

A mining research contract report
October 1984

STANDARD TEST CRITERIA FOR EVALUATION OF UNDERGROUND FIRE DETECTION SYSTEMS FINAL REPORT

(Phases I - IV)

Contract H0113017
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BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR





STANDARD TEST CRITERIA FOR EVALUATION OF UNDERGROUND FIRE DETECTION SYSTEMS

Prepared for
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

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Final Report (including Phase IV)

Contract No. H0113017

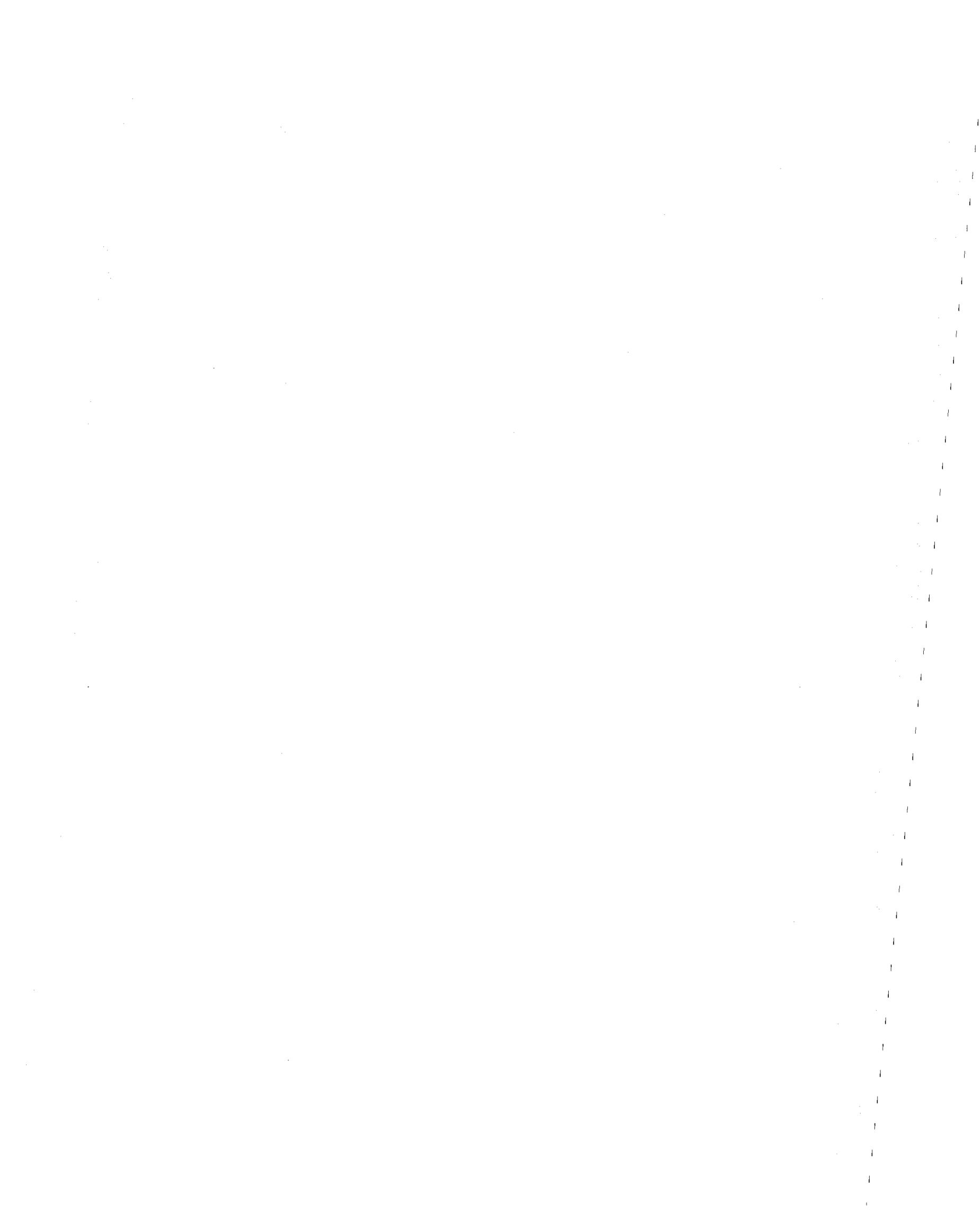
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FOREWORD

This report was prepared by Factory Mutual Research Corporation (FMRC), Factory Mutual System, Norwood, Massachusetts under USBM Contract No. H0113017. It was administered under the technical direction of the Pittsburgh Research Center with Dr. A. F. Cohen acting as Technical Project Officer. Mr. A. G. Young was the contract administrator for the Bureau of Mines. The report is a summary of the work recently completed as part of this contract during the period November 20, 1983 to August 30, 1984. The report was submitted by the authors on October 15, 1984.

The authors wish to acknowledge gratefully the following persons who contributed to this project: Mr. S. D. Ogden and Ms. J. A. Steciak for assistance in data acquisition and analysis; Dr. A. F. Cohen, Dr. G. Heskestad and Dr. A. Tewarson, for valuable contributions; and Mr. L. A. Post and Ms. J. L. Dower for their efforts in producing this report.



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I

INTRODUCTION

This program to establish standard test criteria and procedures for the evaluation of underground mine fire detection systems has been accomplished through the following tasks:

- 1) assessment of the combined effect of the preignition mine environment and mine material fire characteristics;
- 2) definition of detection criteria;
- 3) development of a test program capable of evaluating detector spacing requirements;
- 4) design and construction of the necessary test apparatus to evaluate fire detection systems under simulated mine fire environments;
- 5) quantification of several mine fire sources;
- 6) evaluation of several fire detector types including heat, CO and CO₂ gas, and ionization smoke detectors, including the development of a response theory;
- 7) establishment of spacing criteria; and
- 8) development of performance specifications.

These tasks are described individually in the following sections.



II
PROGRAM SUMMARY

2.1 ASSESSMENT OF MINE FIRE ENVIRONMENTS

The technical approach initially consisted of a review of the literature coupled with an analysis of Factory Mutual Research Corporation's (FMRC) existing experimental data in related areas. This review and analysis indicated several areas in which important data were lacking. Primarily, additional data were required to fully assess the stratification of combustion products from a fire in a mine passageway. Therefore, a test program was designed and conducted to obtain the necessary data.

Figure 1 is a sketch of the large-scale mine gallery used in the tests. The gallery is a T-shaped structure with two passageways (drifts), each about 47 m long and about 2.4 x 2.4 m in cross-sectional area. The following variables were investigated in the tests: 1) fire source (both heat release rate and fuel type); and 2) ventilation air velocity. The heat release rates from the various fire sources ranged between 10 kW and 20 MW. The ventilation air velocity was varied between 0.5 and 4.0 m/s. The heat release rates and velocities were selected to give a wider range in the ratio of the heat release rate to the mass flow rate than previous data.

Significant test results from this program were obtained for four major parameters: 1) the source fire heat release rate; 2) the average gas temperature rise downstream of the source fire; 3) gas temperature stratification; and 4) the distribution of combustion products. Details of the analysis of these results are presented in References 1-4.

A heat balance equation was developed which fits the full-scale test data very well and from which the average gas temperature rise at a given distance downstream of the source fire versus time could be predicted if the heat release rate of the source fire was known.

In addition, general relationships for critical conditions required for ignition and flame propagation in mines have been obtained (3). With respect to stratification, the stratification results (4) have a direct impact on flame spread analysis, fire detection control, or extinguishment requirements and fire hazard evaluations such as for determining the possibility of human escape.

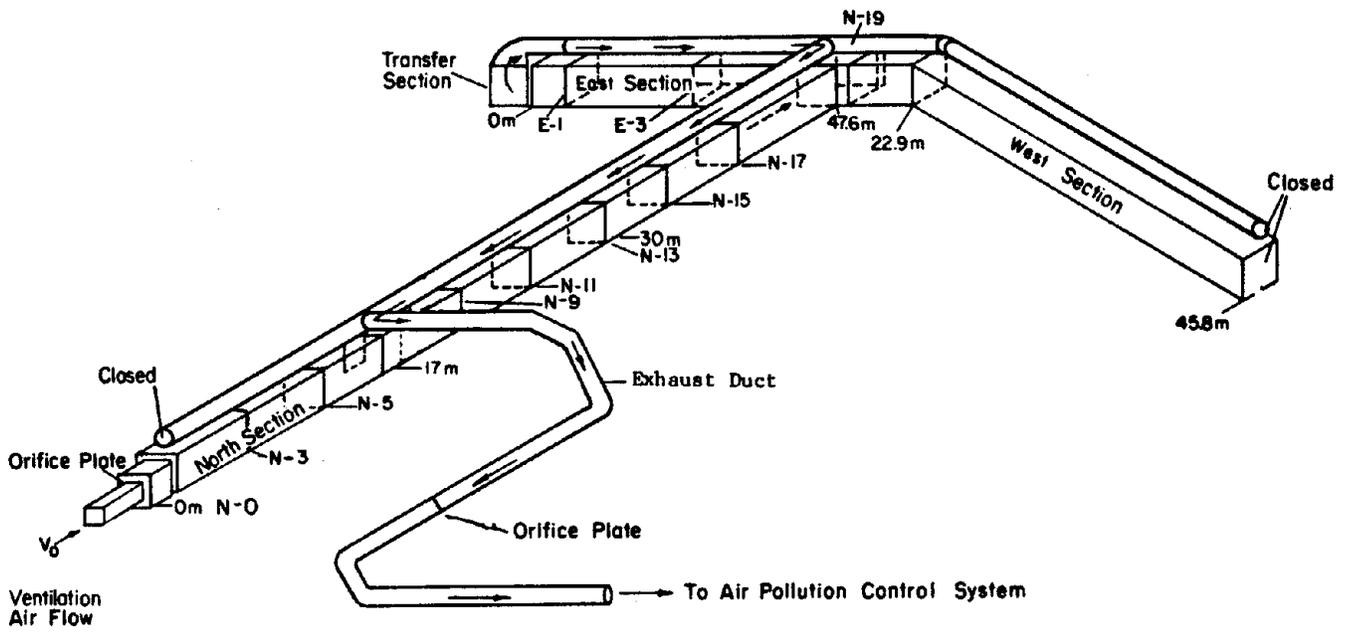


FIGURE 1.- Schematic of the simulated mine gallery

2.2 DETECTION CRITERIA

A universal set of detection criteria have been defined relative to the application of fire detectors in underground mines. This required a time relationship to be established to detect a fire, the time to "effectively" respond after detecting a fire, and the time after the initiation of a fire to reach a defined hazard, i.e., a fire, which becomes seriously life and/or property threatening. This relationship is defined by the following expression:

$$t_r \equiv t_H - (t_t + t_f + t_D + t_E) \geq 0 \quad (1)$$

where t_r = residual time;

t_H = time to specified hazard;

t_t = transit time;

t_f = fire growth time to reach detectable level of fire product;

t_D = detection time once t_f has occurred; and

t_E = "effective" response time once fire has been detected.

The residual time is either zero or positive and is a function of five individual times. The results of the initial program phase have been applied to accurately determine t_t (1) and t_D has been quantified for a variety of detectors (see Reference 5 and Section III). However, t_H , t_f , and t_E are more difficult to quantify.

t_H depends on the defined hazard which is a function of the material properties and configuration. For example, previous work (3) has defined the propagation hazard for timber sets in mines relative to a heat flow parameter and a critical flux. When this parameter is greater than or equal to a given value, a fire will propagate. However, in this example, the "smoke" hazard might be defined as either more important for human escape or occurring more quickly than the propagation hazard. Thus, the time to the smoke hazard would be used for t_H . Table 1 gives some samples of tentative critical values for human escape. These critical values, therefore, could be used to define the level of the hazard. The characteristics of the material(s), the fire configuration, and growth rate must be specified as well to determine the time to this level, t_H . In addition, when coupled with the response characteristics of a given fire detector, these quantities define t_f .

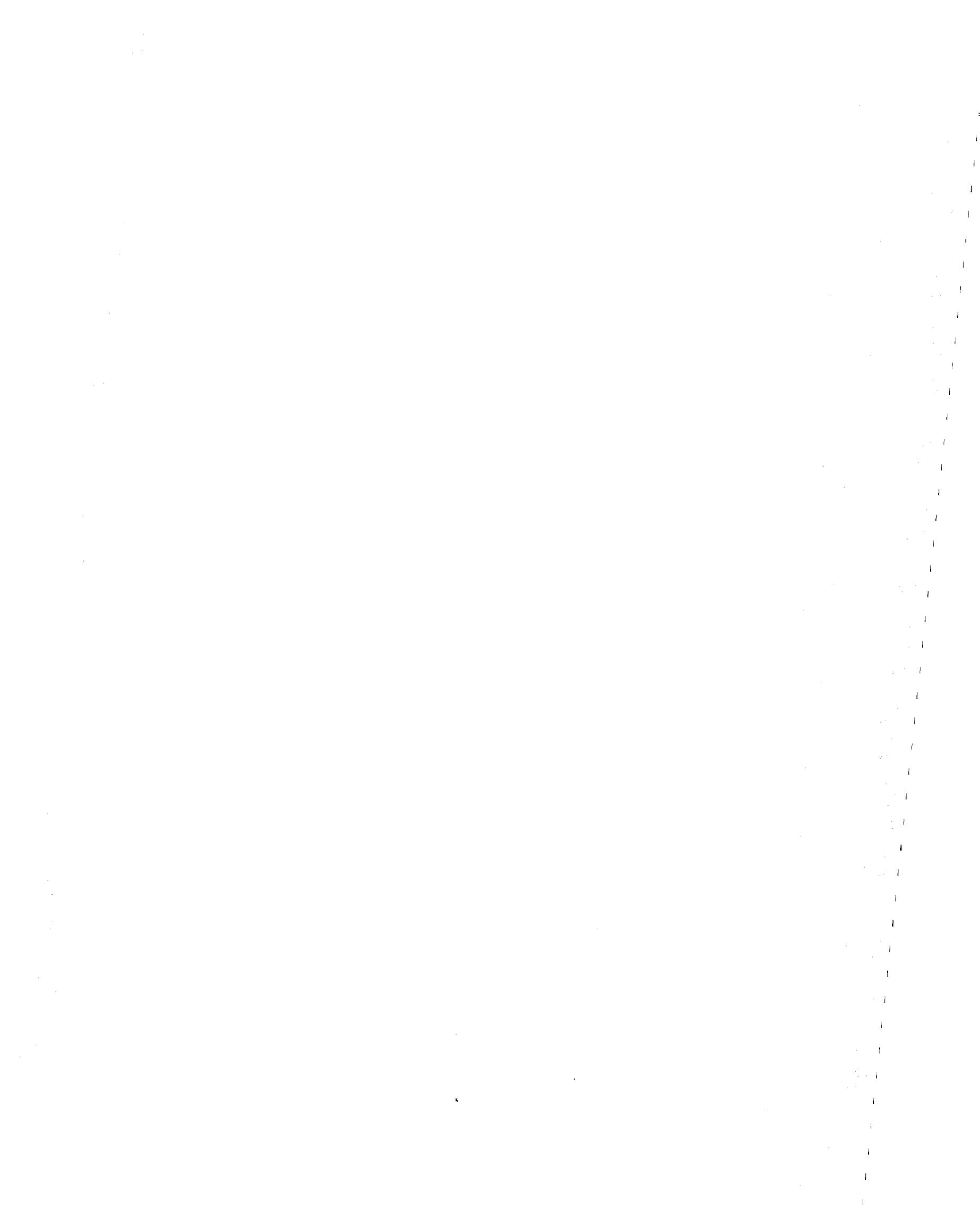


TABLE 1. - Tentative critical values for human escape from fires for tolerable short term exposure* to fire products

Compound	Tentative Critical Values for Human Escape (ppm)**
HCN	30-100
HCl	50-1,000
Benzene	1,500-4,000
NO + NO ₂	100
SO ₂	150
Cl ₂	50
COCl ₂	12.5
NH ₃	2,500
CO	1,500-4,000
CO ₂	40,000-80,000
O ₂	60,000-100,000
Temperature (°C)	140
Smoke (OD)	0.22 m ⁻¹

*Times ranging from 1 to 30 min

**Data from References 6-9



The effective response time, t_E , can be more difficult to assess than t_H or t_f . t_E depends on the individual mine configuration, the location of the fire, and primarily on the method of response to the fire, such as automatic or manual fire fighting, ventilation control (e.g., fire doors), or simply evacuation. Thus, t_E could vary from the order of seconds, as in the case of automatic sprinklers, to the order of hours as in the case of the evacuation of deep mines. In conclusion, t_E can probably best be quantified on the basis of mine experience, practice, and procedures.

2.3 DESIGN OF SENSOR EVALUATION TEST PROGRAM

The design of a sensor evaluation test program allows for the evaluation of detector spacing requirements as influenced by fire and environmental parameters of an underground mine.

