (13 mm) wide strip of kraft paper was attached around the specimen with its lower edge 10 inches (254 mm) above B and with the paper protruding 3/4 inch (19 mm) to provide a flag. See Figure 3.

The test procedure was to apply flame to point B for 15 seconds, turn it off for 15 seconds, on again to point B for 15 seconds, etc., for a total of five 15-second applications of the gas flame to the specimen with 15 seconds between applications. In no case was the specimen flaming from the previous application of the flame when the 15 second "off" period had ended. The duration of flaming of these specimens after each removal of the gas flame never exceeded five seconds. After the cable specimens cooled, burn lengths were measured beginning at point B.

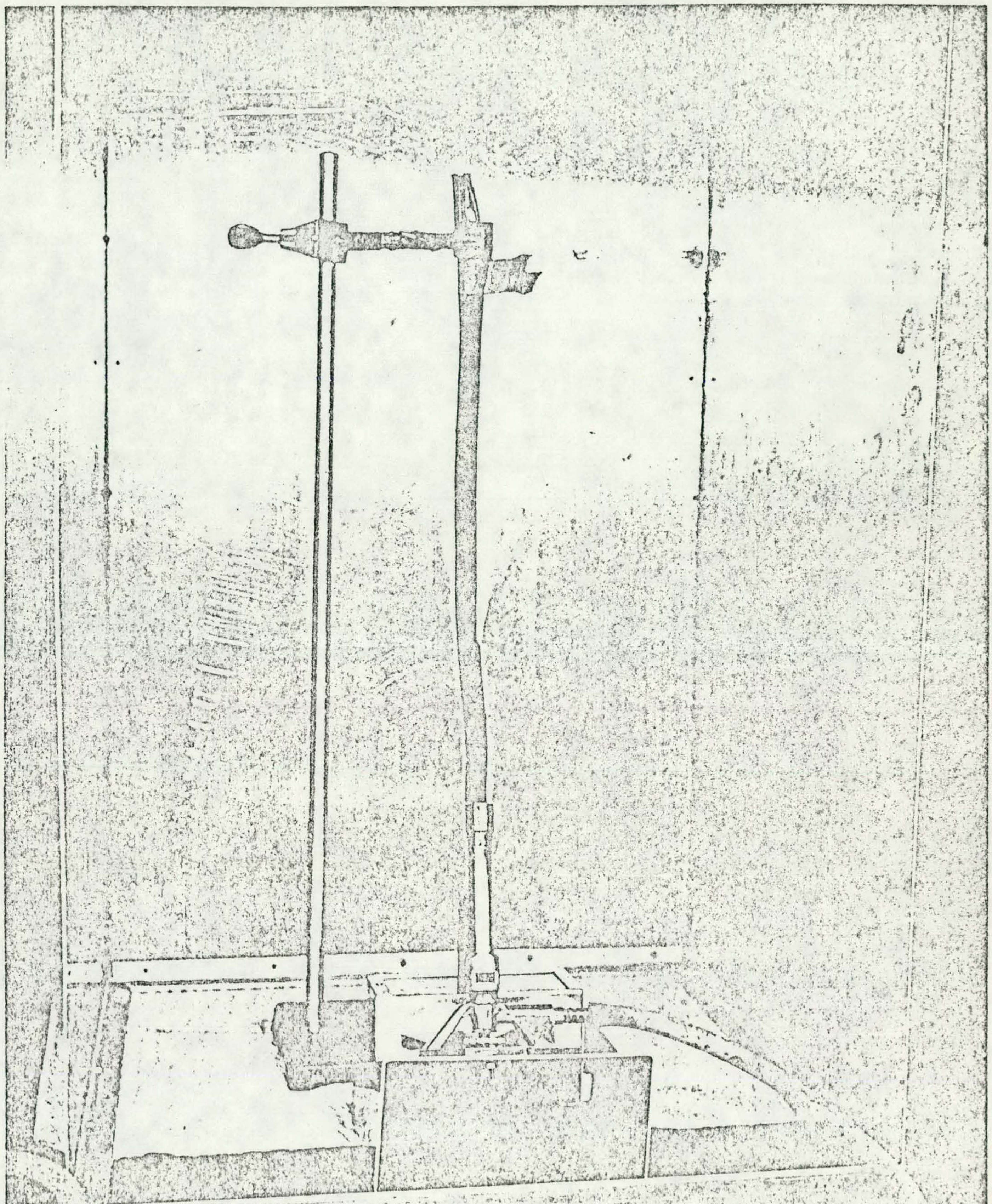

Figure 3. FR-1 Test

Eight cables were used as test specimens.†

Cable #1 - Single conductor #12 AWG, 45 mil (1.14 mm) EPR, 30 mil (0.76 mm) Hypalon jacket, 600 V.

Cable #2 - Three conductor #12 AWG, 15 mil (0.38 mm) EPR, 60 mil (1.52 mm) Hypalon jacket, 600 V.

Cable #3 - Single conductor #12 AWG, 47 mil (1.19 mm) chlorinated rubber (proprietary), 47 mil (1.19 mm) chlorinated polymer (proprietary) jacket, 600 V.

Cable #4 - Single conductor #12 AWG, 47 mil (1.19 mm) chlorinated rubber (proprietary), 65 mil (1.65 mm) chlorinated polymer (proprietary) jacket, 600 V.

Cable #5 - Three conductor #12 AWG, 47 mil (1.19 mm) chlorinated rubber (proprietary), 65 mil (1.65 mm) chlorinated polymer (proprietary) jacket, 600 V.

Cable #6 - Single conductor #12 AWG, 47 mil (1.19 mm) EPR, 15 mil (0.38 mm) Neoprene jacket, 600 V.

Cable #7 - Three conductor #12 AWG, 30 mil (0.76 mm) crosslinked PE, silicon glass tape, 65 mil (1.65 mm) crosslinked PE jacket, 600 V (Supplier A).

Cable #8 - Single conductor #12 AWG, 30 mil (0.76 mm) crosslinked PE, no jacket, 600 V (Supplier B).

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†Eight cables were used in the two screening tests requiring short samples while five were used in the electrical test requiring longer samples. If those three which had not seen all three tests had been marginal performers additional lengths would have been obtained and given the electrical test.

Comparative results from UL FR-1 test were:

Cable Type	Burn Length (mm)	Comments
#1	76.2	jacket opened
#2	44.5	jacket not opened
#3	50.8	jacket opened
#4	63.5	jacket opened
#5	63.5	jacket not opened
#6	61.0	jacket opened
#7	69.9	jacket opened
#8	73.7	no jacket

Pyrolizer and Thermal Chromatograph Test

The last screening test used a pyrolizer on a thermal chromatograph interfaced to a gas chromatograph/mass spectrometer. Thermodecomposition chromatographs were obtained as a function of temperature and the area under each curve was measured. Approximately 50 mg of jacket material was used in each test and the temperature of the specimen raised from ambient to 600 °C at 20 °C/min. The material driven off below 300 °C was analyzed to test the hypothesis that large amounts of material driven off at lower temperatures was an undesirable characteristic. Since outgassing of combustible materials or fire retardants at these low temperatures was theorized as being undesirable, larger areas under the thermodecomposition chromatographs were assigned an undesirable rating. Figure 4 shows a typical chromatograph.