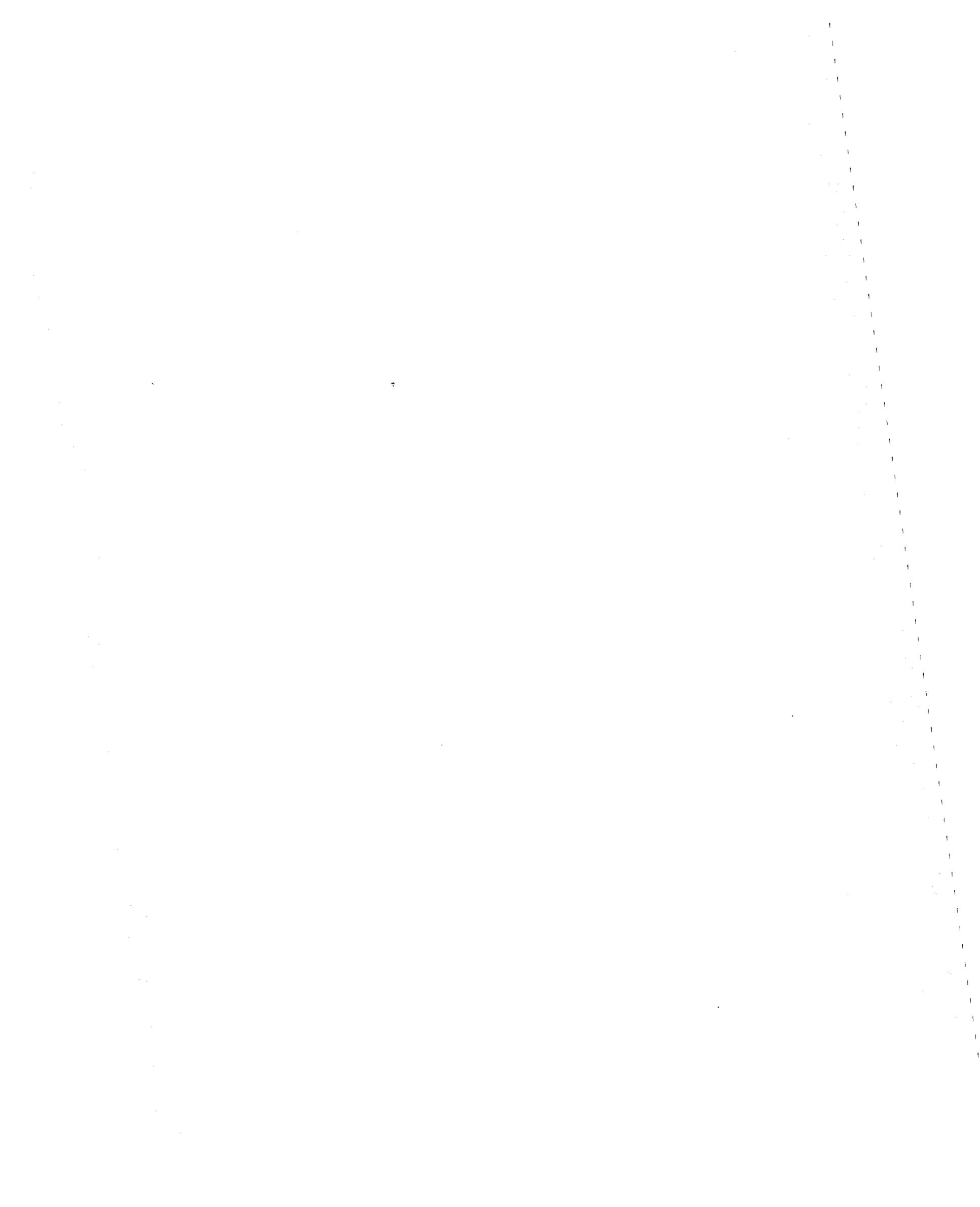
Tests to measure detector characteristics consist of baseline tests and use tests. Baseline tests provide information necessary for the evaluation of the detector characteristics under fire environment conditions. These tests measure:

- 1) calibration (if required);
- 2) warm-up (if required);
- 3) noise/drift (if required);
- 4) characteristic time; and
- 5) characteristic response.

Use tests specify testing conditions which provide information to extend the baseline evaluation of the device characteristics to field ambient environments. Use tests could consist of:

- 1) interference (secondary gas species, electromagnetic); and
- 2) environment (temperature, pressure, humidity, dust, orientation, velocity, shock, vibration, etc.).

After evaluation in the test apparatus, it is suggested that the selected detectors be installed, in the field, within an existing underground mine to test for the effects of: temperature, humidity, pressure, dust shock, vibration, etc. Alternatively, some of these effects could be simulated using environmental testing procedures as suggested in Reference 10. After the in-field underground mine conditioning or simulated environmental conditioning, the fire detectors could be further tested in the test apparatus to determine response characteristics versus source fire and ventilation rate.



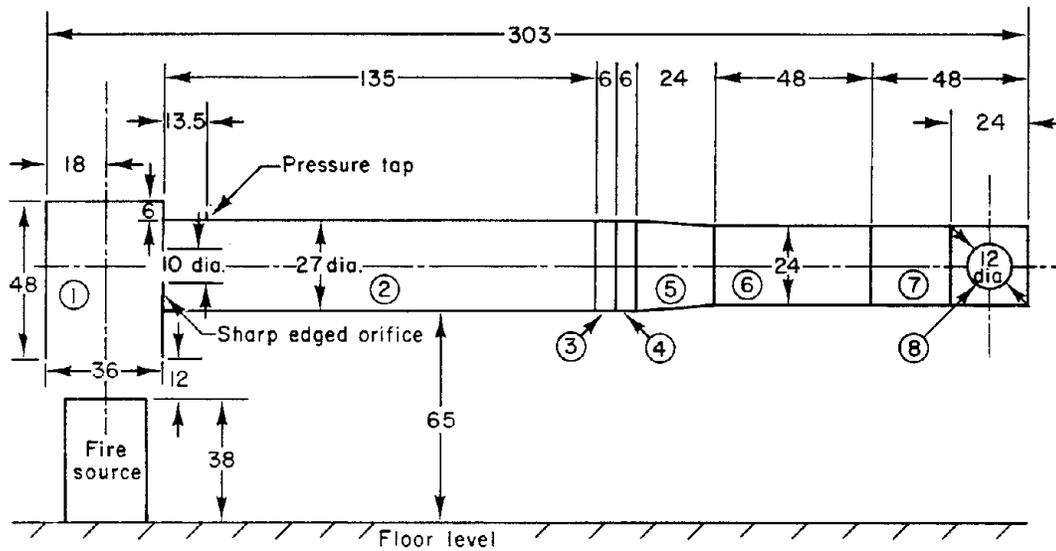
In addition to the above described tests, other possible use tests could consider: durability (stability, operation, and shelf lifetime); human factors (safety, information transfer, workmanship, special features); and support (device manual, repair and maintenance procedures, quality assurance practice and procedures).

2.4 DESIGN AND CONSTRUCTION OF THE TEST APPARATUS

The test apparatus configuration developed in this program is shown in Figures 2-4. Detailed design drawings are given in Reference 2. This apparatus consists of essentially two parts: 1) a fire source and 2) a duct work for combustion product collection and distribution.

In operation, all of the fire products (i.e., materials typical of a mine environment) generated by the fire source together with room air are drawn into the intake section (see Figures 2 and 3) by a downstream exhaust blower. After passing through the intake section, the total mass of fire products and room air mixture flow, in proportion to the setting of the blast gate, through the orifice plate positioned at the upstream end of the mixing section. Optical density and particle size of gaseous products are determined by a smoke turbidimeter. Gas concentration data for determination of mass generation rates of CO, CO₂, H₂O and total hydrocarbons, together with associated temperatures, are collected at the "measuring section" while gas velocity is determined by measuring the differential pressure across the upstream orifice plate. Measurements of gas as well as duct wall temperatures are also obtained. The "test section" is suitable for testing up to four fire detectors at one time. Test section view ports are provided for visual observation, and separate ports for gas flow velocity and temperature probes are also included. After passing through the test section, the gas flows through the transition ell and is exhausted through the blast gate and outlet duct to the exhaust blower.

The fire source apparatus is capable of generating products of fire from a variety of fuels typical of those found in an underground mine environment, e.g., coal, wood, conveyor belting, flammable liquids, etc. In addition, the amount of fire products generated by a specific fuel is adjustable by: 1) varying the surface area of the fuel up to a maximum of 0.3 m x 0.3 m (12 in. x 12 in.) or typically 0.2 m x 0.2 m (8 in. x 8 in.) with the quartz tube in place (see Figure 4); and 2) varying the external heat flux applied to the fuel surface up to a maximum of approximately 85 kW/m².

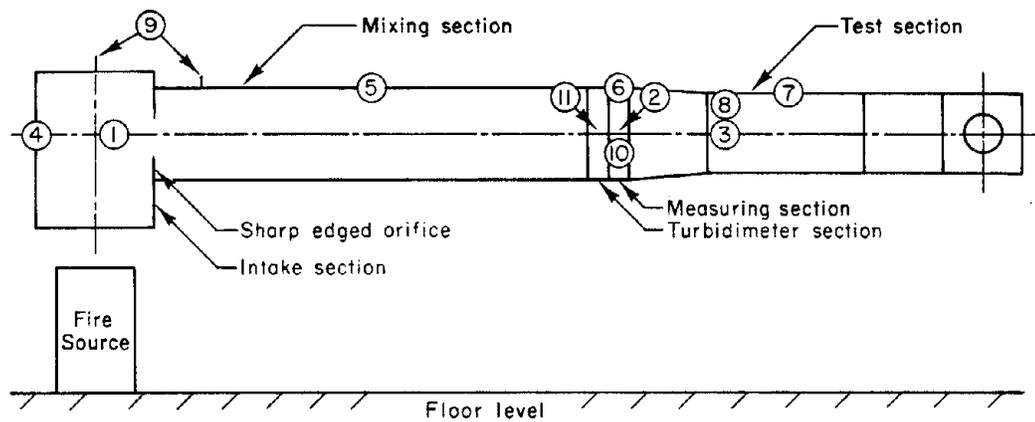


NOTES :

All dimensions in inches

- ① Intake section (square duct)
- ② Mixing section (round duct)
- ③ Turbidimeter section (round duct)
- ④ Measuring section (round duct)
- ⑤ Transition section (round to square)
- ⑥ Test section (square duct)
- ⑦ Transition ell (square to round)
- ⑧ Blast gate (stock type 12 in.)

FIGURE 2. - Test apparatus schematic (elevation view)



LOCATION	INSTRUMENTATION DESCRIPTION
① - ③	Gas temperatures
④ - ⑦	Wall temperatures
⑧	Pilot - static probe
⑨	Differential pressure transducer
⑩	Gas sampling probe
⑪	Smoke turbidimeter

FIGURE 3. - Duct instrumentation

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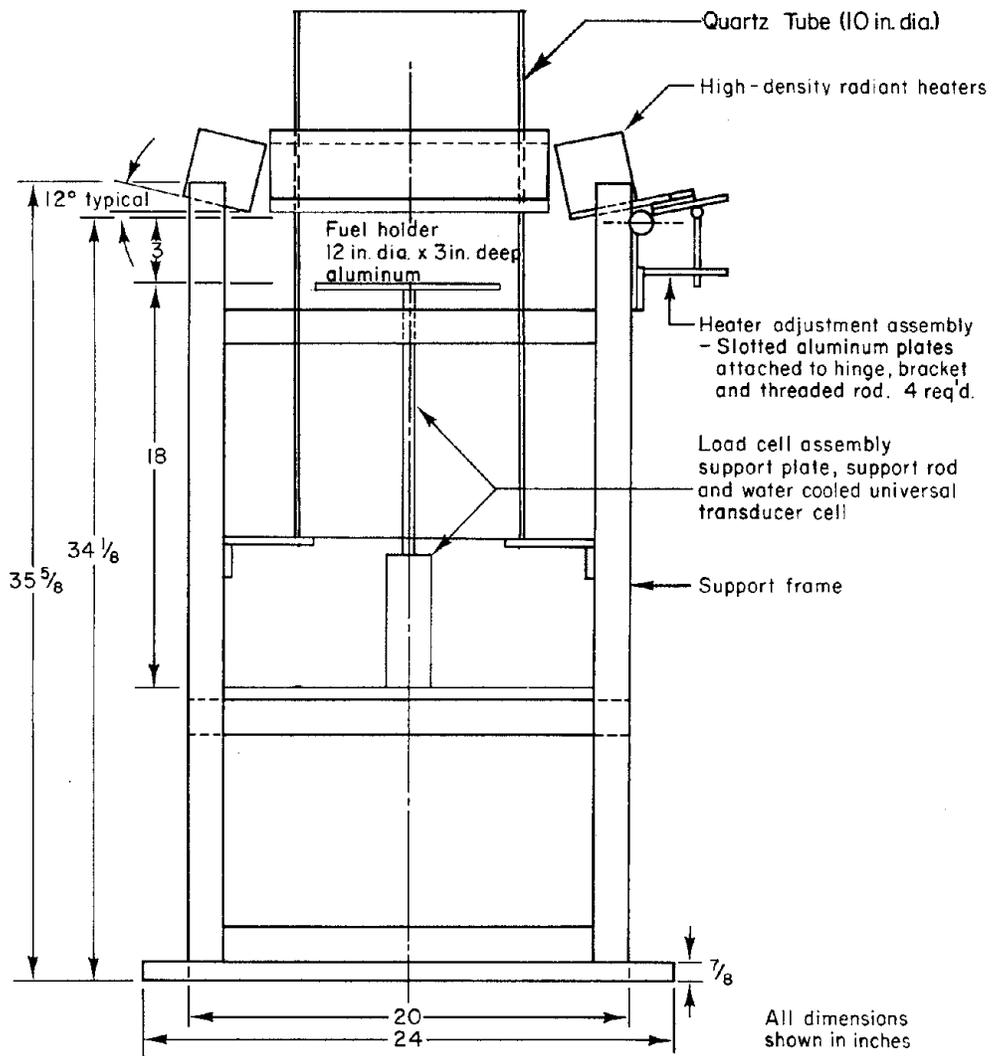


FIGURE 4.- Fire source apparatus

2.5 QUANTIFICATION OF MINE FIRE SOURCES

A number of research efforts (11-14) have resulted in the characterization of the fire properties for a variety of materials which could be present within an underground mine. The following properties are considered important in the assessment of the influence of any specific material on the post-ignition environment in a mine: 1) the mass loss rate per unit surface area, \dot{m}'' ; 2) the actual heat of fire of the material, H_A (determined by the ratio of the actual heat release rate per unit surface area, \dot{Q}_A'' to \dot{m}''); and 3) the fractional yield of the fire product species i , Y_i (defined as the ratio of the mass generation rate of species i to the total mass loss rate). These properties combined with the mine geometry and the ventilation conditions determine the mine fire environment. Previous efforts have quantified the influence of the fire source characteristics on the mine fire environment (1-4).

Recent efforts have focused on: 1) supplementing previous data for combustion properties for mine materials, particular for coal; and 2) defining "standard" fire sources for detection purposes.

In this program, six materials were selected for extensive evaluation of combustion characteristics using the test apparatus - Pittsburgh seam coal, styrene butadiene rubber (SBR) belting, wood (Douglas fir), polystyrene, polyvinyl chloride (PVC), and heptane. Pittsburgh seam coal, SBR belting, and Douglas fir were chosen as typical potential fire sources in the underground coal mine environment and therefore important to quantify for fire detection evaluation. Polystyrene, PVC, and heptane were selected as well-defined and reproducible fuels which can be used to generically represent a variety of materials, e.g., electrical cabling, belting, lubricating fluids, diesel, and other liquid fuels.

Table 2 gives a summary of the following fire characteristics for Pittsburgh seam coal, SBR belting, Douglas fir, PVC, and polystyrene at applied external flux $\dot{q}_e'' = 40 \text{ kW/m}^2$, and heptane with no external flux: 1) fractional yields, Y_i , where $i = \text{CO}_2, \text{H}_2\text{O}, \text{CO}$ and THC (total hydrocarbons); 2) mass attenuation coefficient (m^2/g) at $0.4579 \mu, \xi$ (defined as the ratio of the optical density (base e in m^{-1}), OD , to the mass loss rate, \dot{m}'' , times the volumetric flow rate, \dot{V}); 3) H_A ; 4) χ_A , combustion efficiency (defined as the ratio of H_A to the theoretical heat of combustion); 5) \dot{m}'' at steady state; and 6) \dot{m}''/\dot{q}_e'' .



TABLE 2. - Fire source quantification

Fuel	Coal ^b	SBR Belting ^b	Polystyrene ^b	Heptane	Douglas Fir ^b	PVC ^b
Y_{CO_2} (g/g)	0.96	1.28	1.88	2.84	1.44	0.46
Y_{H_2O} (g/g)	NA	0.76	0.83	1.30	NA	-
Y_{CO} (g/g)	0.030	0.059	0.097	0.008	0.003	0.049
Y_{THC} (g/g)	0.0001	0.0070	0.0224	0.0005	0.0033	0.033
ξ (m ² /g)	0.70	1.40	1.82	0.38	0.05	1.25
H_A (kJ/g)	9.5	16.9	24.5	41.0	13.4	6.0
χ_A^a	0.28	0.49 (0.49)	0.62 (0.65)	0.93(0.90)	0.81	0.37
\dot{m}'' (g/m ² s)	NA	17	38 (38) ^c	32 (62) ^c	16	13
\dot{m}''/\dot{q}'' (g/kJ)	NA	0.43	0.95	NA	0.40	0.33

^abased on CO and CO₂ or H₂O (in parentheses) showing that either C or H balances give similar results

^bmeasured at $\dot{q}_e'' = 40 \text{ kW/m}^2$

^casymptotic limit

NA - not applicable



The data for Douglas fir, PVC, polystyrene and heptane combustion characteristics are in good agreement with previously reported results (13, 14). The data for SBR belting are also in good agreement with limited data from the literature (11). Although no data are available for comparison with the Pittsburgh seam coal flaming combustion results, the pyrolysis mass loss rates (15) as discussed in Reference 5 have been shown to be consistent with current combustion data and equally well-characterized by the analytical expression given by eq (1) in Reference 5.

In conclusion, needed data for fire source quantification have been accurately obtained. These data will be used for: 1) fire detector evaluation as described in Section 2.6; and 2) fire detector spacing guidelines as a function of the fire source (and corresponding fire environment) which are reported in Section 2.7.

2.6 FIRE DETECTOR EVALUATION

The response characteristics of fire detectors may be initially described by the detector type. Generally, fire detectors may be classified as either: 1) heat detectors, which include the fixed temperature type and the rate-of-rise type; or 2) product(s) of combustion type, which includes ionization detectors, photo-electric detectors and gas detectors. For each detector type, the response characteristics of the detector may be measured by a combination of the following factors:

- 1) response (alarm) time;
- 2) temperature, rate of temperature rise, velocity, obscuration, gas concentration, etc. of local environment; and
- 3) repeatability (precision), reliability, etc.

Selected heat detectors were evaluated using a "plunge-test" tunnel which is conventionally used for sprinkler approval (16). Selected product of combustion type detectors were evaluated using the test apparatus shown in Figure 3 under laboratory ambient conditions with the source fires described in the previous section to simulate mine fire environments.

2.6.1 Heat Detector Evaluation

The "plunge" test method (16) consists of suddenly immersing an object, such as a heat detector (or sprinkler), in a gas flow of constant temperature and velocity. This method allows accurate and reproducible measurements of



heat detector sensitivity and provides test results that are directly relatable to the expected performance of the heat detector in the field. The test apparatus, as shown in Figure 5, is a closed-circuit, hot-air tunnel, heated electrically, and incorporates an insulated test section with a test velocity of approximately 2.5 m/s. Other details are given in Reference 16.

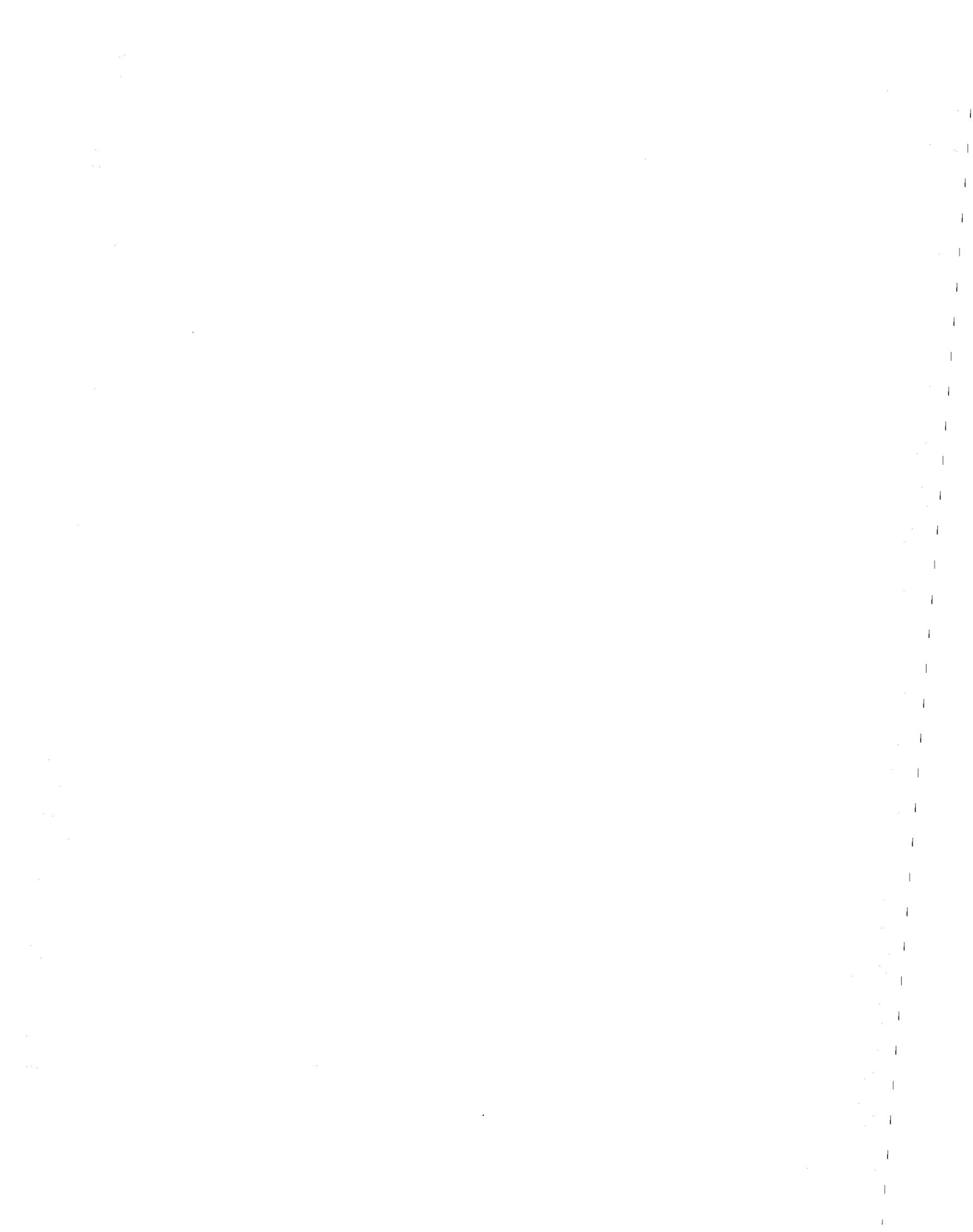
Previous work (16) has shown that the only variables of importance in the response of a sensing element of a sprinkler (or heat detector) are the actuation temperature ("temperature rating") and the time constant, τ . In addition, the time constant has been shown to depend on the square root of the gas velocity. Therefore, if the time constant is known at a reference velocity, v_0 , the time constant at any other velocity, v , can be calculated from:

$$\tau = \tau_0 (v_0/v)^{1/2} \quad (2)$$

where τ (s) corresponds to v (m/s) and τ_0 (s) corresponds to v_0 (m/s). For convenience, the product $\tau v^{1/2}$ is used as measure of sensitivity and is termed the "Response Time Index" or RTI. Therefore,

$$\text{RTI} = \tau v^{1/2}. \quad (3)$$

Values of the RTI for three types of heat detectors used in "mine-permissible" systems are given in Table 3. As shown, these values vary over a wide range between 12 and 382 (m s)^{1/2}. To put these numbers in perspective, the estimated range of RTI values for UL-listed heat sensors is approximately 40-120 (m s)^{1/2}. Further, Factory Mutual approved sprinklers range in RTI from approximately 100-400 (m s)^{1/2}. These numbers should also be compared to the "ideal" heat sensor referenced in Title 30 CFR 75.1103 for spacing specifications. A close approximation to an ideal heat sensor would be a fine wire thermocouple. For example, a 0.25 mm (0.01 in.) dia thermocouple has an RTI of approximately 1 (m s)^{1/2}. Thus, at a velocity of 1 m/s, the time constants for the fine wire thermocouple, Thermotech, MSA and Pyott-Boone heat sensors would be 1, 12, 59, and 382 s, respectively.



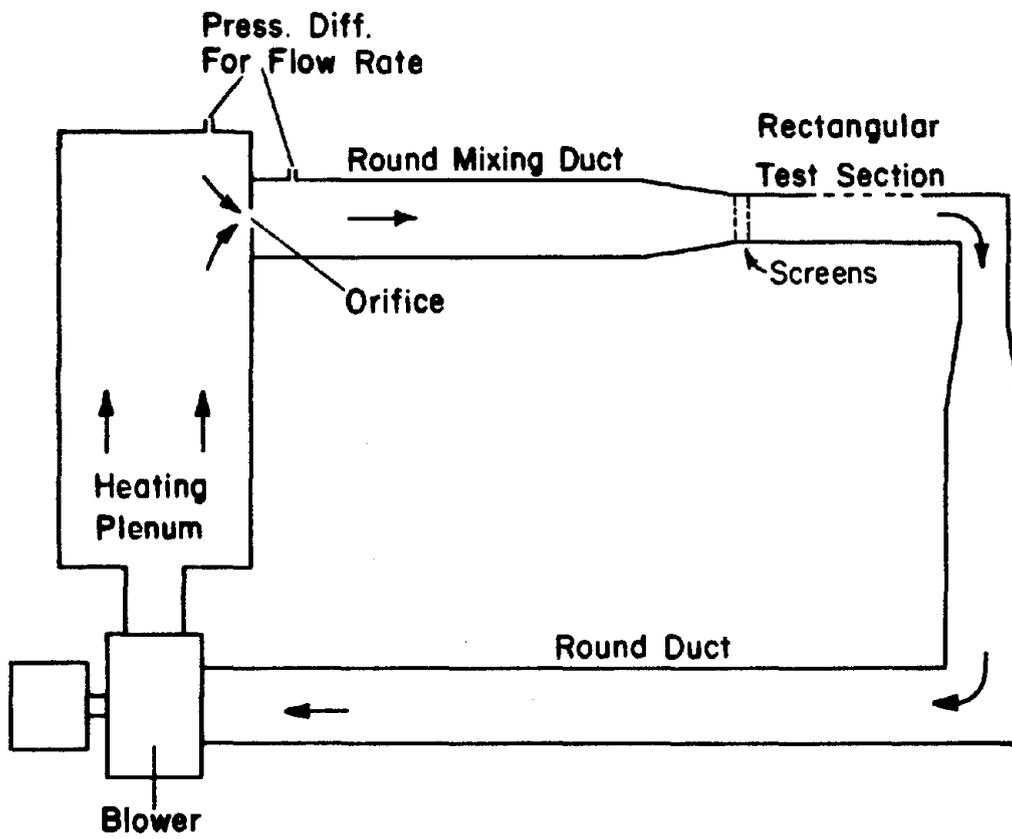


FIGURE 5.- Schematic design of plunge-test tunnel

TABLE 3. - Heat detector response

Manufacturer	RTI (m·s) ^{1/2}	Actuation Temp. (°C)
Thermotech ^{a,b}	12±2	52.8 (127°F)
MSA ^b	53±3	57.2 (135°F)
Pyott-Boone	382±56	55.0 (131°F)

^a Sensor used in system manufactured by Notifier of Western Pennsylvania

^b Factory Mutual System Approved

2.6.2 Product of Combustion Detector Evaluation

The following two types of carbon monoxide gas detection systems/sensors were evaluated using the test apparatus (previously shown in Figures 2-4): 1) an Energetics Science Ecolyzer Model 5100 System with 5001-DGFR-50/500 remote sensing heads; and 2) an MSA prototype CO transducer under joint development by the Bureau of Mines and Mine Safety Appliances Co. (MSA). In addition, one Spanair carbon dioxide Model 458 analyzer and three Becon Mark IV ionization smoke detectors (available from Wormald International Electronics, Sydney, Australia) were evaluated.

Ecolyzer CO Detection System - The Ecolyzer System was ordered with three sensing heads, each of which was calibrated according to the manufacturer's instruction manual prior to testing. A series of "cold flow" tests was initially performed to investigate the response and accuracy of the sensors to a step input of a known CO source at a given ambient velocity. The CO source was a gas jet from a compressed gas bottle of known CO content (balance nitrogen) introduced at the bottom of the intake section shown in Figure 2. The velocity was fixed in the test section, as previously described, before each test. Assuming that each Ecolyzer sensor behaves as a first order system coupled with a time lag, then the time response of the sensor can be given as:

$$\frac{dC_s}{dt} = \frac{1}{\tau} [C_o (t-t_\ell) - C_s(t)] \quad (4)$$

where t is the time in s; C_s is the instantaneous CO gas concentration in ppm as measured by the sensor at time t ; C_o is the reference CO gas concentration in ppm at time $t-t_\ell$; τ is the sensor time constant in s; and t_ℓ is the lag

time in seconds. In addition, it appears that t_ℓ is associated with a delay in mass transport through the diffusion filter, while τ can be thought of as the time constant for the sensor cell.

If it is assumed that the CO gas concentration is introduced as a step input, then the fractional response, C_s/C_o , of the sensor can be expressed as:

$$C_s/C_o = 1 - e^{-(t-t_\ell)/\tau} \quad (5)$$

where t is time in s relative to the time when the sensor was first exposed to the step input. The values of τ and t_ℓ were first obtained by best fit of eq (5) to the actual response curves, then cross-checked with eq (4). The following average values were obtained for the Ecolyzer sensors, averaged over three sensors, and all velocities investigated:

$$\begin{aligned} \tau &= 23 \pm 2 \text{ s} \\ t_\ell &= 16 \pm 2 \text{ s.} \end{aligned}$$

Figure 6 plots measured-versus-predicted CO concentrations for the Ecolyzer sensors. The points plotted are composite data for three sensors with the symbol size representative of the variation in the data. Predicted values were obtained using $\tau = 23 \text{ s}$ and $t_\ell = 16 \text{ s}$ and solving eq (4) for $C_s(t)$. The agreement is very good and confirms that the Ecolyzer response can be accurately determined for any specified source using eq (4) with averages of τ and t_ℓ .

MSA CO Sensors - Three MSA CO sensors were tested in a fashion similar to the Ecolyzer sensors.

The following average values of τ and t_ℓ were obtained for the MSA sensors using the method previously described:

$$\begin{aligned} \tau &= 29 \pm 2 \text{ s} \\ t_\ell &= 14 \pm 2 \text{ s} \end{aligned}$$

Again, τ and t_ℓ were found to be essentially velocity independent. Figure 7, similar to Figure 6 plots measured-versus-predicted CO concentrations for the MSA sensors. The points, as before, are composite data for the

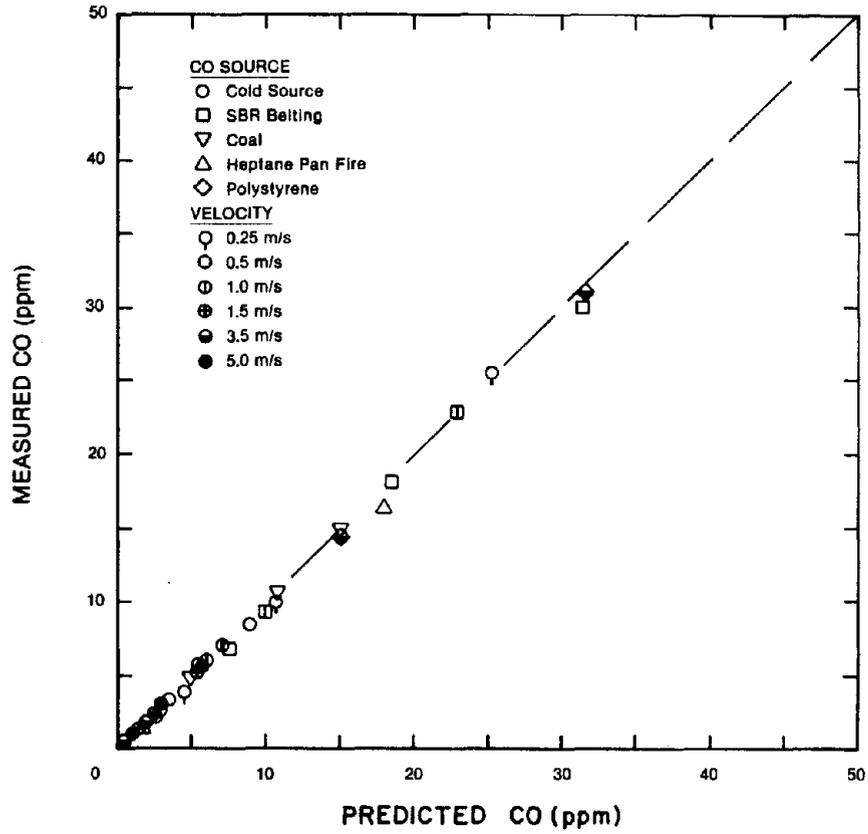


Figure 6 Measured versus predicted CO concentration for EcoLyzer sensors

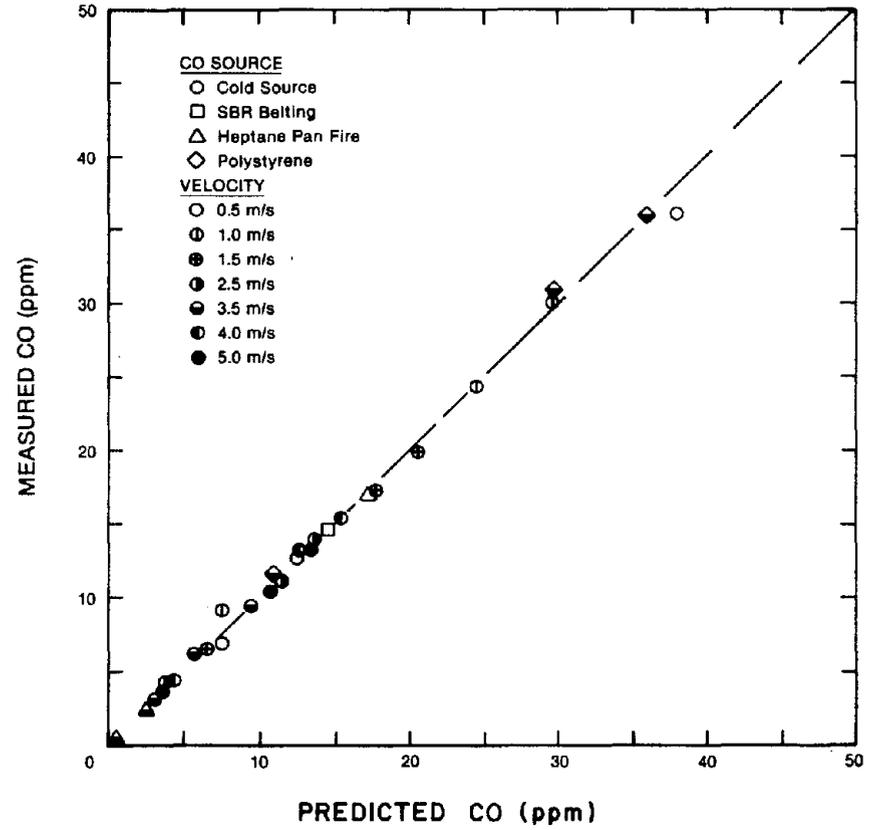


Figure 7 Measured versus predicted CO concentration for MSA sensors



three sensors and were obtained by the same method used for the Ecolyzer sensors. The very good agreement for various fire sources at various velocities as noted in the figure justifies the use of average values of τ and t_{ℓ} with eq (4).

Spanair CO₂ Analyzer - One Spanair CO₂ analyzer was evaluated in a manner similar to the CO sensors. However, unlike the CO sensors, both τ and t_{ℓ} were found to be strong functions of the gas velocity. Figure 8 plots the Spanair time response, as either $(\tau + t_{\ell})$ or t_{ℓ} versus the gas velocity, v . From Figure 8, the following two equations can be obtained:

$$(\tau + t_{\ell}) = 190 v^{-1.0} \quad (6)$$

$$t_{\ell} = 44 v^{-0.5} \quad (7)$$

Figure 9 plots measured-versus-predicted CO₂ concentrations for the Spanair analyzer. Predicted values were obtained using eqs (6) and (7) and solving eq (4) for $C_s(t)$. The agreement is again good, although with somewhat larger variations than previously obtained with both types of CO detectors.