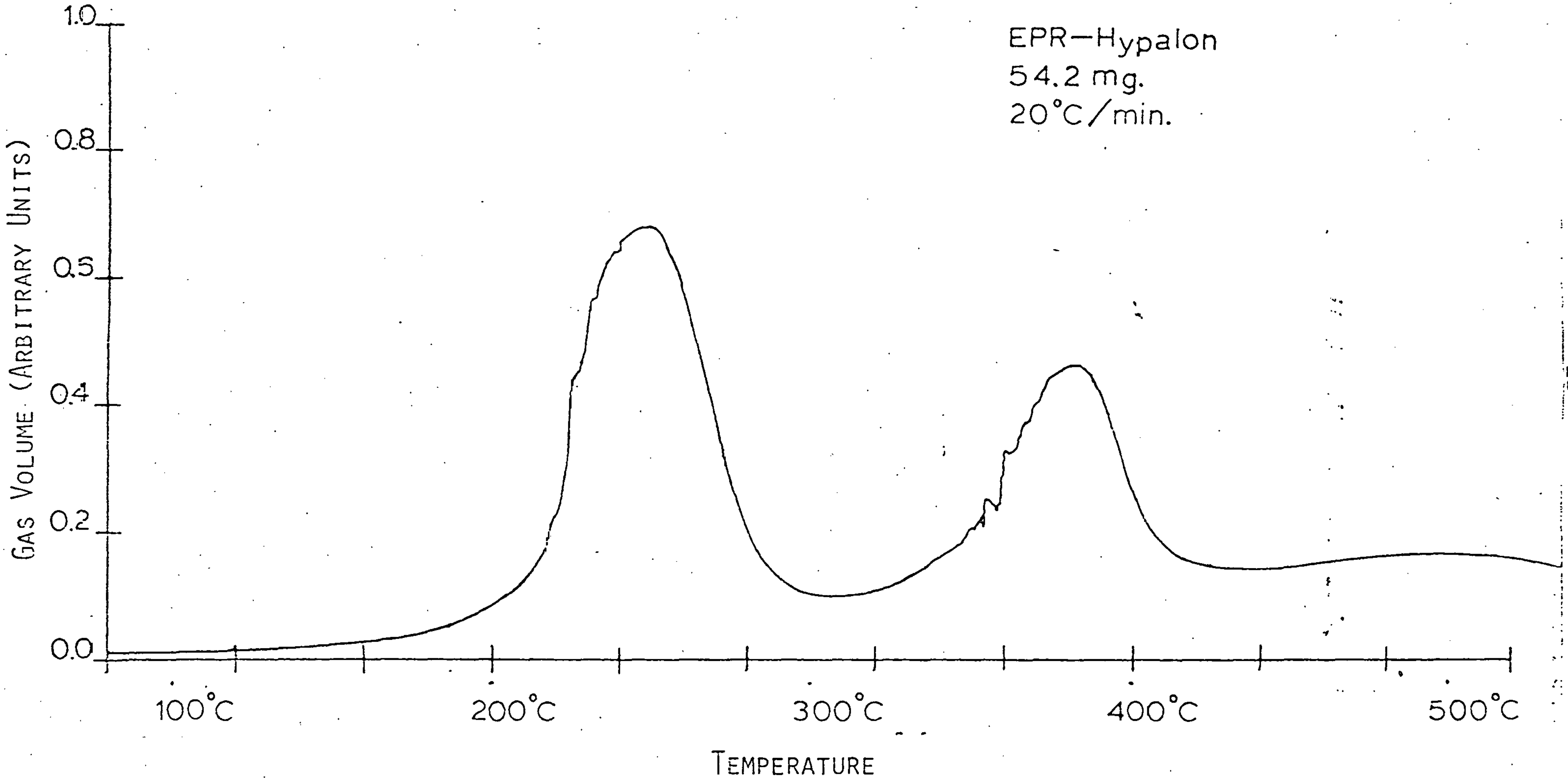


Figure 4. Gas Chromatograph

The normalized areas on the chromatographs for the same cable types previously described in the UL FR-1 test are:

Cable Type	Normalized Area
#1	1.2
#2	1.6
#3	4.3
#4	4.6
#5	1.8
#6	1.0
#7	4.9
#8	7.7

Screening Test Conclusions

Although the small scale electrically initiated cable insulations fire test and the UL FR-1 Fire Test indicated none of these cables would be capable of propagating a fire (in support of IEEE 383 qualification) cables #7 and #8 in the last two tests (same as cables #4 and #5 in the first test) were designated as the cable types to be used in the full scale tests by a relative figure of merit. Work performed in Europe in 1975[5] on radiation and fire resistance of cable-insulating materials was recently brought to our attention and is in good agreement with our ratings.

Full Scale Testing

Three phases of full scale testing have been completed. All involved electrically initiated fires in horizontally oriented cable trays. The first phase was intended to evaluate the adequacy of cable tray spacing as designated in Regulatory Guide 1.75, "Physical Independence of Electrical Systems, Section 5.14, General Plant Areas." For this phase vertical separation of independent division is designated as 5 feet (1.52 m) and the horizontal separation as 3 feet (0.91 m).

The second phase was concerned with varying the separation distance between cable trays. Phase three required a stacking or matrix of fourteen cable trays as one division with cable trays representing the second division separated by distances as specified in Regulatory Guide 1.75. The vertical and horizontal separation in the first division was 10.5 inches (0.27 m) and 8 inches (0.20 m) while the separation between divisions was 5 feet (1.52 m) and 3 feet (0.91 m). All testing involved equipment and cables representative of that going into new nuclear power plant designs. See Figures 5, 6, and 7 depicting the three different test setups for the three phases.

Coupons of aluminum, galvanized iron, and mild steel were hung in the building and periodically removed for corrosion analysis. A profilometer is used for this purpose and has not shown significant corrosion products.

An oxygen analyzer and gas sample manifold were installed and gas samples were taken before and during the fires. There was no depletion of oxygen found in the fire area. Flame retardant antimony bromide and an organophosphate were found in the gas samples as well as a high molecular wax material.

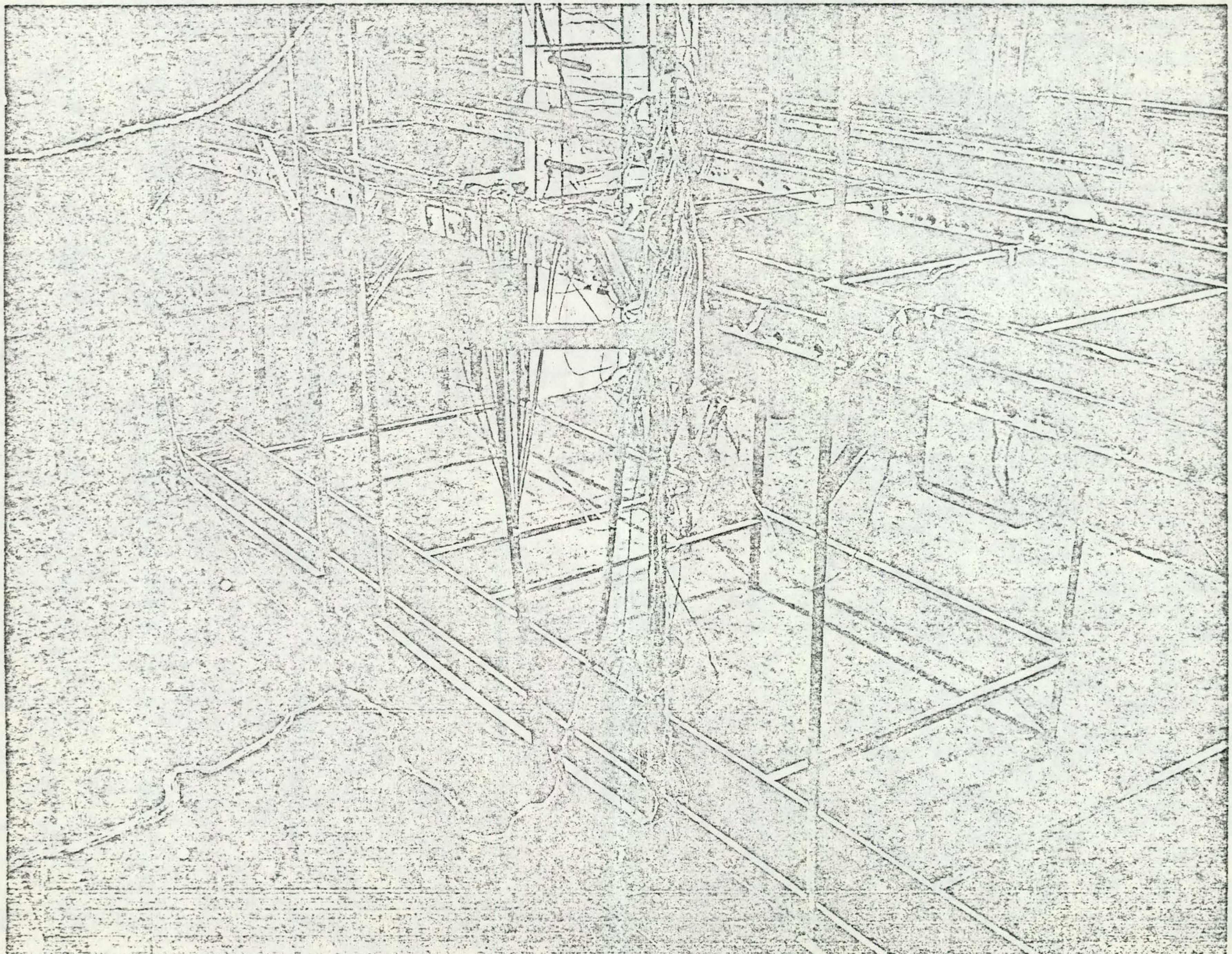


Figure 5. Phase One Test Setup

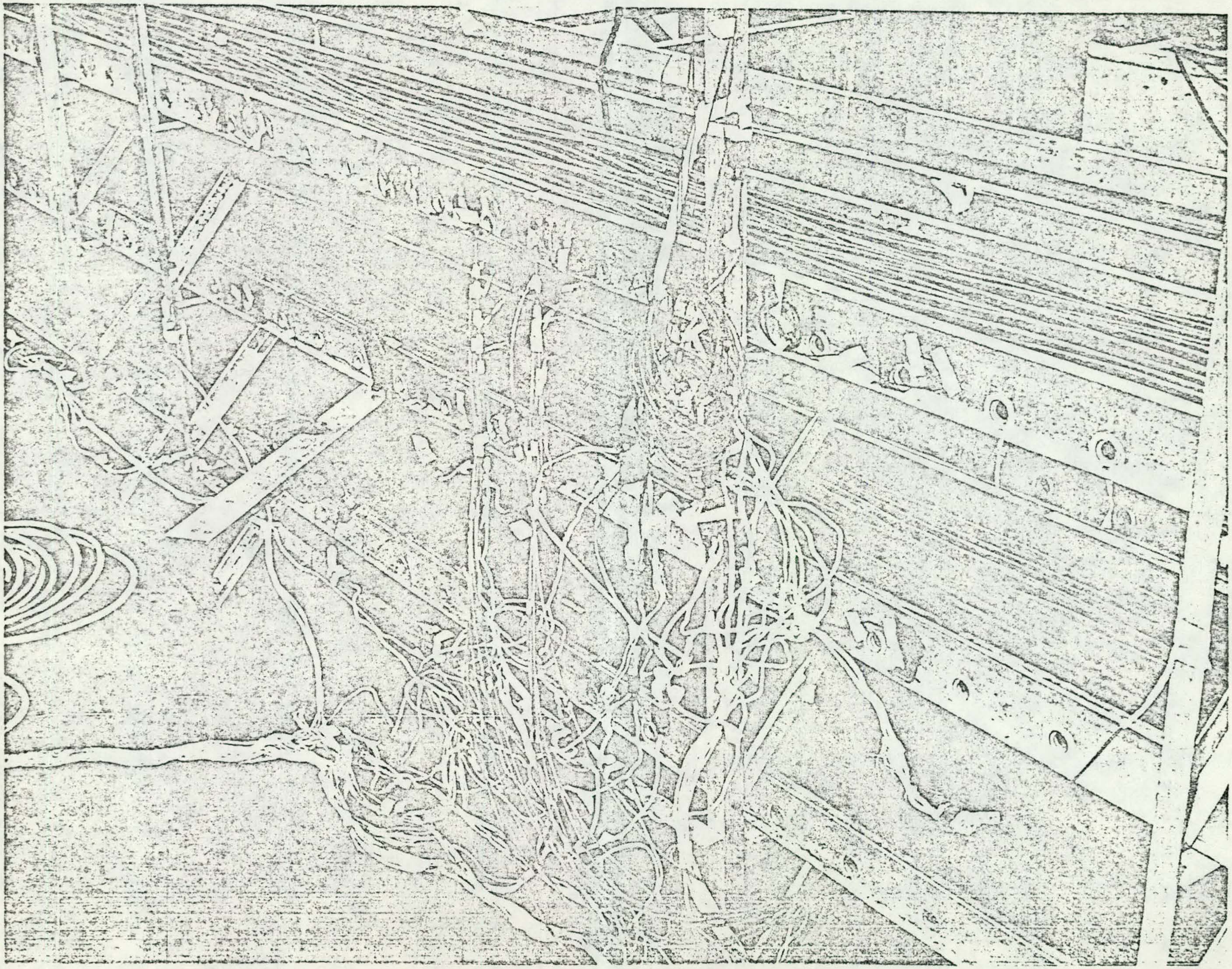


Figure 6. Phase Two Test Setup

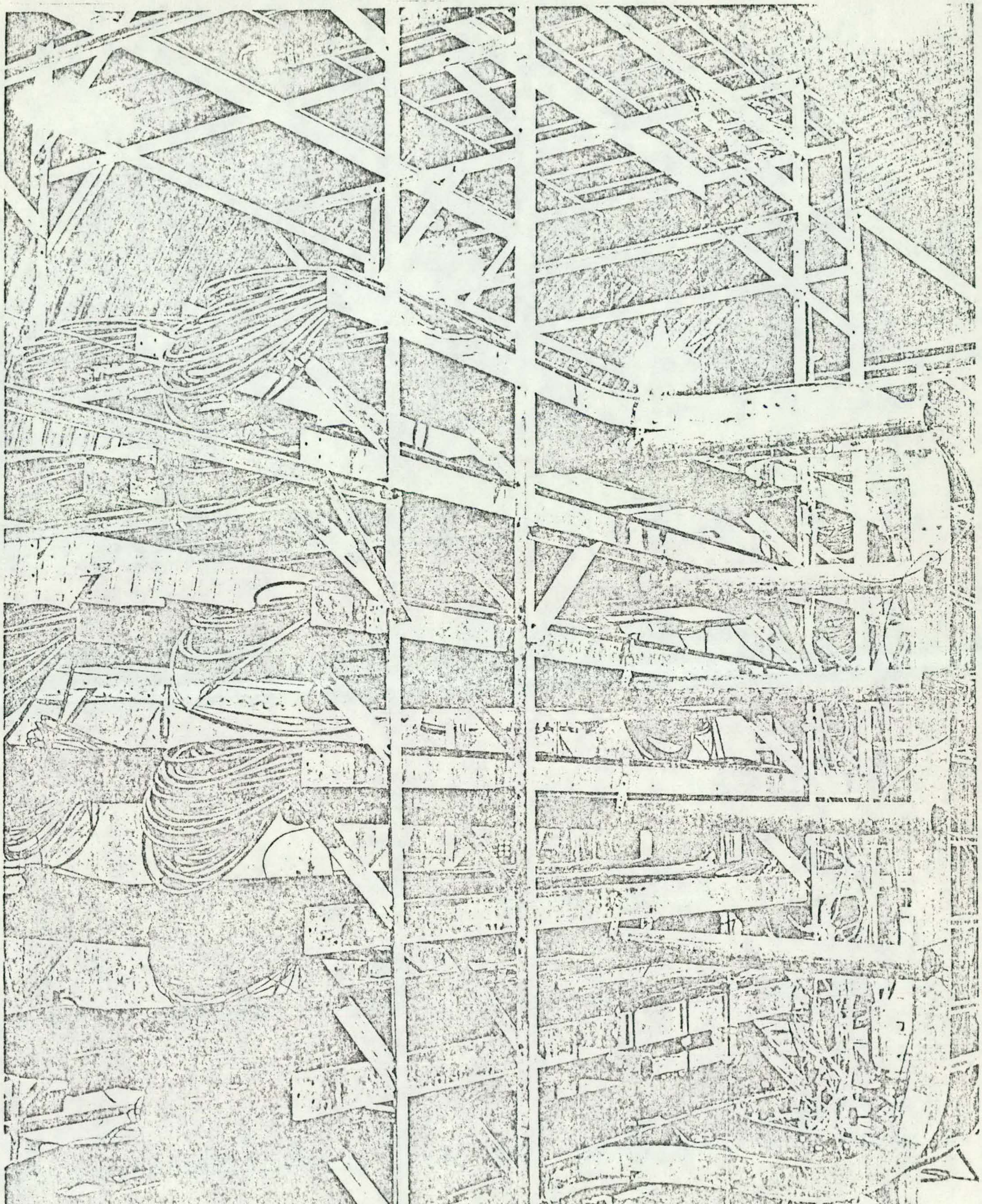


Figure 7. Phase Three Test Setup

Remote controlled cameras were installed for closed circuit television, color movies, photographic thermometry, and infrared thermography. Television was used to monitor the testing and in determining the proper time to attempt gas ignition (explosive bridgewires and electric matches were spaced over the ignition point and simulated arcing), to take gas samples, and to start movie cameras. The movies not only provided a record of the event but gave information on the ignition mechanism as well as measurement of flame velocity. Despite a lack of success in igniting the gases with simulated arcing the movies show the combustible gases do indeed ignite as the flame producing mechanism. Measurement of flame velocity was needed so that the convective heat transfer coefficient could be calculated. The photographic thermometry and infrared thermography were to supplement the discrete spatial measurements taken with thermocouples and slug calorimeters.

On each test a minimum of 31 thermocouples and slug calorimeters were placed in the test setup and connected to recorders. Results of these measurements are discussed in the following section on the characterization of the fires.

Air velocity was varied somewhat during the tests because of conflicting opinions on worst case conditions. Opinions varied between zero flow, which might be encountered in a cable spreading room, to high air velocity providing abundant oxygen, which might be encountered near an exhaust fan in the open plant area. As a compromise, air velocities for the different tests ranged between 2 ft/min (0.01 m/sec) and 30 ft/min (0.15 m/sec). These measurements were made with a hot wire anemometer before each test; only fan exhaust velocities were monitored during the test.

Seven full scale tests were run in the three phases previously described. Spacing was reduced in phase two to 10.5 inches (0.27 m) vertically and 8 inches (0.20 m) horizontally. In all seven tests all circuits other than the ignition tray circuits remained functional. This was determined by operation of these circuits for some period of time after the test. In addition, samples of the cable insulation at the bottom of the tray over the fire zone were given insulation elongation measurements to determine mechanical change. These measurements showed less than a 10% increase in elongation due to the fire. Quite often this small increase is attributed to a small change in crosslinking due to heat.