Becon Ionization Smoke Detectors - Figure 10 plots the Becon response, $\ln(I_0/\Delta I)$, where $I_0/\Delta I$ is the ratio of the initial current to the change in current) versus the optical density at 0.4579 μ . Variations in the optical density were obtained by changing both the velocity between 0.5 and 5 m/s and the size of the fire source. Therefore, velocity effects are implicitly shown in Figure 10. The data indicate a good correlation of detector response with optical density for a given material, but not a universal correlation for all materials. However, all the response curves have essentially the same slope of -0.7 and can be expressed by the following equation:

$$\ln(I_0/\Delta I) = a OD^{-0.7} \quad (8)$$

where a is the detector/material sensitivity given in Table 4 and OD is the optical density. Finally, Figure 11 gives the measured OD versus predicted OD from eq (8) and Table 4, for the Becon detectors. A good correlation is



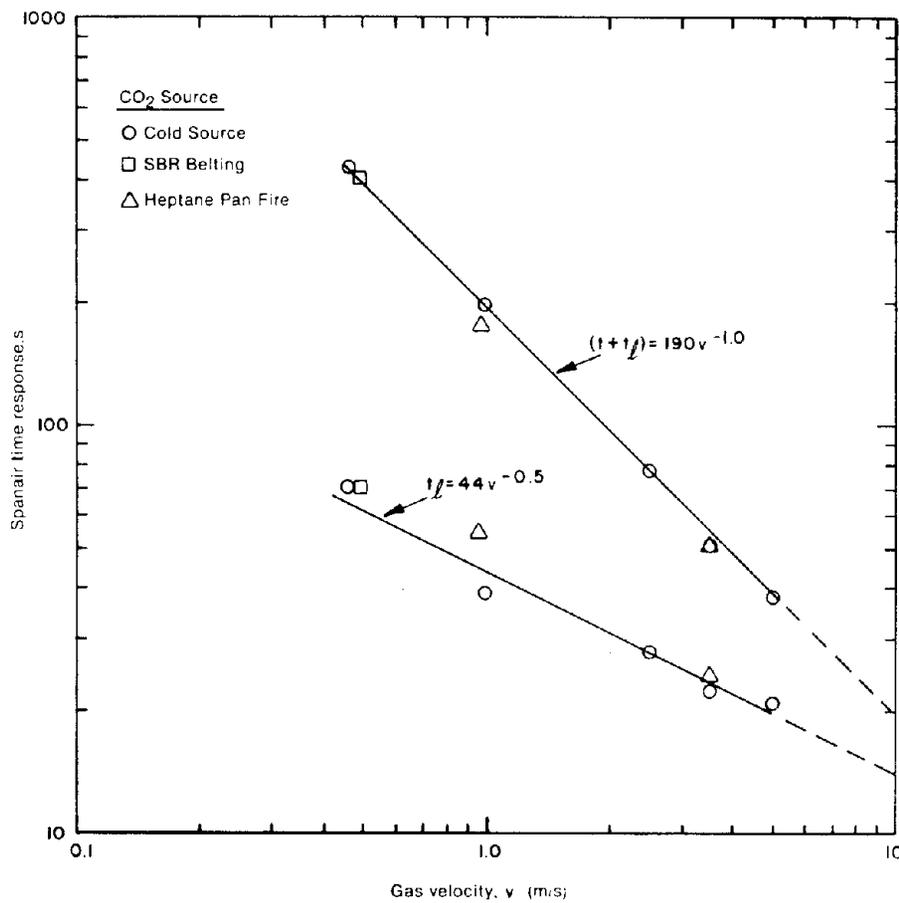


FIGURE 8.- Spanair time response versus gas velocity

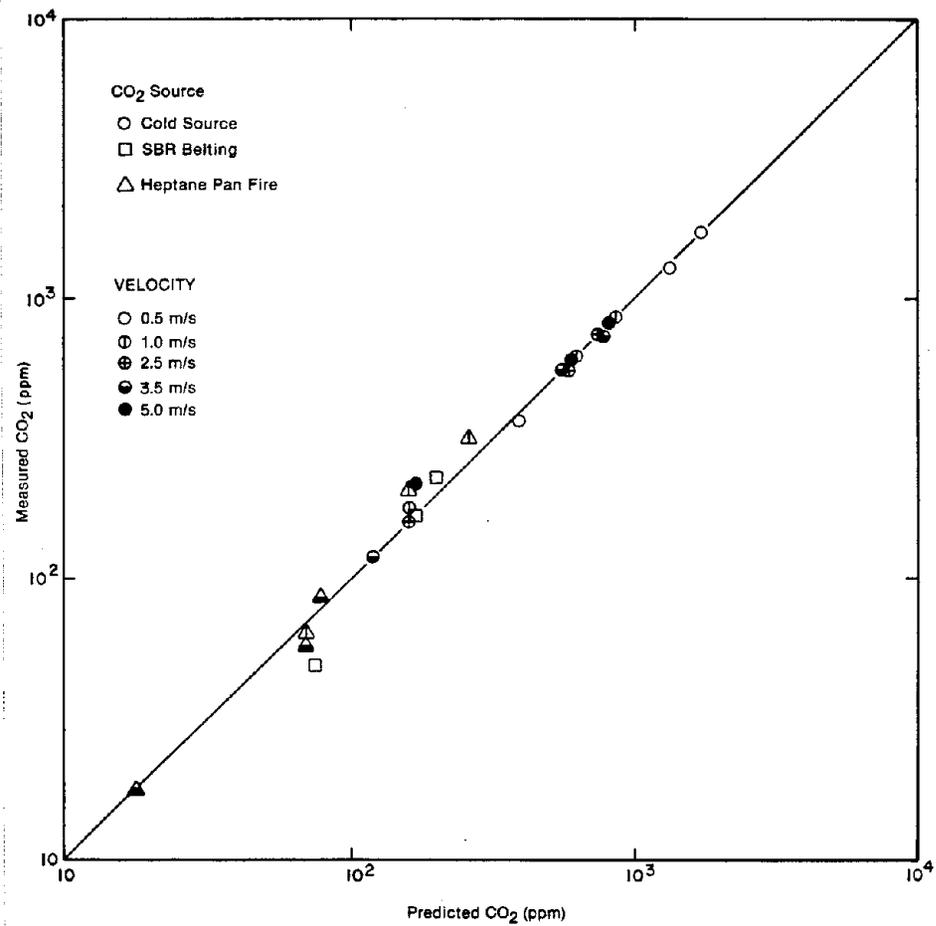


FIGURE 9.- Measured versus predicted CO₂ Concentration for Spanair Analyzer

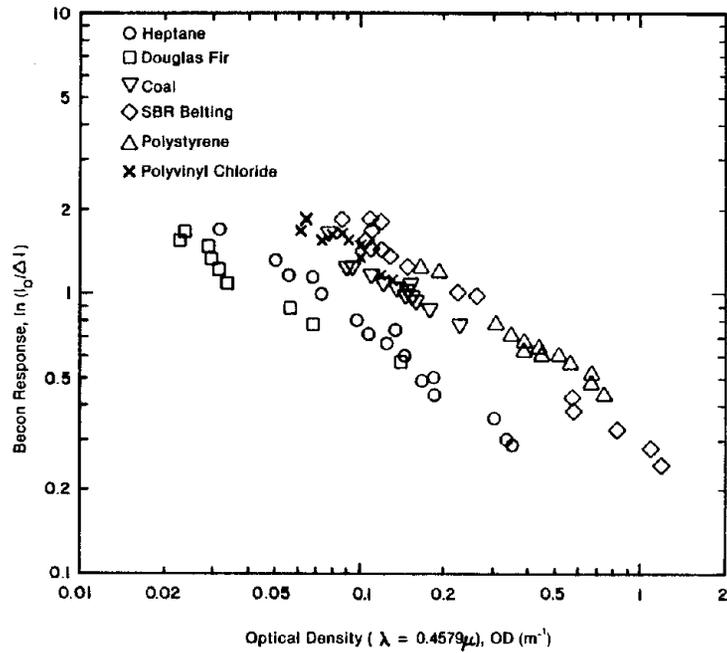


FIGURE 10.- Beacon response versus optical density

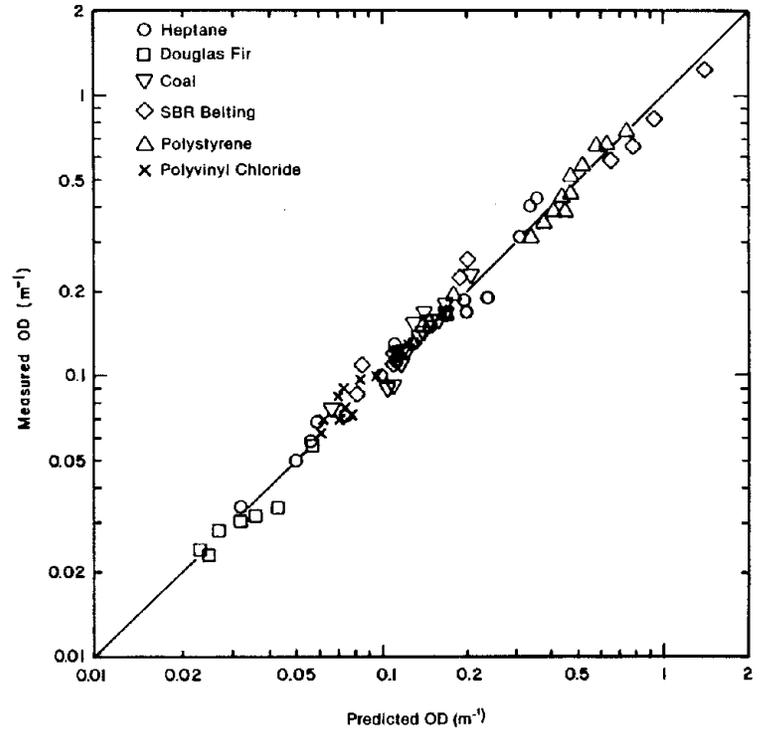
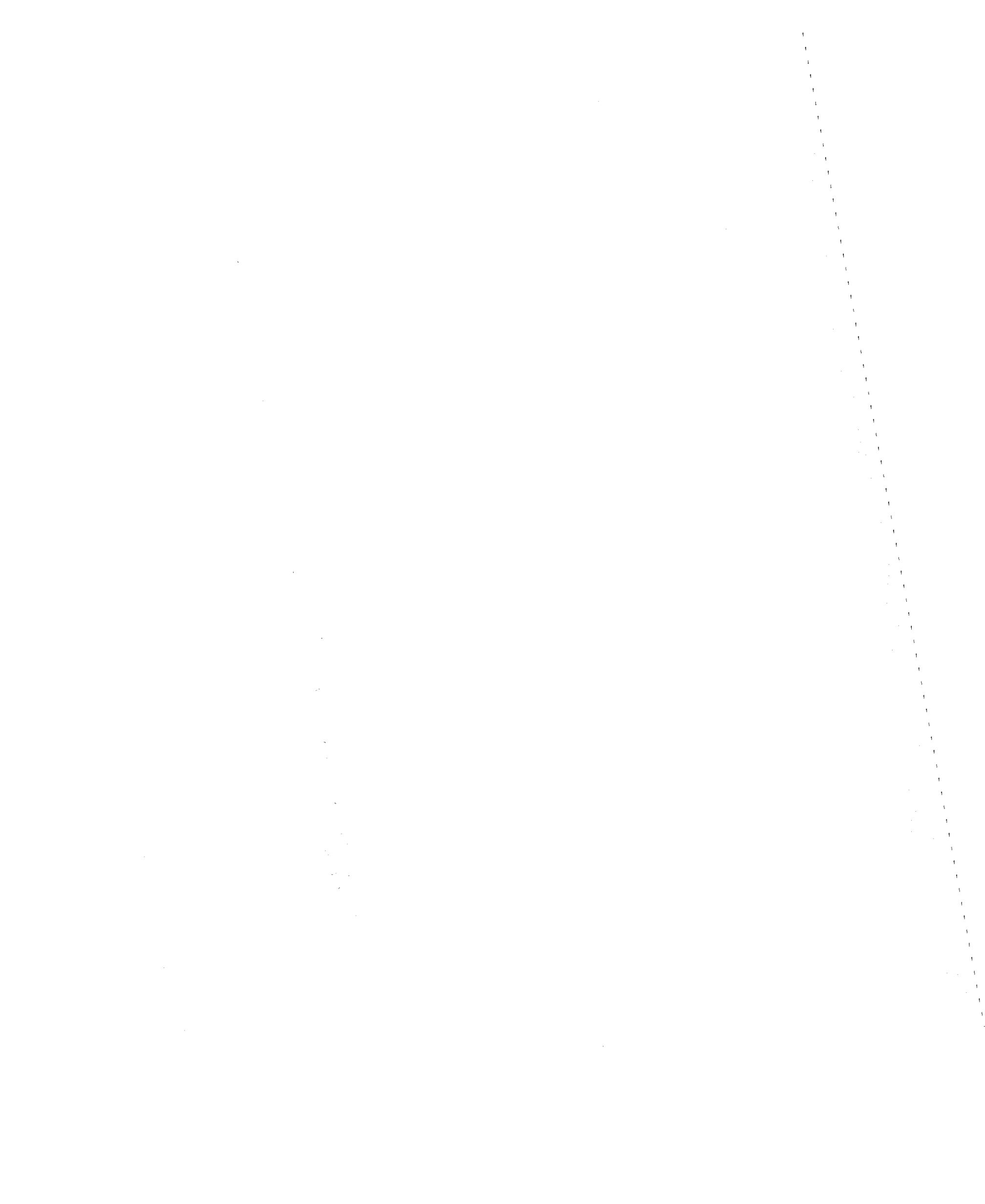


FIGURE 11.- Measured versus predicted OD using Beacon Detectors



indicated, confirming the use of eq (8) to quantify the Becon ionization smoke detector response.

TABLE 4. - Becon ionization smoke detector response

<u>Fuel</u>	<u>a</u>
Douglas fir	0.12
Heptane	0.16
Coal	0.26
Polyvinyl Chloride	0.26
SBR Belting	0.32
Polystyrene	0.36

2.7 SPACING CRITERIA

Spacing criteria were developed based on the detection criteria summarized in Section 2.2. Three mine fire scenarios were considered: 1) a coal fire in a conveyor belt haulageway which served as the ignition source for the belting; 2) a coal wall fire; and 3) a wood wall fire.

For the beltway fire (scenario 1), both "equivalent" spacing prescribed by Title 30 CFR and generalized spacing for fire detectors were determined. (For further discussion on equivalency see Reference 1.) Since equivalent spacing is a strong function of the mine geometry and ambient conditions, a "typical" beltway configuration was assumed and is given in Table 5. Table 6 gives the following information for each detector tested in this program: 1) the detector type; 2) alarm/alert level; 3) equivalent spacing; 4) the safety parameter, X (defined below) ; and 5) the corresponding spacing for each detector at $X \geq 0.50$. $X \equiv (t_r + t_E)/t_H$ is the time available for response to the fire after detection defined as a fraction of the hazard time. Thus, the larger the value of X, the more time is available. Equivalent spacing was assessed using X, such that the spacing for a non-heat detector was determined at the minimum safety parameter given by a "mine permissible" heat detector, i.e., $X = 0.45$. The recommended maximum spacing for each detector is given for $X \geq 0.50$ and ranges from 3 m (10 ft) for the slowest heat detector to 300 m (1000 ft) for the fastest POC (product of combustion) detector.

TABLE 5. - "Typical" conditions in a conveyor belt haulageway

Ambient temperature, T_o	= 291 K (65°F)
Ventilation rate, \dot{V}	= 1.9 m ³ /s (4000 cfm)
Ceiling height, H	= 1.5 m (5 ft)
Passageway width, W	= 4.9 m (16 ft)
Cross-sectional area, A_f	= HxW = 7.4 m ² (80 ft ²)
Ambient velocity, v_o	= \dot{V}/A_f = 0.25 m/s (50 fpm)

TABLE 6. - Equivalency for fire detectors (Beltway Fires)

<u>Detector</u>	<u>Type</u>	<u>Alarm/Alert Level</u>	<u>Equivalent Spacing</u>		<u>Recommended</u>
			<u>l_D, m (ft)</u>	<u>X</u>	<u>Maximum Spacing*</u>
			<u>l_D, m (ft)</u>		<u>l_D, m (ft)</u>
"Ideal"	heat	$\Delta 39^\circ\text{C}$	15 (50)	0.70	55 (180)
Thermotech	heat	$\Delta 35^\circ\text{C}$	15 (50)	0.70	55 (180)
MSA	heat	$\Delta 39^\circ\text{C}$	15 (50)	0.65	50 (150)
Pyott-Boone	heat	$\Delta 37^\circ\text{C}$	15 (50)	0.45	3 (10)
Ecolyzer	CO	$\Delta 10$ ppm/ $\Delta 5$ ppm**	300 (980)	0.45	270 (870)
MSA	CO	$\Delta 10$ ppm/ $\Delta 5$ ppm**	300 (980)	0.45	270 (870)
Spanair	CO ₂	$\Delta 200$ ppm/ $\Delta 100$ ppm**	130 (430)	0.45	95 (310)
Becon	Smoke	0.05 m ⁻¹ / 0.025 m ⁻¹ **	340 (1,100)	0.45	300 (1,000)

* l_D for $X \geq 0.50$

**Suggested levels

Tables 7-9 give the generalized spacing criteria for each of the fire scenarios considered. In each table the quantity ($l_D/v_o + t_D$) is listed versus \dot{V} (the ventilation rate in 1000 cfm) and X (t_H in s is also given for reference.) It should be noted that these criteria are tabulated only for POC type detectors. For heat detectors, either the equations described in Section 3.3.2 or the calculator program given in Appendix A can be used.

The procedure for determining l_D is as follows:

- 1) Select the detector type of interest (CO, CO₂, or OD (smoke));
- 2) Select a value of X and \dot{V} ;

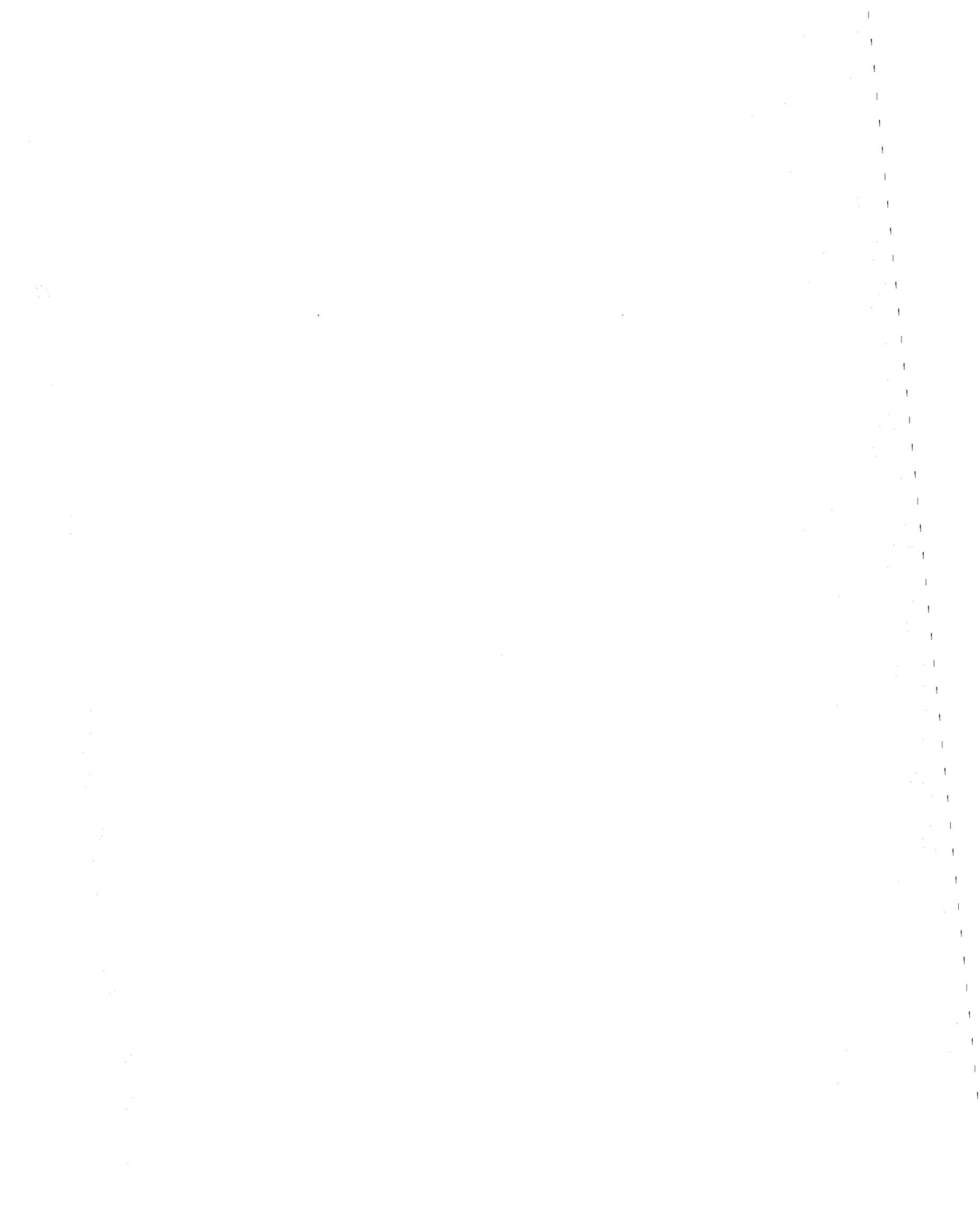


TABLE 7. - Spacing criteria for beltway fires ($t_H = 2700$ s)
 $(L_D/v_o + t_D)$, sec