Characterization of Cable Tray Fires

Characterization of the cable tray fires is based upon a review of the data that were collected in the full scale testing described above.

The sources of data include:

1. Color Movies
2. Radiation Thermometry
3. Slug Calorimeters and Thermocouples
4. Thermovision (infrared detection)

This information is used to investigate the following characteristics of the fire:

1. Size and Duration
2. Flame Temperature
3. Gas Velocity
4. Optical Thickness (apparent emissivity)

Consideration is also given to the thermal response of simple cylindrical objects which are engulfed by the fire. Approximate calculations provide estimates for:

1. Convective and Radiative Heat Transfer
2. Equilibrium (Steady-State) Surface Temperature

There is no attempt to use the data to evaluate the likelihood of fire spreading to an overlying tray, because this requires consideration of the geometric arrangement of the exposed cables and the kinetics of decomposition[6].

It is emphasized that the measurements and analysis techniques are approximate in nature, and are intended only to provide an overview of the gross characteristics of the fire. Within this framework, the data are found to be self-consistent and in reasonable agreement with theoretical expectations and comparative data.

Color Movies

Observation and analysis of the 16 and 100 frames/second motion pictures of the cable tray fire tests have proved enlightening in characterizing cable fires. (Figure 8 is an illustrative sequence shot at 16 frames/second.) For example, the following observations tend to characterize the pictured fires.

(1) The flame zone does not comprise a continuous line fire, but instead consists of one or more "axisymmetric" luminous zones which are on the order of 5 to 8 inches in "diameter" at the base.

(2) Although migration along the tray may occur, the propagation is quite slow.

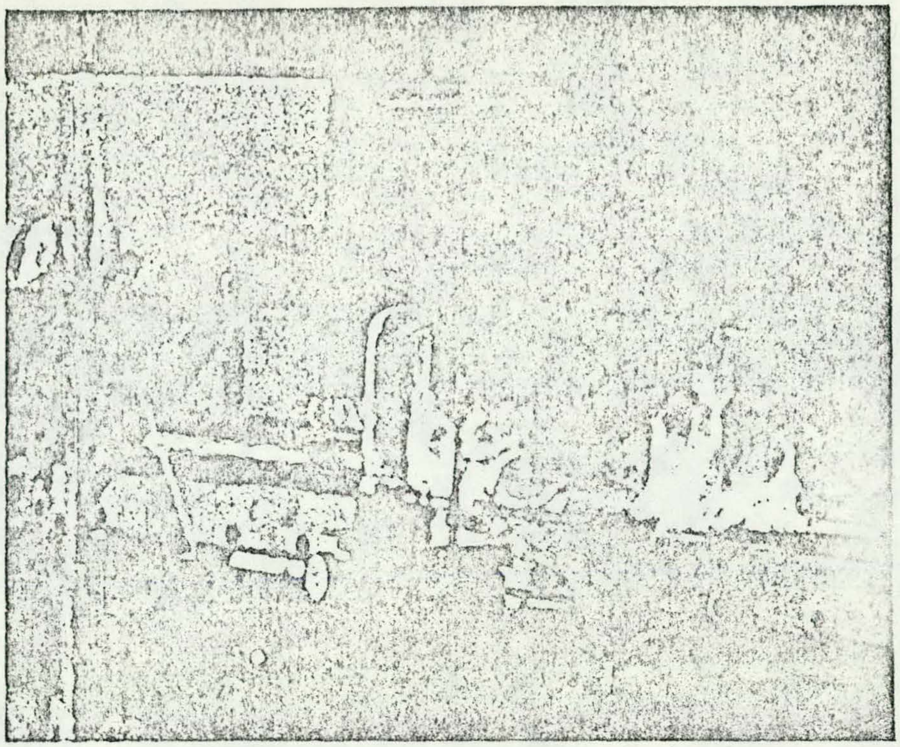
(3) The height of the luminous zone varies rapidly, ranging from 5 to 10 inches above the burning tray.

(4) The time scale for variations of the luminous zone extent is on the order of 1/10 second.

(5) The flame is turbulent with luminous eddies clearly visible.