\dot{V} <u>1000 cfm</u>	X = 0			X = 0.25			X = 0.50			X = 0.75		
	<u>CO</u>	<u>CO₂</u>	<u>OD</u>									
0	2700	2700	2700	2030	2030	2030	1350	1350	1350	680	680	680
1	2570	2590	2640	1890	1920	1970	1220	1240	1290	550	570	620
2	2510	2550	2620	1840	1870	1950	1160	1200	1270	490	530	600
3	2470	2520	2600	1790	1840	1930	1120	1170	1250	450	500	580
4	2430	2490	2590	1760	1810	1910	1080	1140	1240	410	470	570
5	2400	2460	2570	1730	1790	1900	1050	1110	1220	380	440	550
6	2370	2440	2560	1700	1760	1890	1020	1090	1210	350	420	540
7	2350	2420	2550	1670	1740	1880	1000	1070	1200	330	400	530
8	2320	2400	2540	1650	1720	1870	970	1050	1190	300	380	520
9	2300	2380	2530	1620	1710	1860	950	1030	1180	280	360	510
10	2280	2360	2520	1600	1690	1850	930	1010	1170	260	340	500
11	2260	2350	2510	1580	1670	1840	910	1000	1160	240	330	490
12	2240	2330	2500	1560	1660	1830	890	980	1150	220	310	480

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TABLE 8. - Spacing criteria for coal wall fires

$$(P_D/v_o + t_D), \text{ sec}$$

\dot{V} 1000 cfm	t_H (s)	X = 0			X = 0.25			X = 0.50			X = 0.75		
		CO	CO ₂	OD	CO	CO ₂	OD	CO	CO ₂	OD	CO	CO ₂	OD
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1630	1500	1520	1570	1090	1120	1170	680	710	760	280	300	350
2	2300	2110	2150	2220	1530	1580	1650	960	1000	1070	390	420	490
3	2820	2590	2630	2720	1880	1930	2020	1180	1230	1320	480	520	610
4	3250	2990	3040	3140	2170	2230	2330	1360	1420	1520	550	600	700
5	3640	3340	3400	3510	2430	2490	2600	1520	1590	1700	610	670	780
6	3980	3660	3720	3850	2660	2730	2850	1670	1740	1860	670	740	860
7	4300	3950	4020	4150	2870	2950	3080	1800	1880	2010	730	790	930
8	4600	4230	4300	4440	3070	3150	3290	1920	2010	2150	780	850	990
9	4880	4490	4560	4710	3260	3350	3500	2040	2130	2280	830	900	1050
10	5140	4730	4810	4960	3430	3530	3680	2150	2250	2400	870	950	1110
11	5390	4960	5040	5210	3600	3700	3860	2250	2350	2520	910	990	1160
12	5630	5180	5270	5440	3760	3860	4040	2360	2460	2630	950	1040	1210

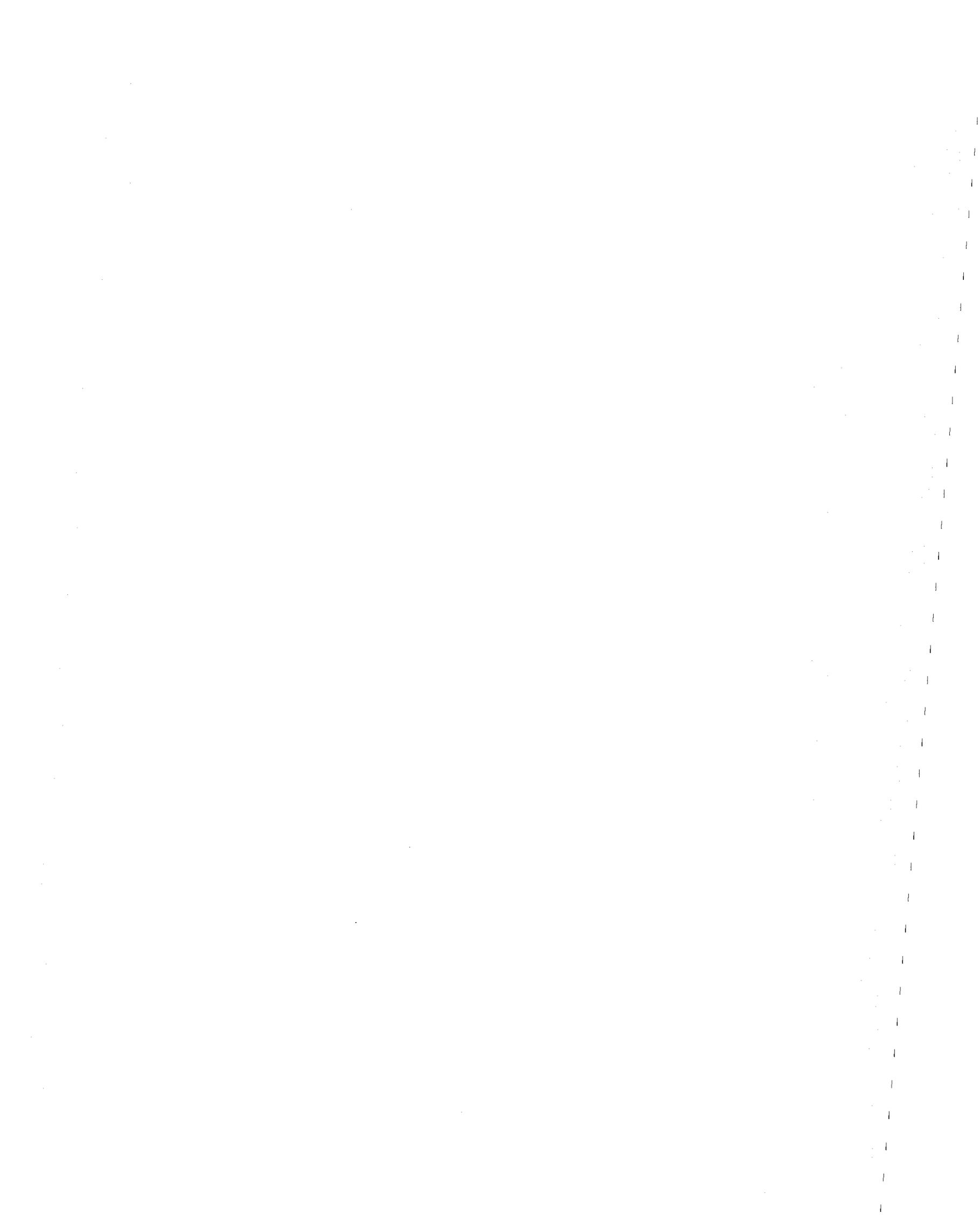


TABLE 9. - Spacing criteria for wood wall fires

$(P_D/v_o + t_D)$, sec

\dot{V} 1000 cfm	t_H (s)	X = 0			X = 0.25			X = 0.50			X = 0.75		
		CO	CO ₂	OD	CO	CO ₂	OD	CO	CO ₂	OD	CO	CO ₂	OD
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	450	290	420	370	180	300	260	70	190	150	0	80	40
2	630	400	590	520	250	420	360	90	270	210	0	110	50
3	770	490	720	640	300	520	440	110	330	250	0	140	60
4	890	570	830	740	350	600	510	130	380	290	0	160	70
5	1000	640	930	830	390	670	570	150	420	320	0	180	80
6	1090	700	1020	910	430	740	620	160	470	360	0	200	90
7	1180	750	1100	980	460	790	670	170	500	380	0	210	90
8	1260	810	1170	1050	490	850	720	180	540	410	0	230	100
9	1340	860	1250	1110	530	900	770	200	570	440	0	240	100
10	1410	900	1310	1170	550	950	810	210	600	460	0	250	110
11	1480	950	1380	1230	580	990	850	220	630	480	0	260	110
12	1540	990	1440	1280	610	1040	880	230	660	500	0	270	120

3) Read the corresponding value of (ℓ_D/v_o+t_D) in the table for the scenario of interest and designate this value as "b".

4) Obtain t_D for the specific detector (Table 10 summarizes t_D for the detectors examined in this program).

5) Recalling that $v_o = \dot{V}/A_f$, calculate ℓ_D in ft by the following:

$$\ell_D = \frac{v_o (b-t_D)}{0.3} \quad \text{for } v_o \text{ in m/s(9a)}$$

or

$$\ell_D = \frac{v_o (b-t_D)}{60} \quad \text{for } v_o \text{ in fpm(9b)}$$

TABLE 10. - Values for t_D

<u>Detector</u>	<u>Type</u>	<u>t_D(s)</u>
Ecolyzer 5100 Series	CO	39
MSA/BUMINES Prototype	CO	43
Spanair Model 458	CO ₂	190/ v_o *
Becon Mark IV	OD (smoke)	0

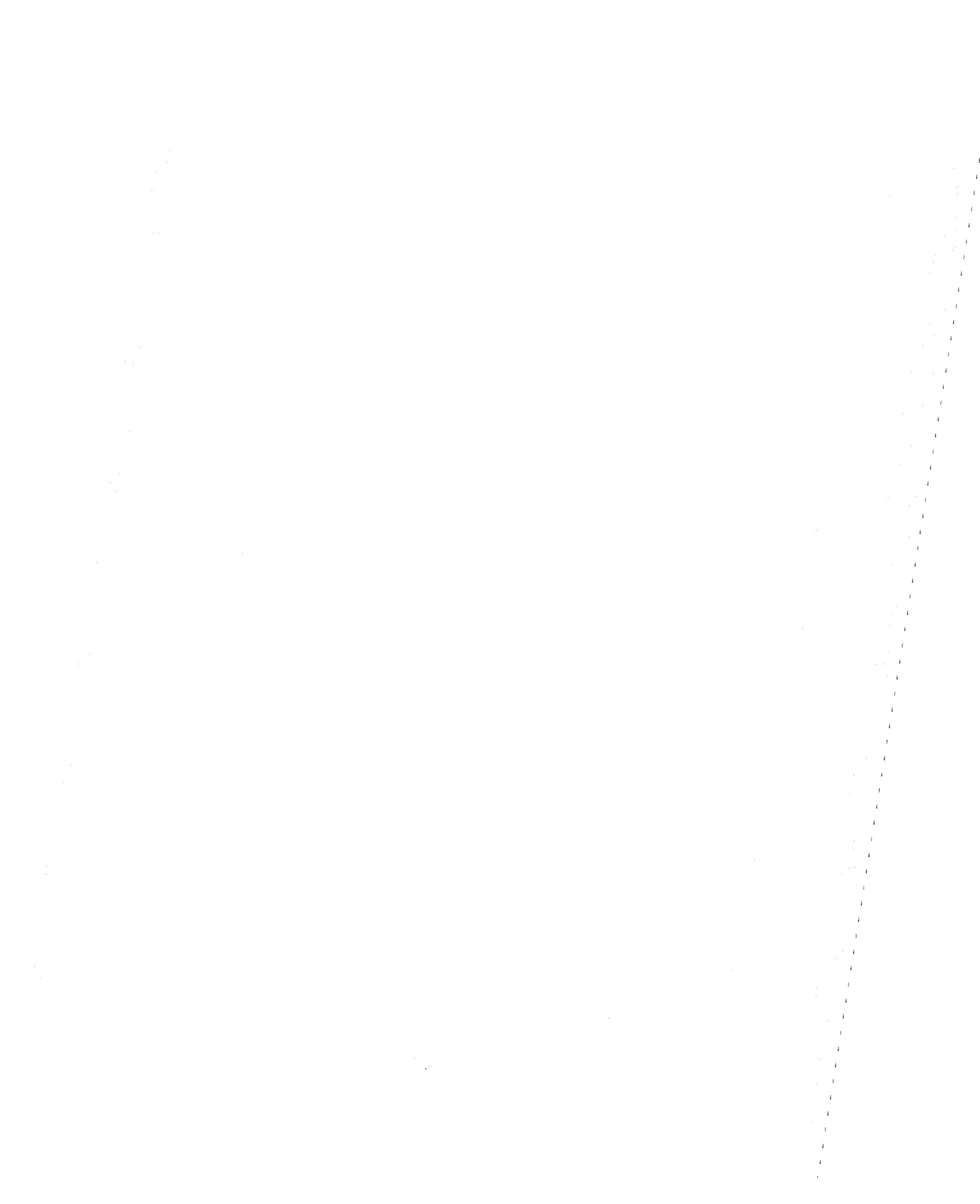
* v_o has units of m/s

2.8 PERFORMANCE SPECIFICATIONS

The recommended fire environmental performance specifications for the acceptance of mine fire detectors include response characteristics at a prescribed alarm level as a function of source fire (representative of mine materials), ventilation rate (0.5 to 5.0 m/s) and ambient temperature up to 60°C.

Prior to setting an alarm level for detectors in mine fire environmental performance tests, the performance base line information (for mine ambient environment) for each detector must be specified by the manufacturer such as through a testing program as outlined in various approvals standards (17-24) and guidelines (10, 25).

In addition, after a suggested program, including in-field underground mine conditioning or simulated environmental conditioning, the fire detectors should be further tested in the test apparatus, as developed in this program, to determine response characteristics versus source fire and ventilation rate.



2.9 ADDITIONAL RESEARCH NEEDS

A number of significant research needs are strongly indicated based on the major research efforts pursued in this program. These needs are described in terms of generalized program areas. While the required funding and manpower levels are a function of the depth in which each area is evaluated; a minimum of 1500 labor hours per year, or approximately \$100,000 plus travel and expenses, would assure continued progress and development in the field of mine fire detection. The following areas require additional work effort.

1. "Equivalency"

It is apparent that spacing according to the concept of "equivalent protection" as currently defined in Title 30 CFR is grossly inadequate. The definition is vague, has multiple meanings due to conditions not covered (e.g., ambient temperature, mine geometry, fire growth rate, etc.), and is difficult to apply or enforce. The spacing criteria developed in this program should be incorporated into mining regulations. A hand-held calculator program for detector spacing was specifically developed to facilitate this effort.

2. Fire Hazard Evaluation

Hazards other than those associated with fire propagation in beltways, coal, or wood lining materials should be evaluated. Of particular interest are toxic hazards associated with the pyrolysis of mine materials including the effects of fire retardants. These hazards should be assessed under realistic mine fire conditions to determine at what level they occur relative to other fire hazards. Fire detector spacing criteria should in turn be assessed relative to detector performance when these hazards are potentially present.

3. In-Mine Detector Evaluation

Evaluation of the fire detectors tested thus far should continue with a combination of two types of testing: 1) long-term reliability testing of detectors installed in "typical" working mines; and 2) evaluation of detectors in experimental mine facilities under fire conditions to further validate the developed spacing criteria. Subsequent laboratory evaluation of detector performance using the developed procedures and test apparatus would reveal any changes in detector response characteristics.



4. Fire Scenario Evaluation

In this program three fire scenarios have been evaluated covering a wide range in potential mine fire environments. Other scenarios should be investigated. In particular fire growth rates and product generation rates should be determined.

5. Evaluation of Additional Detectors

All detectors going into a mine should be evaluated through the fire environment/performance criteria developed in this program.

6. Mine Material Testing

The testing of mine materials should be performed to: 1) assure that fire hazards are acceptable in terms of allowable times for fire detection; and 2) obtain required information for prediction of detector response.

7. Mine Practices

The interaction of fire detection methods with mine practices and procedures should be investigated. The level of effectiveness of detection in fire situations is highly dependent on the response of mining personnel to the fire alarm and determines what is an allowable value for the safety parameter, X.

III
PHASE IV

This section details the efforts of the final phase of a four-phase approach to establishing standard test criteria for the evaluation of underground mine fire detection systems/sensors. The objectives of Phase IV were to: 1) continue development of a response theory initiated in Phase III; 2) develop performance specifications; and 3) establish spacing criteria for mine fire detectors.

The developed response theory has been applied, but is not limited, to the following detector types: heat, CO and CO₂ gas, and ionization smoke detectors. During this phase, the following two additional types of fire detection sensors were evaluated in a manner similar to that followed in Phase III: 1) one Spanair carbon dioxide Model 458 analyzer and 2) three Becon Mark IV ionization smoke detectors Model C121B (available from Wormald International electronics, Sydney, Australia). Both systems were shown to respond accurately and reliably to the mine fire sources tested (and previously described in Phase III). The response time of the Spanair CO₂ analyzer is well characterized by a time constant and a lag time, while the response of the Becon can be well-correlated with the optical density and a detector/material sensitivity factor.

Performance specifications were developed which describe the fire and environmental conditions under which detectors used for mine applications must operate. Performance specifications combined with response characteristics of the detectors and the mine fire environment were used to establish spacing criteria for underground mines. These spacing criteria define "equivalency" and equivalent spacing as given in CFR Title 30 for a "design" fire scenario in a conveyor belt haulageway. In addition, spacing relations are given for three limiting fire scenarios: 1) a coal fire in a beltway; 2) a coal wall fire, and 3) a wood wall fire. The spacing relations are presented in tabular form. A computer program for hand-held calculators is also available to facilitate spacing design for mine fire detectors.



3.1 TECHNICAL APPROACH

The overall program objective was to develop standardized test criteria and procedures to assure that fire detectors selected for installation in mines will:

- 1) be reliable in operation;
- 2) be located in the most effective position; and
- 3) function routinely with minimal maintenance.

The technical approach developed to meet this objective comprised the following four distinct program phases:

Phase I (see Appendix B)

The Phase I effort (1) was primarily directed toward identification and acquisition of the data necessary to establish preliminary standard test criteria for mine fire detectors.

Phase II (see Appendix C)

A detailed design of a sensor evaluation test program and associated test apparatus was prepared under Phase II (2).

Phase III (see Appendix D)

The test apparatus, designed by FMRC and approved by the Bureau under Phase II, was constructed (5) and calibrated.

Phase IV

Within this phase, fire and environmental performance specifications for the acceptance of mine fire detection sensors and sensing systems were developed. The developed criteria specify 1) optimum sensor spacing capability as related to Title 30 Code of Federal Regulations Paragraphs 75-1103-4, 75-1103-10, and 2) the environmental conditions under which detectors used for mine applications must operate. This specification includes any special conditions and practices which should be followed by detector installers.

Further, two additional types of fire detection systems were evaluated based upon the Phase III results. This evaluation was coupled with the development of a response theory for the various types of detectors.



3.2 RESPONSE THEORY

The response theory initiated in Phase III for heat and two types of CO gas detectors was extended to include two additional types of combustion detectors: 1) one Spanair carbon dioxide analyzer (Model 458) and 2) three Becon Mark IV ionization smoke detectors (Model C121B). Both of these detector types were supplied by Wormald International Electronics, Sydney, Australia.

3.2.1 Spanair CO₂ Analyzer

After calibrating the Spanair analyzer according to the manufacturer's instruction manual, a series of "cold flow" tests was initially performed to investigate the response and accuracy of the sensors to a step input of a known CO₂ source at a given ambient velocity. The CO₂ source was a gas jet from a compressed gas bottle of known CO₂ content (balance nitrogen) introduced at the bottom of the intake section of the test apparatus (described in detail Reference 5 (Appendix D)). The velocity was fixed in the test section before each test. Figure 8 plots the Spanair time response versus gas velocity. Two response curves, as noted in the figure, can be described by the following equations:

$$(\tau + t_{\ell}) = 190 v_o^{-1.0} \quad (10)$$

$$t_{\ell} = 44 v_o^{-0.5} \quad (11)$$

where τ is the sensor time constant in s; t_{ℓ} is the lag time in s; and v_o is the gas velocity in m/s. As previously described in Reference 5, it appears that t_{ℓ} is associated with a delay in mass transport through the filter and sensor housing, while τ can be thought of as the time constant for the sensor cell. Also shown in Figure 8 are the time responses for two fire sources, SBR conveyor belting and heptane pan fires which represent a wide range in fire source characteristics potentially available from mine materials (5). These additional data for τ and t_{ℓ} are equally well fit by eqs (10) and (11).

Figure 9 plots measured-versus-predicted CO₂ concentrations for the Spanair analyzer. Predicted values were obtained using eqs (10) and (11) and solving eq (4) for $C_s(t)$, the instantaneous CO₂ gas concentration in ppm as measured by the sensor at time t . The agreement is good, although with some-



what larger variations than previously reported for the two types of CO sensors tested (5). It is important to note, however, that the manufacturer's supplied calibration was not used to obtain this good correlation. The manufacturer's calibration was first linearized using the following equation:

$$C_s = B \left(\frac{1.0-V}{V} \right) \quad (12)$$

where C_s is the CO_2 concentration measured by the sensor in ppm and V is the voltage output from the analyzer in volts D.C. The value of B from the manufacturer's data was determined to be 1110 ppm/volt, while the value of B obtained from the cold flow test data was (1340 ± 20) ppm/volt. It was this latter value which was subsequently used for the analysis presented in Figure 9.

3.2.2 Becon Mark IV Ionization Detectors

Since there was no well-defined "cold source" for testing the Becon detectors, the detectors were immediately tested versus various mine fire sources upon completion of a calibration procedure*. Figure 10 plots the Becon response, $\ln(I_o/\Delta I)$, where $I_o/\Delta I$ is the ratio of the initial current to the change in current, versus the optical density at a wavelength of 0.4579μ . The data are composites for the three detectors (with the symbol size representative of the variation between detectors) and for a range in ventilation conditions. The magnitude of optical density for a given material was determined by the dilution rate, i.e., the gas velocity. A good correlation of detector response with optical density for a given material is indicated, but not a universal correlation for all materials. However, all the response curves have essentially the same slope of -0.7 and can be expressed by the following equation:

$$\ln(I_o/\Delta I) = a OD^{-0.7} \quad (13)$$

* The signal current under normal ambient environmental conditions should be adjusted to 0.9 mA. The correct reading on the calibration meter (which is a detector accessory) should be 0.857 volts for a 1000-ohm, current-sensing resistor (according to the manufacturer).

where a is the detector/material sensitivity given in Table 11 and OD is the optical density. Figure 11 gives the measured OD versus predicted OD (from eq (13) and Table 11) for the Becon detectors. A good correlation is indicated, confirming the use of eq (13) to quantify the Becon ionization smoke detector response. It should be noted that since these detectors have different material detector sensitivities, variable alarm thresholds could be assigned instead of the fixed values given for convenience in Table 1.

TABLE 11. - Becon ionization smoke detector response

<u>Fuel</u>	<u>a</u>	<u>ξ (m²/g)</u>
Douglas Fir	0.12	0.05
Heptane	0.16	0.38
Coal	0.26	0.70
Polyvinyl Chloride	0.26	1.25
SBR Belting	0.32	1.40
Polystyrene	0.36	1.82

Finally, also included in Table 11 are values for ξ , the mass attenuation coefficient at 0.4579 μ in m²/g, which is defined by:

$$\xi = \left(\frac{OD}{\dot{m}} \right) \dot{V} \quad (14)$$

where OD is the optical density at 0.4579 μ (m⁻¹); \dot{V} is the ventilation rate (m³/s); and \dot{m} is the fuel mass loss rate (g/s). ξ is particularly useful for the prediction of OD for a given fuel and fire scenario.

3.2.3 General Observations on Spanair and Becon Sensors

The following is a composite list of observations about the two sensor types:

Spanair CO₂ Analyzer

1) A number of difficulties had to be surmounted before the analyzer could be tested:

a) The first analyzer shipped by the manufacturer never worked properly;

b) The second analyzer shipped as a replacement arrived with the filament driver board not in its socket and two "dummy" boards missing which

were necessary to obtain the voltage signal from the analyzer. These problems were solved by field adjustments considered to be beyond what the typical user could be expected to perform.

2) The documentation describing the analyzer and its components is incomplete and, in many cases, obsolete.

3) The calibration as provided by the manufacturer is both cumbersome to use and inaccurate as described in Section 3.2.1. The calibration procedure is also difficult to employ.

4) The analyzer was observed to respond accurately at ambient temperatures up to 60°C for the duration of the tests.

5) Analyzer drift at laboratory ambients is approximately ± 20 ppm/month.

6) The analyzer remained in calibration throughout the course of testing (approximately three months).

Becon Ionization Detectors

1) Apparently electrical polarities are reversed in Australia, i.e., ground reference is "positive". This must be considered when wiring up the detectors.

2) The calibration procedure is simple and the meter accessory for the detector is recommended.

3) The documentation describing the detectors is adequate.

4) The detectors responded rapidly with no perceptible time constant or lag time over the velocity range of 0.5 to 5.0 m/s and ambient temperature up to 60°C in the fire tests.

5) Little variation was observed between the responses of the three detectors.

6) Detector drift at laboratory ambients appeared to be negligible.

3.3 SPACING CRITERIA

3.3.1 Development of Spacing Criteria

The spacing criteria for fire detectors in underground mines are based on the following detection criteria which are slightly modified from those described previously in Reference 1 to include a fire growth time:

$$t_r \equiv t_H - (t_t + t_f + t_D + t_E) \geq 0 \quad (15)$$



where t_r = residual time; t_H = time to specified hazard; t_t = transit time; t_f = fire growth time to reach detectable level of combustion product; t_D = detection time once t_f has occurred; and t_E = "effective" response time once fire has been detected.

To conveniently handle the t_r and t_E terms in eq (15), the concept of a safety parameter has been employed, such that

$$(t_r + t_E) \equiv X t_H \quad (16)$$

where the safety parameter, X , has values between 0 and 1, i.e., the larger the value of X , the more time available for response to the fire after detection. Combining eqs (15) and (16) and using l_D/v_o for t_t (where l_D is the horizontal spacing between detectors and v_o is the ambient gas velocity) yields:

$$(1 - X) t_H - t_f = l_D/v_o + t_D \quad (17)$$

In eq (17), t_H must be defined for each fire scenario. t_f is dependent on: 1) the fire growth rate and fuel assumed in determining t_H ; and 2) the specific product of combustion as well as level to be detected. t_D is determined for a given detector. Three limiting fire scenarios have been assumed in order to specify detector spacing: 1) a coal fire in a conveyor belt haulage-way (beltway); 2) a coal wall fire; and 3) a wood wall fire. These scenarios have been developed from a combination of full-scale fire test results on conveyor, coal, and wood fires and have incorporated mine experience where applicable.

3.3.2 Beltway Fires

Figure 12 illustrates the fire growth rate for PVC conveyor belting based on data from Reference 26. In the figure the square root of the actual heat release rate, $\dot{Q}_A^{1/2}$ is plotted versus time $(t-t_o)$. This particular form is a mathematical convenience for assessing the fire intensity assuming a power law fire of order, two, i.e.,

$$\dot{Q}_A = \alpha (t-t_o)^2 \quad (18)$$



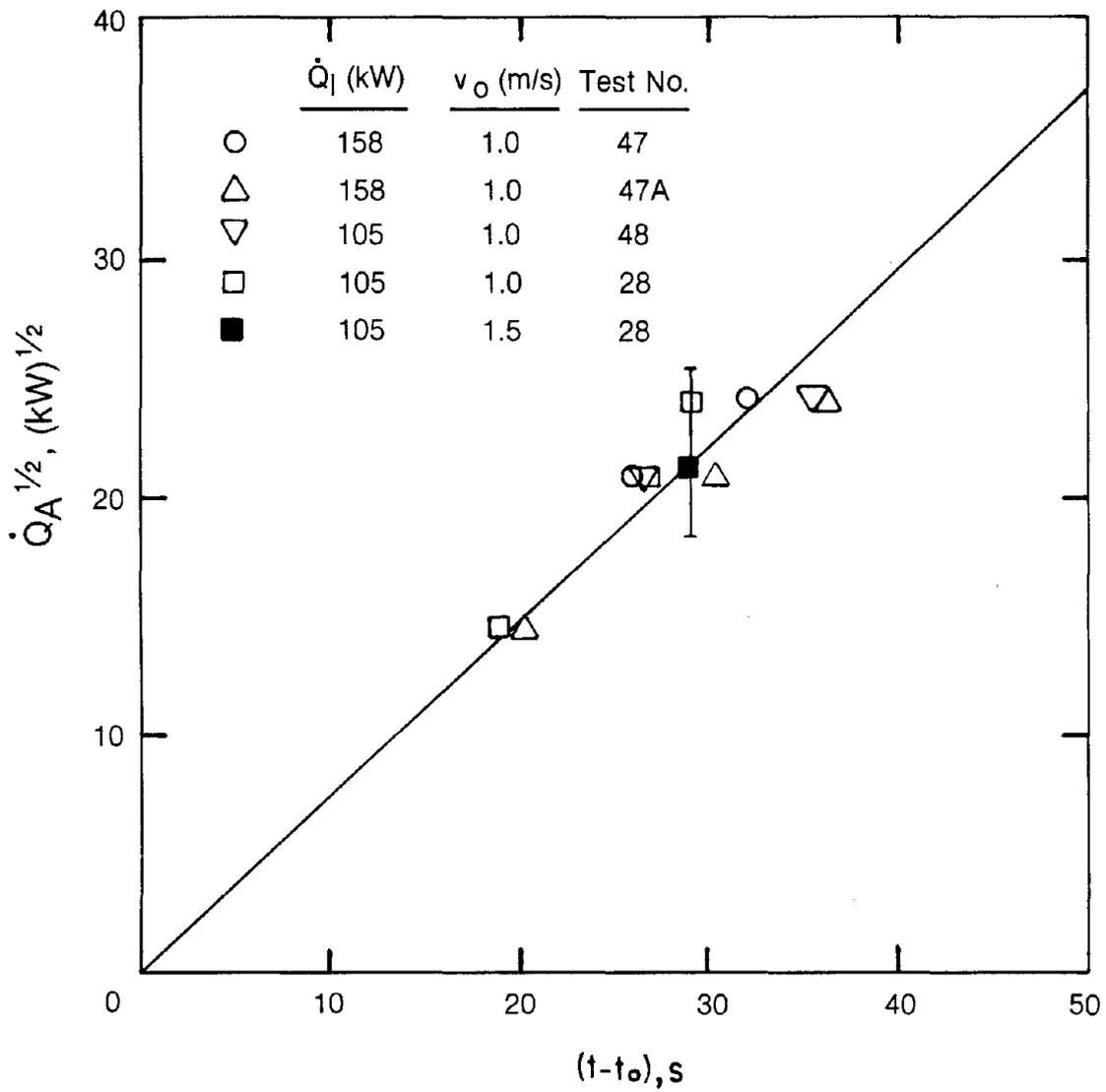


FIGURE 12.- Fire growth rate for PVC conveyor belting

where α is the fire intensity parameter, kW/s²; t is the time s; and t_0 is a reference time selected for convenience, s.

The data in the figure were obtained from several fire tests at various ignition source intensities (\dot{Q}_I) and ambient velocities, v_0 . Most of the data were obtained based upon PVC belt fire characteristics (26, 27) and flame spread rate information. While limited gas composition data were available to assess \dot{Q}_A directly, the data from Test 28 (the solid symbol with error bars) indicate that the assumptions leading to \dot{Q}_A are reasonable. The following equation, representing the line in Figure 12, describes the heat generation rate for the PVC belting:

$$\dot{Q}_A = 0.6 (t-t_0)^2 \quad . \quad (19)$$

The data generalized by eq (19) appear to be independent of \dot{Q}_I and v_0 for the range of conditions investigated in Reference 26. Finally, it is important to note that the flame propagation data strongly indicate a critical value of ($\dot{Q}_A + \dot{Q}_I$) below which the belt fire remains localized, i.e., does not propagate. This value, \dot{Q}_{cr} , is approximately 700 kW.

Figure 13 is a plot for SBR conveyor belting similar to Figure 12. Again there appears to be little influence of either \dot{Q}_I or v_0 on the fire intensity. In addition, the fire retardant belting (FR in the figure) has negligible influence on the intensity. \dot{Q}_A for the SBR belting is given by:

$$\dot{Q}_A = 0.004 (t-t_0)^2 \quad . \quad (20)$$

Although the fire intensity parameter, α , is much less for SBR than for PVC belting (0.004 versus 0.6), the value for \dot{Q}_{cr} from the flame propagation data was still approximately 700 kW. The similarity of \dot{Q}_{cr} values is most likely due to both comparable flame and critical heat fluxes for SBR and PVC belting (26, 27).

Equations (19) and (20) combined with $\dot{Q}_A = \dot{Q}_{cr} = 700$ kW can now be used to assess a hazard time, t_H based upon flame propagation, i.e.,

$$t_H = 34 \text{ s (0.6 min) for PVC}$$

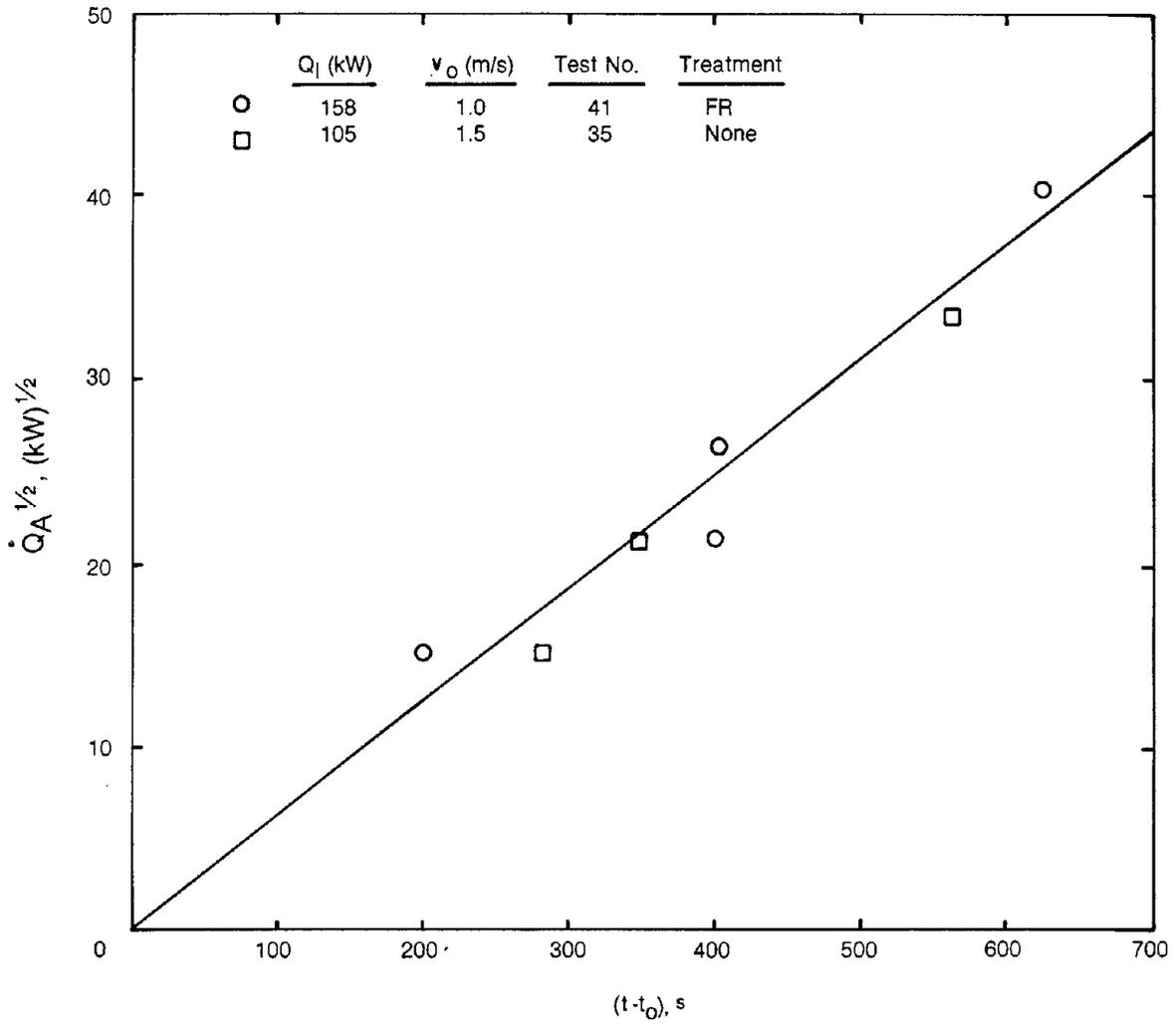


FIGURE 13.- Fire growth rate for SBR conveyor belting

$$t_H = 420 \text{ s (7.0 min) for SBR.}$$

t_H of either 0.6 or 7.0 min is unacceptable from a fire detection viewpoint, i.e., insufficient time is available to detect and respond to the fire. Therefore, if the fire scenario where a flaming fire originates on these types of belting is realistic, it must be handled separately from detection. For example, the use of belting materials with low heat release rates and low susceptibility to ignition (27) would be strongly indicated.