(6) By tracking the upward progress of small luminous eddies which are shed from the flame, the gas velocity (time-mean) is estimated to be in the range from 3 to 4 feet/second (0.9-1.22 m/s) Variations from this range are quite small, even over a large number of measurements in different cable tray fire tests. Also it does not appear that velocity is decreasing substantially in the vertical direction, at least in the first foot of rise.

These characteristics of the cable fires do not vary greatly from one fire to the next, even though significant variations in the duration are observed.



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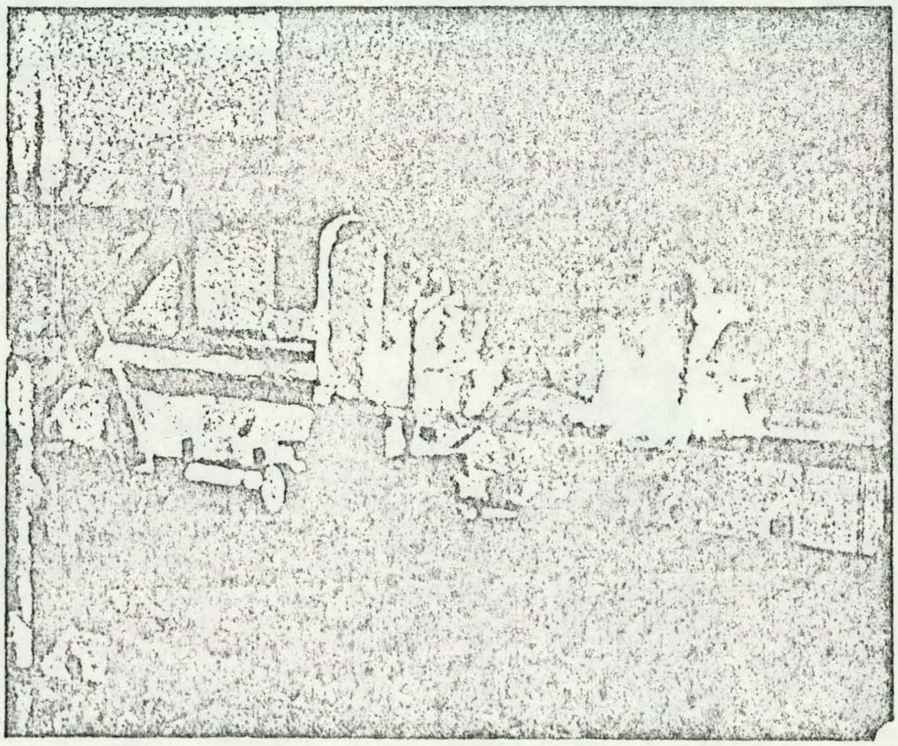

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Figure 8. Cable Tray Fire (1/16 Second between frames)

Flame Temperatures

Radiation thermometry is used to determine the temperature distribution in the fire. At chosen times, photographs are taken through two different narrow band filters ($\Delta\lambda = .03\mu$) which are centered at $\lambda = .55\mu$ and $\lambda = .65\mu$. The negatives are scanned with a microdensitometer to determine the exposure distribution. The intensity of radiation received along a particular line of sight is found by a comparison of the exposure at a particular point (small area) on the negative with that produced by a calibrated lamp which is also in the field of view. The "brightness temperature" or corresponding blackbody temperature for each point is then calculated from the Planck function.[7]

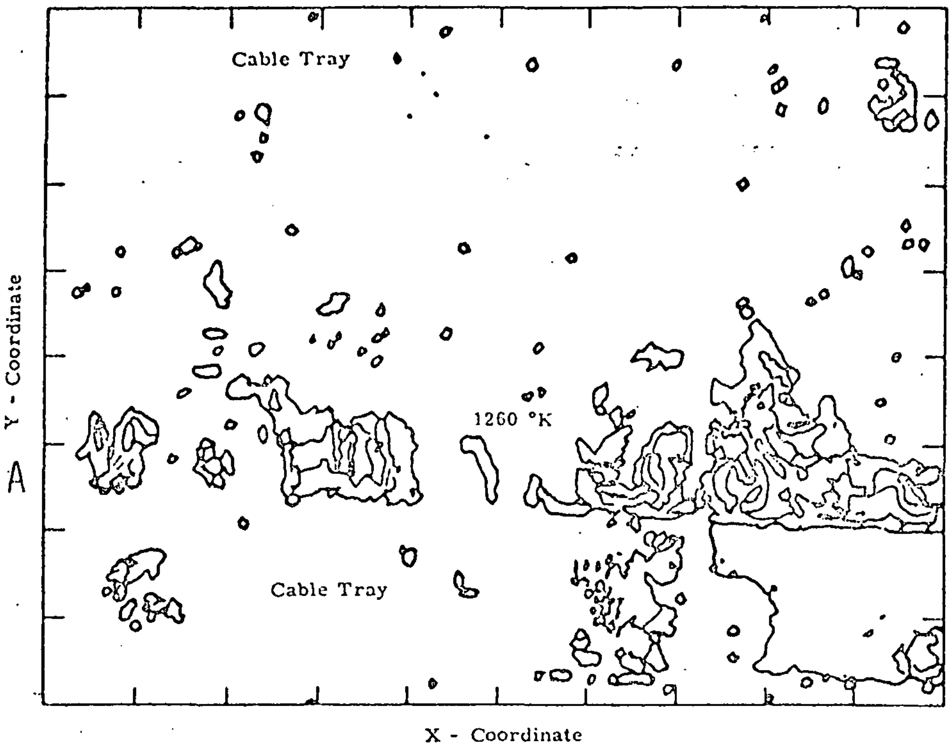
A typical plot of the isotherms (brightness temperature) obtained from the radiation thermometry is included in Figure 9. All areas enclosed by the isotherms are at temperatures above 1260°K, the lower cutoff on sensitivity of the film. Maximum temperatures are roughly 1500°K. Figure 9 also shows the variation of temperature with horizontal position, taken as the hottest vertical location just above the tray (Section A-A in isotherm plot).

Since the flame zone is not optically thick, the apparent emissivity is less than unity and it is necessary to correct the temperature measurements.[7] However, the magnitude of temperature corrections is relatively small. For example, a five-fold reduction in apparent monochromatic emissivity ($\epsilon\lambda = 1.0 \rightarrow 0.2$) only requires a correction of about 100°K between the true temperature of the flame and the above brightness measurements. The measured flame temperatures are well below adiabatic flame temperature, and are in agreement with theoretical expectations.[8]

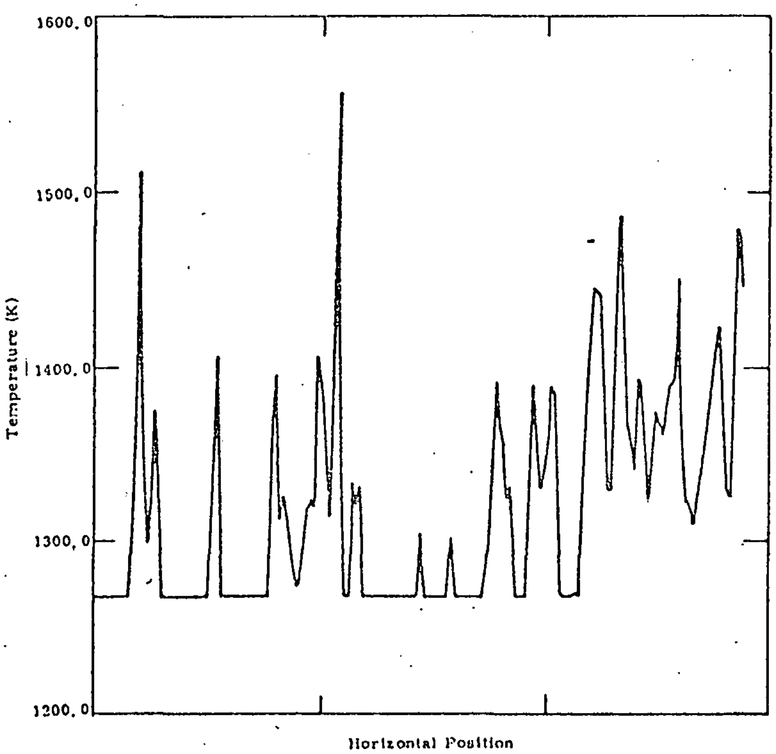
Thermocouples and Calorimeters

The array of thermocouples and copper slug calorimeters above the ignition tray provides two types of information:

(a) heat fluxes (combined convection and radiation) that are determined from the transient temperature response of the calorimeters;



Isotherm Contours



Temperature Profile Along Tray at Height A/A in Above

Figure 9. Photometric Thermometry (11/15/76)

(b) steady state temperature which may be significantly less than the local gas temperature due to radiation through the flame.

Figure 10 shows the temperature response of selected calorimeters (Nos. 1, 7, 9, and 11) and a sheathed thermocouple (No. 2) for the fire test of 5 October 1976. The separation between cable trays is approximately two feet. This particular fire is one of the most intense and longest duration of those studied. It is seen that the intensity of the thermal environment falls off very rapidly in the region from 5 to 11 inches (.13 to .28 m) above the fire. This height roughly corresponds to the the upper edge of the luminous zone.

In view of their relatively slow time response, the calorimeters and even the thermocouple rarely reach a quasisteady temperature level. However, in the fire test of 5 October 1976, thermocouple No. 2 reaches and holds 1150°F for a short period at early and at late times, and in the intervening period the temperature is clearly steady at 700°F. These quasisteady temperatures are confirmed by similar data from calorimeter No. 1 which is also located about 3/8 inch (9.5 mm) above the burning tray. It is noted that these temperatures do not represent local gas temperatures, but rather the temperature of a surface immersed in the flame.

Figure 11 shows the variation of cold-wall heat flux with height above the burning tray for several fires. Each of these data points is calculated from the initial slope of the temperature vs. time curve for a particular calorimeter. It is seen that a significant reduction in heating rate occurs from the base of the flame to the upper reach of the luminous zone. Although these are significant variations in heat flux distribution from one fire to the next, the two more intense fires (October 5 and November 15) are very similar, as are three lesser fires (July 21, August 13, and December 16). It is likely that some of the differences are due to unintentional changes in position of the instrumentation relative to the flame zone because the exact location of the flame could not be controlled.

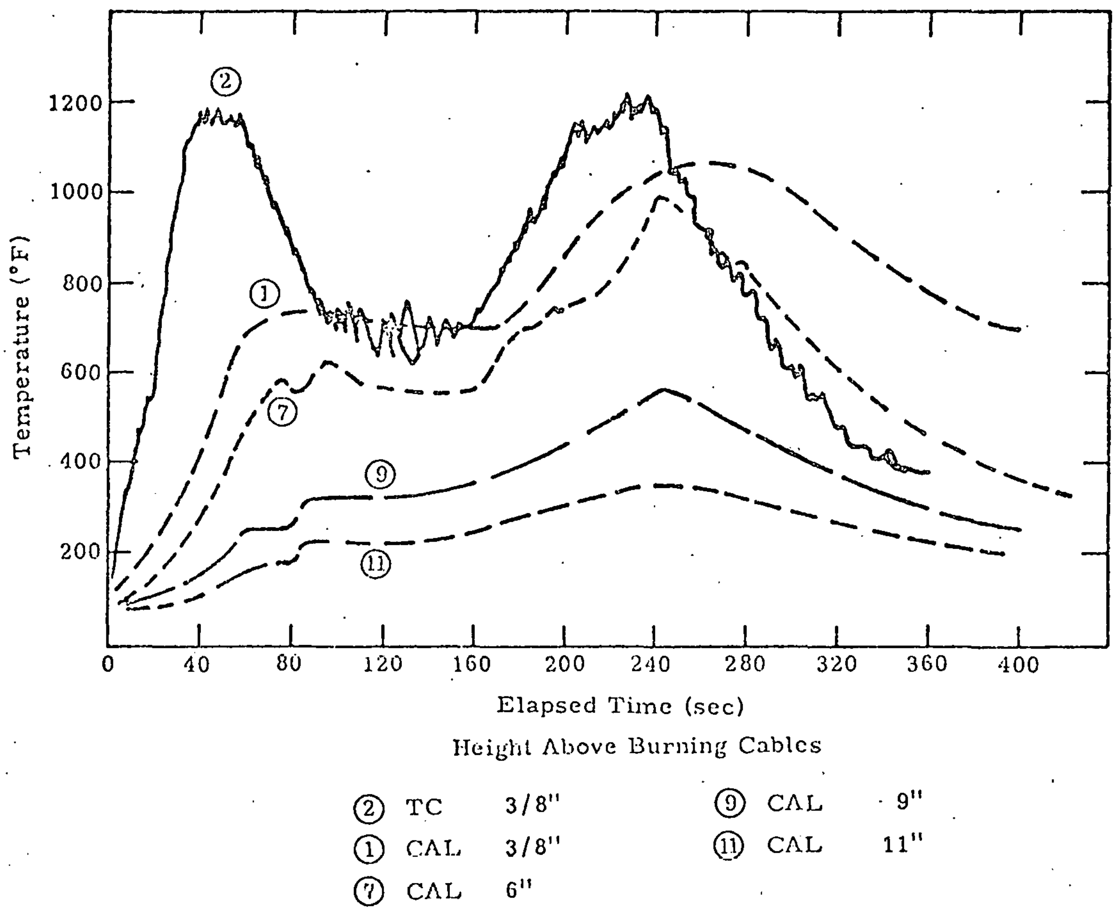


Figure 10. Temperature Response of Thermocouples and Slug Calorimeters (10/5/76)