However, another fire scenario, known to occur in beltways, is the ignition of coal such as by a stuck conveyor roller assembly which in turn ignites the belting (28). In this case the growth in fire intensity of the coal is of particular importance. Figure 14 illustrates the fire growth rate for oil shale rubble in full-scale fire tests from Reference 29. Oil shale rubble can be considered representative of coal (based on data from Reference 29 and coal data detailed in Reference 5), particularly in terms of heat generation rates. Two distinctive regions can be noted on Figure 14: 1) a region with a steep slope most likely associated with heat generation from a combination of oil shale rubble and the diesel fuel used for ignition; and 2) a region with less steep slope occurring from oil shale rubble burning alone. These regions can be represented by the following equations:

$$\text{For oil shale and diesel fuel, } \dot{Q}_A = (1 \times 10^{-4}) (t - t_o)^2 \quad (21a)$$

$$\text{For oil shale alone, } \dot{Q}_A = (4 \times 10^{-6}) (t - t'_o)^2 \quad (21b)$$

where t_o and t'_o are again convenient reference times.

If it is assumed that a fast-flaming start to coal rubble followed by belt ignition is a "credible worst case" fire scenario, then the hazard time is defined by the time at which $\dot{Q}_A = \dot{Q}_{cr} = 700 \text{ kW}$ in eq (21a), i.e.,

$$t_H = 2700 \text{ s (45 min).}$$



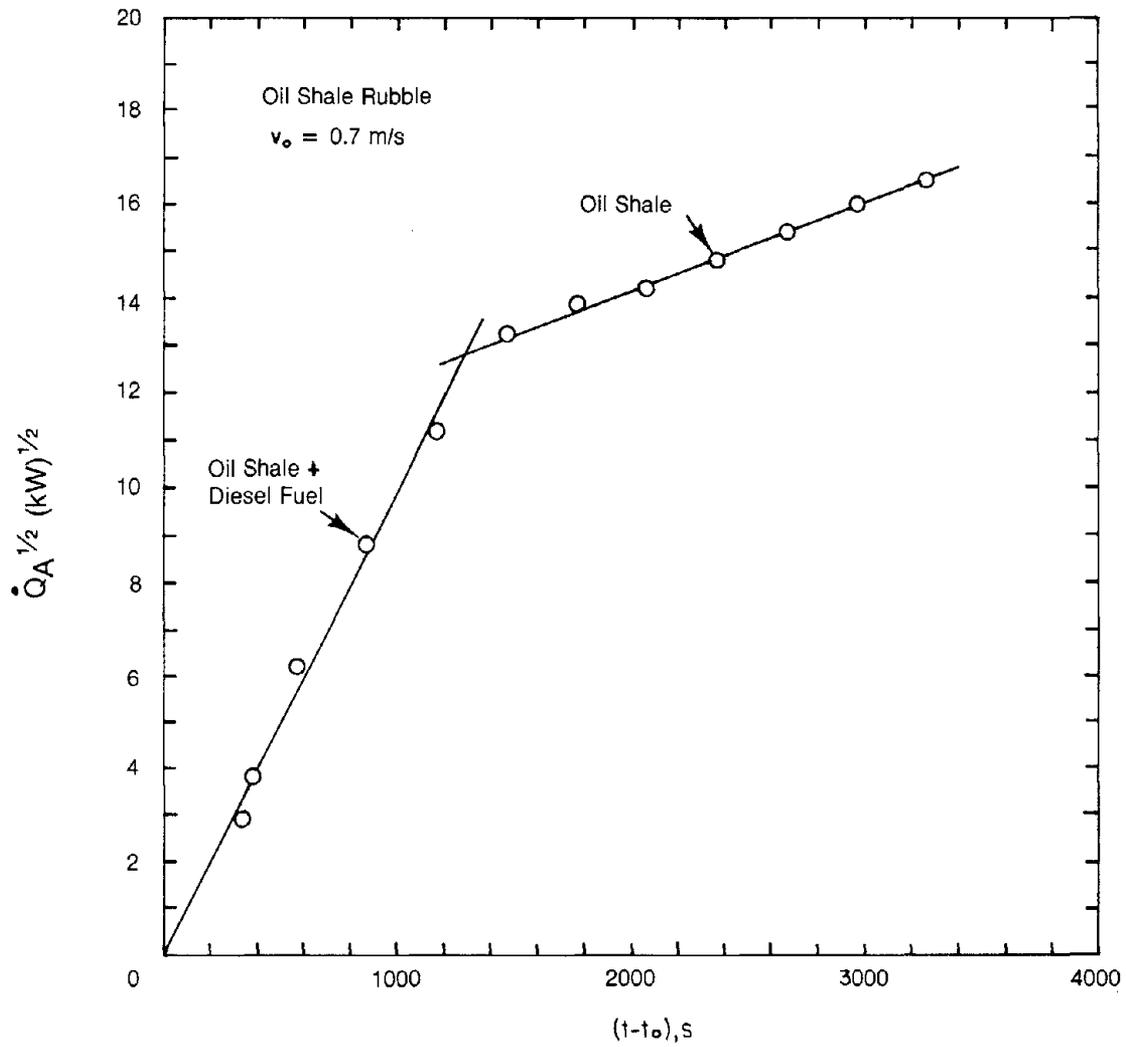


FIGURE 14.- Fire growth rate for oil shale rubble

A value for t_H of 45 min allows a reasonable time frame in which eq (17) may be applied to conveyor belt haulageways, while still dealing with realistic fire scenarios. It should be noted that t_H for eq (21b) is 220 min or ~ 4 hours. This latter value appears to be consistent with general mine experience which states that "walking the belt", which is required two times each eight-hour shift, generally assures that fires are small enough to easily extinguish (30).

Equation (21a) can now be used to determine the fire growth time, t_f , for a given product of combustion (POC)*, i.e.,

For a gas detector,

$$t_f = \left[\frac{\rho_o v_o A_f}{1000 \alpha} \left(\frac{\Delta C_{i,f}}{Y_i / H_A} \right) \right]^{1/2} \quad (22a)$$

For a smoke detector,

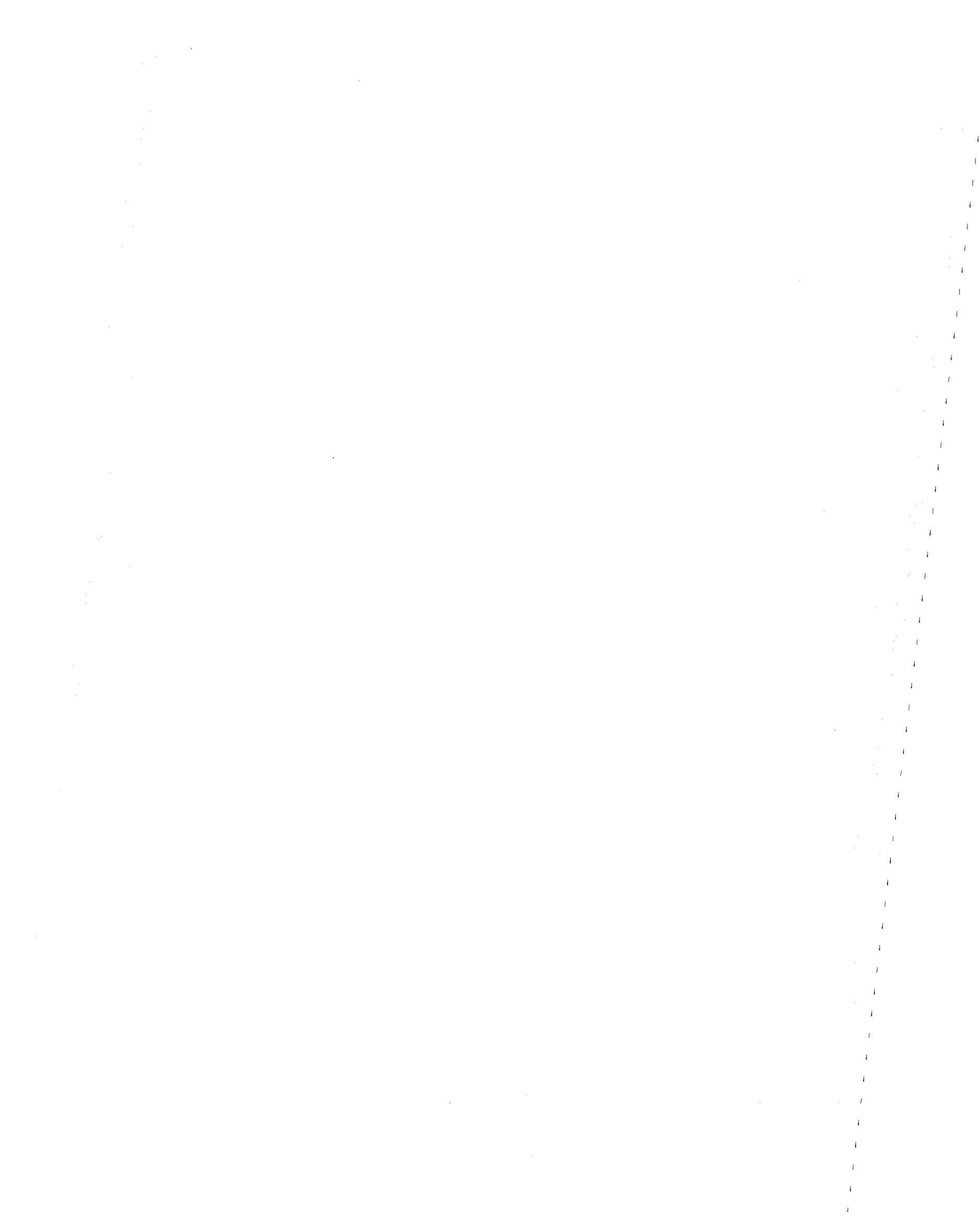
$$t_f = \left[\frac{v_o A_f}{\alpha} \left(\frac{OD_f}{\xi / H_A} \right) \right]^{1/2} \quad (22b)$$

where ρ_o = ambient gas density, kg/m³; A_f = cross-sectional area of the mine passageway, m²; $\Delta C_{i,f}$ = alarm level concentration of gas species i, ppm; $\alpha = 1 \times 10^{-4}$ kW/s²; Y_i = yield of gas species i, g/g; H_A = actual heat of combustion for coal, kJ/g; OD_f = alarm level value of optical density, m⁻¹; and ξ = mass attenuation coefficient, m²/g (defined in Section 3.2.2).

Stratification is not considered in t_f for POC type detectors, since little temperature stratification is still present when the required detection levels are obtained (4). In addition, the large distances expected to be present between detectors would tend to reduce stratification through a combination of mixing and gas thermal losses. However, stratification and heat losses must be considered when determining t_f for heat detectors.

From Reference 3 and eqs (16-18), an expression can be obtained for t_f for a heat detector as a function of the average gas temperature in the mine passageway, ΔT_{avg} , i.e.,

* A product of combustion as defined here specifically excludes heat generation.



$$t_f = \left\{ \frac{(1 + k_\ell) \rho_o c_o v_o A_f \Delta T_{avg} + A_w \sigma [(\Delta T_{avg} + T_o)^4 - T_o^4]}{\alpha} \right\}^{1/2} + \ell_D / v_o \quad (23)$$

where k_ℓ is the convective loss coefficient at ℓ_D ;

c_o = ambient gas specific heat, (kJ/kg K);

A_w = surface area of passageway walls, ceiling and floor (m^2);

σ = Stefan-Boltzmann constant; and

T_o = ambient gas temperature (K).

Equation (6) of Reference 4 can be employed to assess the local temperature rise, ΔT_h , at the heat detector versus ΔT_{avg} and v_{avg} :

$$\Delta T_h = 1.8 \left[\frac{gH}{T_{avg} v_{avg}^2} \right]^{0.23} \Delta T_{avg}^{1.23} \quad (24)$$

where g = acceleration due to gravity, and H = ceiling height of passageway, m.

With the assumptions that $v_{avg} \cong v_o$ and $T_h = 330$ K (alarm threshold for 135°F heat detector) and solving for ΔT_{avg} in eq (24),

$$\Delta T_{avg} = \left[\frac{330 - T_o}{1.8} \right]^{0.81} \left[\frac{T_o v_o^2}{gH} \right]^{0.19} \quad (25)$$

Equation (25) combined with eq (23) can now be employed to assess t_f for heat detectors.

3.3.2.1 Equivalency for Beltway Fires - The fundamental relationship defining equivalency, as previously defined in Reference 1, modified to include t_f , is

$$t_{\ell,T} + t_{f,T} + t_{D,T} \geq t_{\ell,P} + t_{f,P} + t_{D,P} \quad (26)$$

where T refers to a thermal (heat) detector and P to a product of combustion detector. As long as the sum of the transit, fire growth and detection times of a product of combustion detector is less than or equal to the sum for a heat detector, then that detector provides equivalent protection. Unfortunately, the limitation on eq (26) is that it cannot be quantified without the specification of the preignition mine environment and the fire to be detected. Table 5 gives a set of "typical" conditions in a conveyor belt



haulageway which have been assumed to specify equivalency for the various detectors evaluated in this program.

Table 6 lists the following information for each detector: 1) detector type; 2) alarm alert level; 3) equivalent spacing assuming nonfire resistant belting; 4) the safety parameter, X , defined in eq (16); and 5) the recommended-maximum spacing for $X \geq 0.50$.

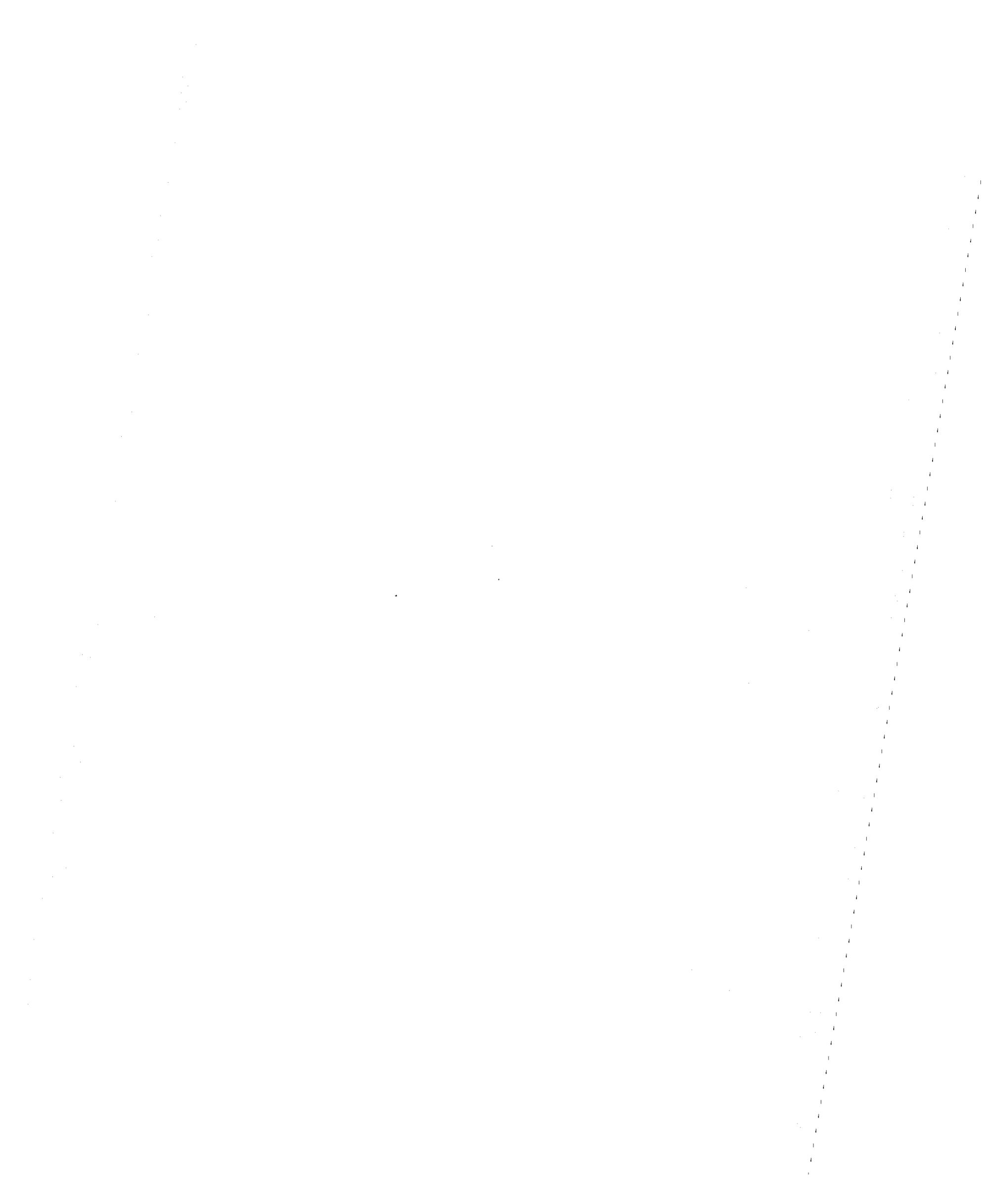
For the heat detectors listed in the table, the concept of response time index, or RTI, was used to quantify detector response as described in Reference 5. The following values of t_D result assuming $v_0 = 0.25$ m/s (50 fpm) and $t_D =$ time constant (τ):

- $t_D = 0$ s ("Ideal");
- $t_D = 24$ s (Thermotech);
- $t_D = 118$ s (MSA); and
- $t_D = 764$ s (Pyott-Boone).

The value of λ_D for each heat detector is stated in Title 30 CFR 75.1103 as 50 ft (15 m) under the specified conditions. Equation (17) combined with a hazard time, $t_H = 2700$ s, t_D and eqs (23) and (25), determine the safety parameter, X for $\lambda_D = 15$ m. X ranges from a high of 0.70 to a low of 0.45 as shown in Table 6. Equivalency, therefore, would be defined at $X = 0.45$, i.e., at the conditions for the slowest responding "mine-permissible" detector. Thus, λ_D for each of the POC detectors is given for $X = 0.45$ and is calculated from eq (17) and t_H using eq (22) instead of eqs (23) and (25). The following are the values of t_D for each POC detector, based on experimental data given in either Reference 5 or Section 3.2, and assuming $t_D = \tau + t_l$ (time constant plus the lag time);

- $t_D = 39$ s (Ecolyzer);
- $t_D = 43$ s (MSA);
- $t_D = 760$ s (Spanair);
- $t_D = 0$ s (Becon).

For three of the four POC detectors tested, "equivalent" spacing would be ~ 300 m (1000 ft). For the Spanair CO₂ detector, the large t_D reduces λ_D to only 130 m (430 ft). It should be noted that, while $t_D = \tau + t_l$ only for "slow" growing fires (which is the case here), this assumption is conservative, i.e., predicts larger values of t_D for "fast" growing fires. Also, the alarm/alert levels are based upon threshold changes above ambient that should be readily detectable for a given detector.



Finally, a recommended maximum spacing at the same safety parameter ($X \geq 0.50$) is given in Table 6 for all the detectors regardless of equivalency. This allows a minimum safety factor of 1300 s (22.5 min) and results in spacings ranging from 3 m (10 ft) to a maximum of 300 m (1000 ft). These values of λ_D should in general allow sufficient time to respond to the detector alarm and fight the fire while still small and localized (30).