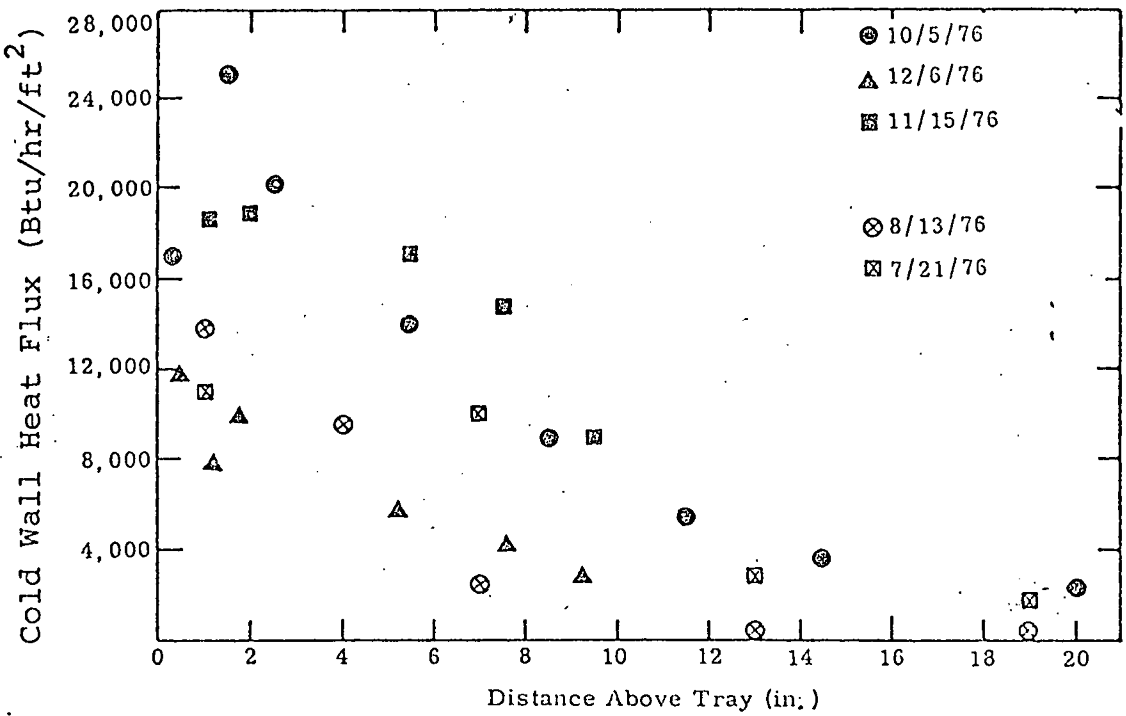


Figure 11. Vertical Variation of Heat Flux

Thermovision

An infrared detection system marketed under the trade name "Thermovision" was used to monitor the cable tray fire tests. The field of view is continuously scanned by a mirror system, and for each point in the field the amplitude of the voltage signal from the detector is converted to a gray "color level" (intensity) which is displayed on a black and white monitor. A movie is made from the monitor to provide a qualitative overview of the development of the fire, and at later times particular frames are extracted for quantitative analysis.

Selected frames from the thermovision movie are scanned by a microdensitometer to obtain a quantitative map of the degree of exposure. The exposure levels are then interpreted as levels of IR radiation intensity using the calibration charts provided by the manufacturer.

Since the broad band (thermovision) measurement of IR intensity is fairly sensitive to the effective flame emissivity, this IR intensity can be used in conjunction with the previous estimates of flame temperature to calculate the flame emissivity. Based on the procedure described by Sato and Matsumoto[9] the total emissivity of the flame is found to be on the order of $\bar{\epsilon} \approx 0.15$. When this result is compared with the theoretical calculations of Felske and Tien[10], it is concluded that particulate (soot) concentrations in flame are on the order of 10^{-6} cm^3/cm^3, which falls within the expected range of concentration.[11,12]

Analysis of Fire Test Data

Heat transfer from the flame to an engulfed object occurs by both convection and radiation. Although the calorimeters provide a measurement of total heat flux, it is also of interest to know the relative importance of convective and radiative contributions. The following paragraphs outline some approximate calculations which answer this question and at the same time show that all of the measurements (flame temperature, total heat flux, velocity, infrared radiation, thermocouples) comprise a reasonably self-consistent characterization of the cable tray fires.

At a location just slightly above the burning tray we have the following measurements of flame temperature, total emissivity, and flame velocity: $T_f \simeq 1300°K$, $\bar{\epsilon} \simeq 0.15$, $V \simeq 3$ ft/sec. Using this velocity and properties of air, the mean convective heat transfer coefficient for a small cylindrical object (e.g., 3/8" colorimeter) is approximately[13] $\bar{h} = 7$ BTU/hr/ft^2/°F. The convective and radiative contributions to the cold wall heat flux can then be separately calculated as follows:

$$q''_c = \left(\bar{h}\ T_f - T_{cw}\right) \simeq 13{,}000 \text{ BTU/hr/ft}^2$$

$$q''_r = \epsilon\sigma\left(T_f^4 - T_{cw}^4\right) \simeq 7{,}000 \text{ BTU/hr/ft}^2$$

This shows that convection accounts for about 67% of the total flux. Note that the total heat flux (convection and radiation) is in good agreement with the calorimeter data shown previously in Figure 11.

In view of the above calculations, it is useful to reconsider the vertical variations of cold-wall heat flux shown in Figure 11. It is seen that the heat flux is roughly 13,000 BTU/hr/ft^2 (the nominal convection rate) at a height of 5 to 7 inches (0.13-0.18 m) above the tray. From the color movies, this level also corresponds to the time-mean height of the luminous zone. It is therefore expected that convection dominates above this level. In the upper nonluminous region the gas temperature falls off rapidly due to entrainment of cool air and turbulent mixing. At a height of 10 inches (0.25 m) above the fire the cold-wall heat flux is only about 6,000 BTU/hr/ft^2, which corresponds to a local gas temperature of 1000°F (900°K), assuming convection alone and a velocity of 3 ft/sec (0.91 m/sec).

Since the flame is optically thin, a cylindrical object placed in the fire (thermocouple, calorimeter, cable) will, if the fire continues long enough, reach an equilibrium temperature which is well below the temperature of the surrounding medium. This steady-state surface temperature T_s can be estimated from the following energy balance in which heating of the surface by convection and radiation is equated with the cooling afforded by radiation from the surface which passes through the flame to the cool surroundings at T_∞:

$$\bar{h}\left(T - T_s\right) + \bar{\epsilon}\sigma\left(T^4 - T_s^4\right) = (1 - \bar{\epsilon})\sigma \left(T_s^4 - T_\infty^4\right)$$

At a point near the tray, $T \simeq 1300°K$, $\bar{\epsilon} \simeq 0.1$, and $\bar{h} \simeq 7$. These values give a steady surface temperature of about 1100°F (870°K), in good agreement with the quasisteady temperature recorded by thermocouple No. 2 in Figure 10. Note that calorimeter No. 1 also approached this temperature before the fire began to die out.

It is interesting also to calculate the equilibrium surface temperature at a height of 10 inches (0.25 m) above the tray. Based on the measurement of cold-wall heat flux the local gas temperature was estimated as 1000°F, assuming convection alone. Using the steady energy balance with T = 1000°F, the equilibrium surface temperature at the 10 inch (0.25 m) level is approximately 650°F.

The above estimates of equilibrium surface temperature are indicative of the steady state surface temperature of a single electrical cable which is subjected to fire. In an overlying tray, cables are closely spaced and the details of the geometric configuration become important. Thus, higher surface temperatures probably are attainable because radiant losses from the exposed cable are blocked by adjacent cables and convective velocities may be higher than in the single cable configuration. On the other hand, the duration of the fire may not be sufficient to realize equilibrium conditions, as was usually observed with thermocouples and slug calorimeters in the test fires. In any case, the temperature of exposed cables cannot exceed the temperature of the surrounding medium which is estimated as roughly 1000°F at a height of 10 inches (0.25 m).

Summary of Characterization

Essential features of the cable tray fires are outlined below. Although based on worst case conditions, these observations are generally representative of the entire sequence of fire tests.

(1) The intense period of the fire persists at a particular location for between 40 and 240 seconds before die-out begins to occur (e.g., 240 seconds in Figure 10).

(2) The luminous flame zones fluctuate rapidly between 4 and 10 inches (0.1-0.25 m) in height.

(3) Gas temperature in the luminous zone is roughly 1900°F (1300°K).

(4) Gas temperature at 10 inches (0.25 m) above the burning tray is estimated as 1000°F.

(5) Velocity of rising gasses is approximately 3 to 4 feet/second (0.91-1.22 m/sec).

(6) The luminous zone is optically thin with an apparent emissivity on the order of $\bar{\epsilon} = 0.1$.

(7) Heat transfer to immersed objects is convection dominated with radiation accounting for no more than 30% of the total heat flux, even in the luminous region.

(8) Equilibrium surface temperature of engulfed cylindrical objects varies from about 1200°F just above the tray to 650°F at a height of 10 inches (0.25 m).

Although the above measurements and analytical estimates are approximate, they are indicative of the gross characteristics of the fire.

It is noted that the present cable tray fires differ greatly from large fires which are often considered in safety studies. Due to the small physical dimensions of the present flame, radiation from the flame is less than 20 percent ($\epsilon \leq 0.2$) of that encountered in large fires, and convection therefore dominates. In large fires convection usually accounts for less than 25 percent of the total heat transfer[14]. Also, objects immersed in a large fire will eventually reach temperature equilibrium with the flames. This may not occur in the optically thin cable tray fires because an engulfed surface is able to radiate through the flame to the cool surroundings. Thus, the cable tray fires comprise a considerably less severe thermal environment than a large fire, even though the flame temperatures are of comparable magnitude for the two cases.

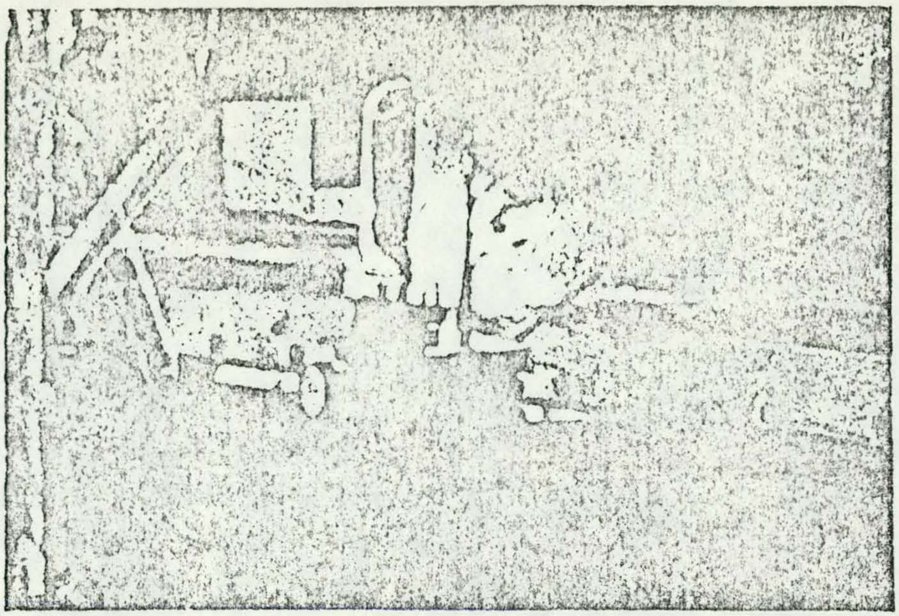
Summary and Conclusions

The first objective was to obtain data through experiments to aid in evaluating the effectiveness of cable tray separation as a means of assuring functional integrity of redundant safety systems. The first task undertaken to meet this objective was to survey the industry in order to determine current design practices particularly with regard to the materials used. Of these materials primary interest was focused on types of electrical cable constructions being used in new nuclear power plant design. A screening test was applied to these types in order to concentrate on two electrical cable constructions representing a conservative approach. The evaluation covered separation of protective systems in areas of the plant where power cables are included and no source of fuel exists except that provided by the cable materials. Thus, all fires in this project have been electrically initiated.

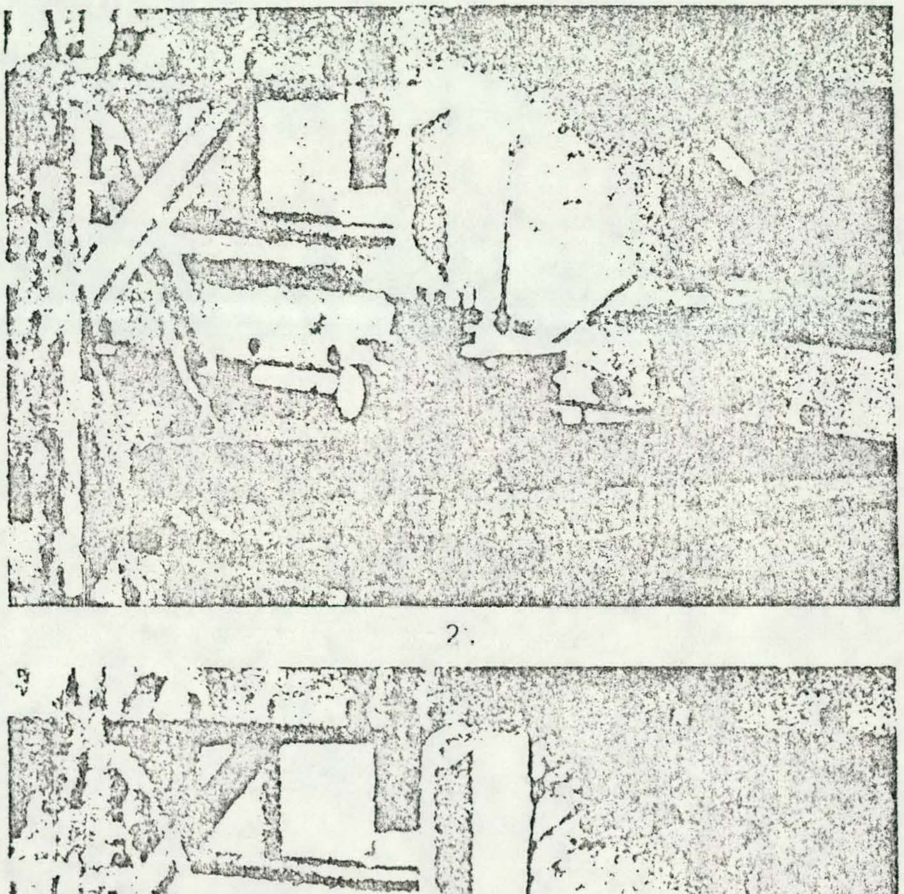
Seven quick-look reports[15-21] and a progress report[22] have been issued describing full scale tests included in the period covered by this paper. Separation distances between cable trays of 5 feet (1.52 m) vertically and 3 feet (0.91 m) horizontally were used in phase one tests. Four tests were run in phase two with spacing reduced in stages to 10.5 inches (0.27 m) vertically and 8 inches (0.20 m) horizontally. Phase three involved three tests of a large matrix of trays arranged in such a manner that 14 cable trays closely spaced represented one division while 3 trays separated 5 feet (1.52 m) vertically and 3 feet (0.91 m) from that matrix represented the redundant division. In all these tests an overcurrent in one or two 12 AWG conductors of an electrical cable in an open cable tray was the source of fire. Trays were filled with electrical cable to the top of the 4 inch (0.10 m) siderails.

Fire initiation appears to be from combustible gas initiation as seen in pictures taken during that time period. Typical of this initiation is the sequence taken during initiation of a fire on November 15, 1976. This is shown by Figure 12 where the gaseous ignition appears beyond a photometric calibration lamp.

The maximum duration of any fire obtained was 29 minutes with the mean time approximately 6 minutes. At no time did the cables in trays displaced from the ignition tray begin to burn. All circuits in these trays remained functional and elongation measurements taken of insulation closest to the fire showed no major (< 10%) change.



1.



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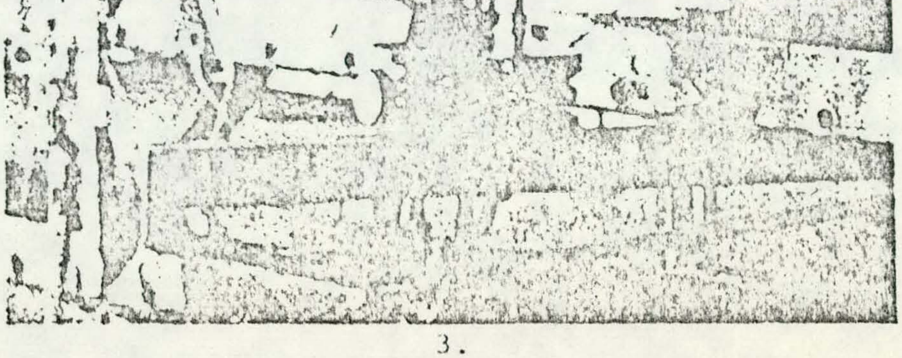

3.

Figure 12. Ignition Mechanism (1/16 second between frames)

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