3.3.2.2 Generalized Spacing Criteria for Beltway Fires - Table 7 gives the quantity $(\lambda_D/v_o + t_D)$ for beltway fires versus the ventilation rate (in multiples of 1000 cfm) for fixed values of the safety parameter, X. These spacing criteria are given only for POC type detectors, although criteria for heat detectors can be determined with some computational difficulty. Spacing criteria for both types of detectors have been included in a program written for hand-held calculators and detailed in Appendix A. It should be noted that the fire growth times (to reach detectable levels of fire products), t_f , for CO, CO₂, and smoke (optical density, OD) are sufficiently different so that variations in t_f are considered in Table 7 by tabulating separate values for CO, CO₂, and OD.

The following procedure can be used to determine the detector spacing, λ_D :

- 1) select the detector type (CO, CO₂, or OD) of interest;
- 2) select a value of X and \dot{V} , the ventilation rate in cfm;
- 3) read the corresponding value of $(\lambda_D/v_o + t_D)$ in the table and designate it as "b";
- 4) obtain t_D for the specific detector assuming $t_D = \tau + t_\ell$ (Table 10 summarizes t_D for the detectors examined in this program);
- 5) recalling that $v_o = \dot{V}/A_f$, calculate λ_D in ft by the following:

$$\lambda_D = \frac{v_o (b - t_D)}{0.3} \quad \text{for } v_o \text{ in m/s} \quad (27a)$$

or

$$\lambda_D = \frac{v_o (b - t_D)}{60} \quad \text{for } v_o \text{ in fpm} \quad (27b)$$

Using for example the MSA/BUMINES CO detector for beltway fires and selecting $X = 0.5$ and $\dot{V} = 4000$ cfm, $(\lambda_D/v_o + t_D)$ is 1080 s from Table 7. t_D from Table 10 is 43 s. Assuming, for example, the previously identified design conditions: $A_f = 80 \text{ ft}^2$ and v_o in fpm is $4000 \text{ cfm}/80 \text{ ft}^2 = 50 \text{ fpm}$. Thus,



$$l_D = \frac{50 (1080 - 43)}{60} = 860 \text{ ft .}$$

3.3.3 Coal Wall Fires

Spacing criteria for coal wall fires were developed similarly to those for beltway fires with the exception that t_H now is associated with propagation of a wall fire and not a belt fire. Consequently, t_H has been assessed using the concept of a critical flux for ignition and a heat flow parameter, abbreviated HFP (3), i.e.,

$$\text{HFP} \equiv (\dot{Q}_A / \rho_o C_o T_o) / v_o A_f . \quad (28)$$

The critical flux for ignition for a given material in a mine passageway prescribes a specific value for HFP as a function of distance from the origin of the fire. Since it is highly desirable to insure that the fire remains localized, the minimum value of HFP should be used. This value for coal is 1.6. Therefore, the following expression describes t_H :

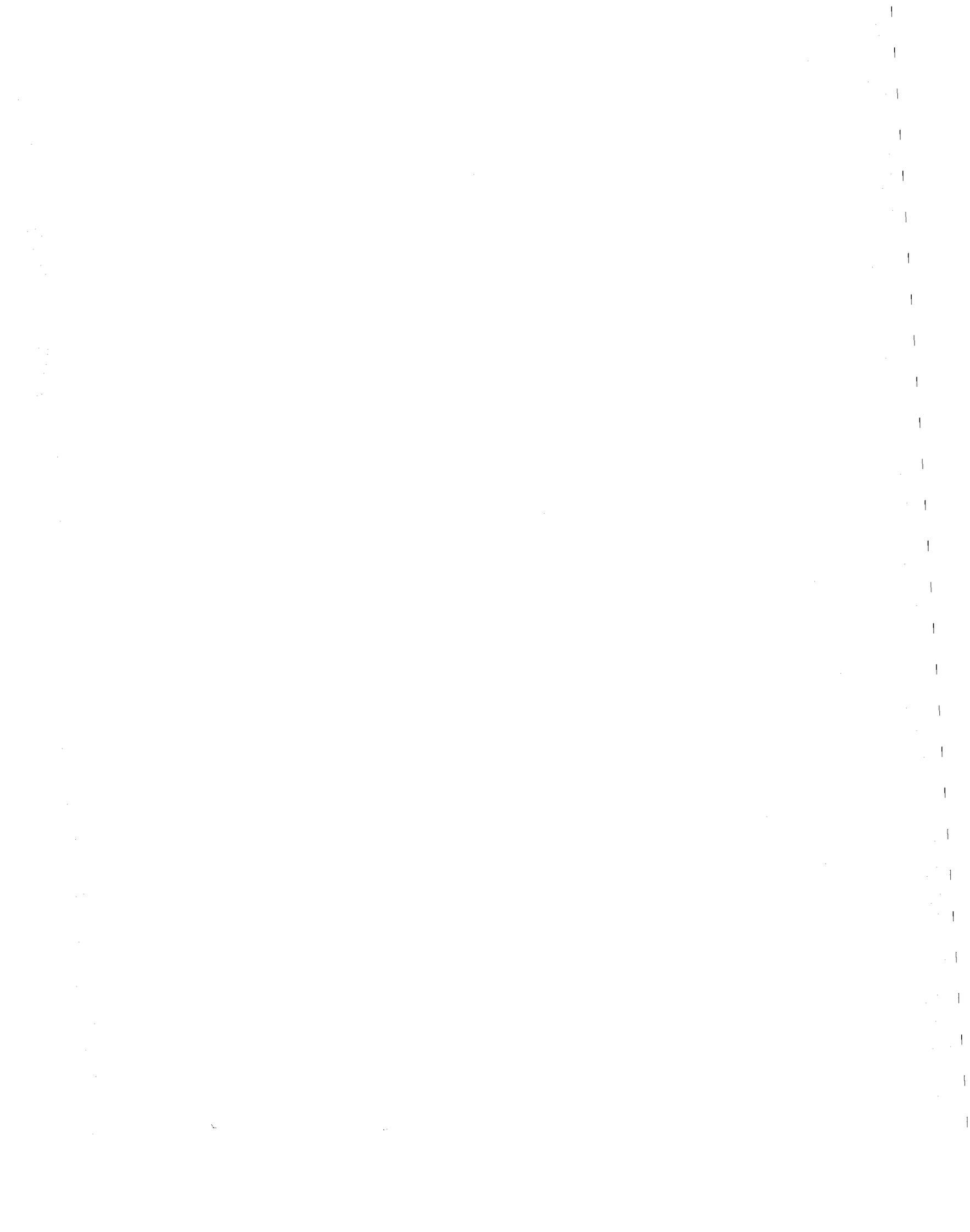
$$t_H = \left\{ \frac{\text{HFP } \rho_o C_o T_o v_o A_f}{\alpha} \right\}^{1/2} \quad (29)$$

where HFP = 1.6 and $\alpha = 1 \times 10^{-4} \text{ kW/s}^2$ for coal.

Table 8 gives the spacing criteria for coal wall fires. Again, similar to the format presented for the beltway fires, the quantity $(l_D/v_o + t_D)$ is given as a function of the safety parameter, X, and the ventilation rate, V in multiples of 1000 cfm. The procedure for employing Table 8 and eq (27) to obtain l_D is identical to that for the beltway fires. Alternately, l_D may be found by using the calculator program described in Appendix A.

3.3.4 Wood Wall Fires

Spacing criteria for wood wall fires require the same definition for t_H as coal wall fires with the exception that HFP = 1.2 and $\alpha = 1 \times 10^{-3} \text{ kW/s}^2$ in eq (29). Again, the value of HFP for wood was obtained assuming that the fire



remains localized; α for wood was developed from large-scale timber fire tests (31) assuming the form of eq (18).

Table 9 gives the spacing criteria for wood wall fires. The previously described procedure (Section 3.3.2) is again followed with $(\ell_D/v_o + t_D)$ read from the table for the conditions of interest and eq (27) used to calculate ℓ_D . The program in Appendix A can also be used to obtain the detector spacing and is particularly useful if values of X other than 0, 0.25, 0.50, or 0.75 are of interest.

3.4 PERFORMANCE SPECIFICATIONS

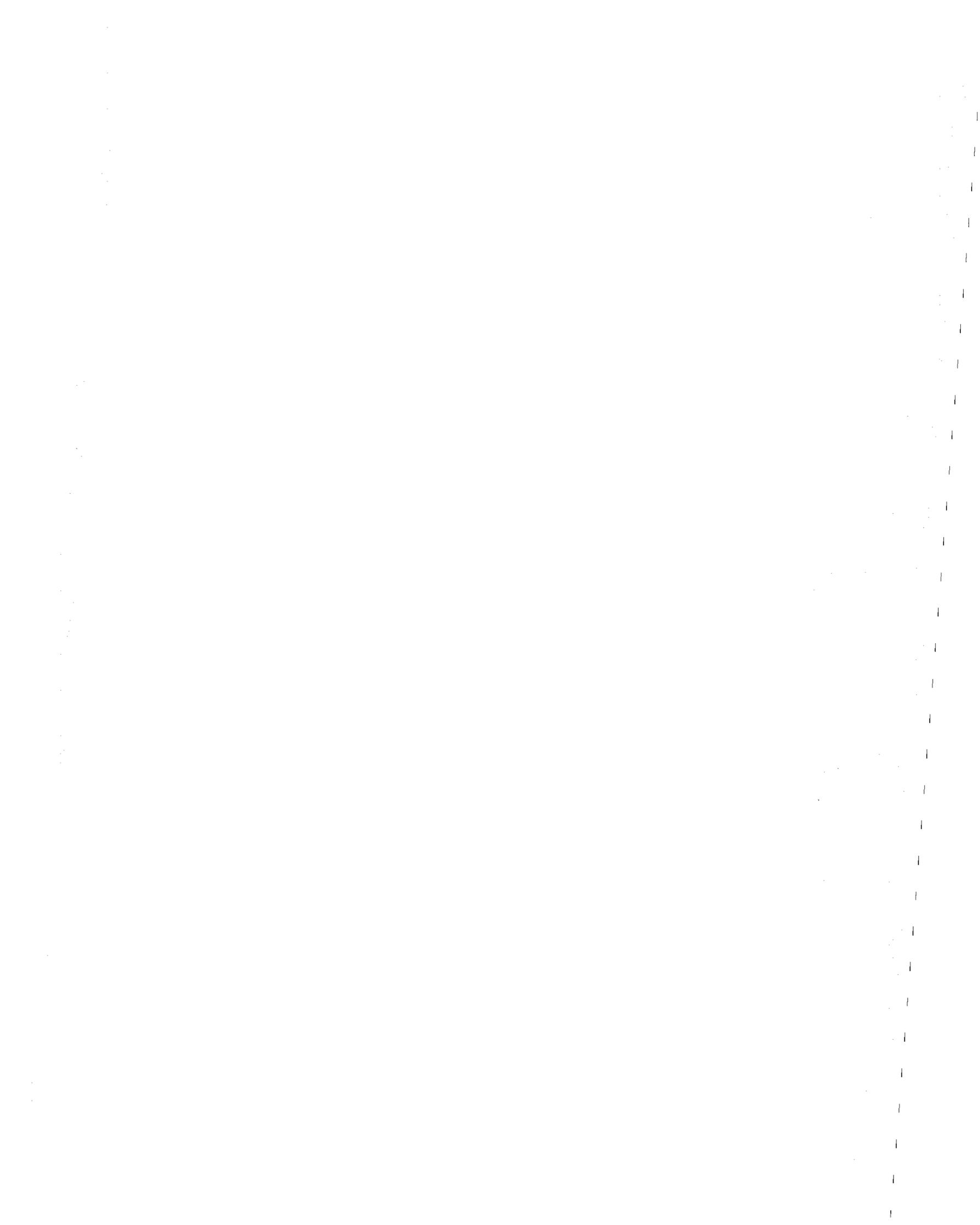
As previously described in Section 3.2, the performance of heat and gas mine fire detectors in mine fire environments is characterized by a time constant, τ , and a lag time (if applicable) determined by the response to several fire sources. The smoke detector (Becon Mark IV) response corresponds to the optical density generated by the products of combustion from the fire sources and a detector/material sensitivity factor. Spacing requirements are prescribed for each detector type at a designated alarm level such that the detecting sensors and sensing systems will operate effectively in a mine fire environment.

The performance specifications for the acceptance of mine fire detection sensors and sensing systems include:

- 1) Alarm level and response time to fire sources;
- 2) Alarm level and response time under various ventilation conditions (ambient velocities of 0.5 to 5.0 m/s); and
- 3) Alarm level and response time at ambient temperatures up to 60°C for the duration of the fire tests.

Several fire sources representative of mine materials have been quantified in this program. The procedure for testing a specific gas detector is to 1) obtain τ (and t_d if appropriate) using the response to a step input of a known composition of cold gas at various ambient gas velocities; and 2) subsequently confirm with various fire sources. SBR conveyor belting, wood, and heptane pan fires, for example, represent a wide range in fire source characteristics potentially available in mine materials, which could routinely be used for mine fire detector tests.

Prior to setting the alarm level for mine fire detection sensors in mine fire environmental performance tests, the individual detector must demonstrate



an acceptable performance baseline. The performance baseline information for mine ambient environment includes:

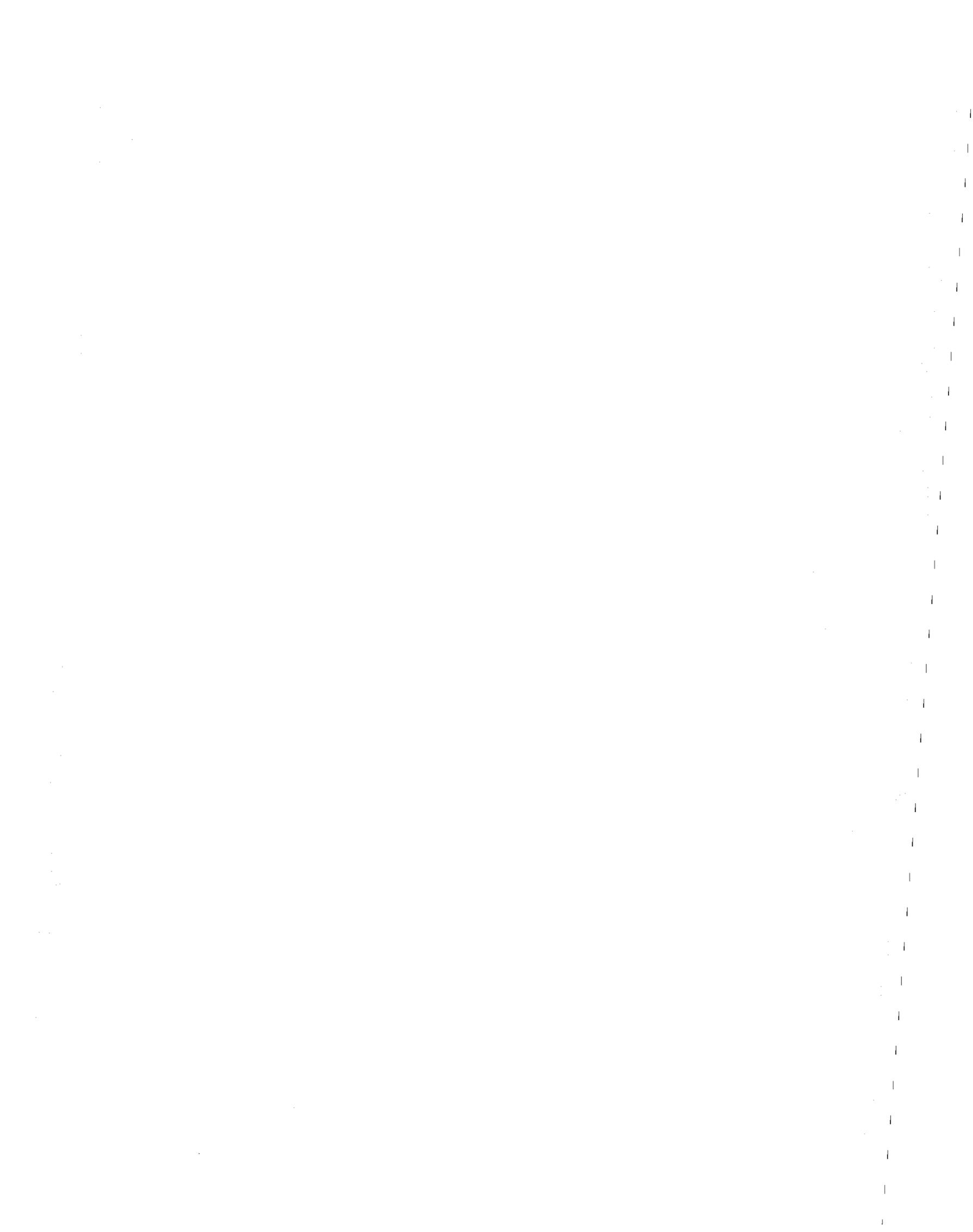
- 1) Warm Up (if required);
- 2) Calibration;
- 3) Accuracy;
- 4) Long-term drift/frequency of calibration;
- 5) Supply voltage variation;
- 6) Response at low and high temperature;
- 7) Temperature-Humidity effect;
- 8) Electromagnetic Interference on response;
- 9) Sand and Dust effect;
- 10) Shock and Vibration; and
- 11) Other:
 - a) Hazardous Location Evaluation: i) Intrinsic Safety, ii) Explosionproof
 - b) Ease of Maintenance
 - c) Specifications on Signaling
 - d) Compatibility with other equipment as part of an alarm signaling

system, etc.

This performance baseline information for each specific type of detector should be specified by the manufacturer through a testing program as outlined in various approvals standards (17-24) and other guidelines (10,25).

In addition, after evaluation in the test apparatus, it is suggested that the selected detectors be installed, in the field, within an existing underground mine to test for the effects of: temperature, humidity, pressure, dust shock, vibration, etc. After the in-field underground mine conditioning, or simulated environmental conditioning, the fire detectors could be further tested in the test apparatus to assess any changes in response characteristics versus source fire and ventilation rate.

Finally, in this program, additional testing was conducted on Ecolyzer Model 5100 CO and MSA CO detectors per FM approval standards (22) in order to determine the feasibility of obtaining the baseline information listed as items 1 through 8 for a gas mine fire detector. Both detectors evaluated met the performance standard, and it was concluded that existing standards were acceptable for obtaining this type of information.



NOMENCLATURE

a	detector/material sensitivity factor [Eq (8)]
A	area of mine passageway (m^2)
b	$(\ell_D/v_o + t_D)$
B	calibration constant for Spanair CO ₂ detector (ppm/volt) [Eq (12)]
c	specific heat (kJ/kg•K)
C	concentration (ppm)
ΔC	concentration rise (ppm)
CO	carbon monoxide
CO ₂	carbon dioxide
g	acceleration due to gravity (m/s^2)
H	ceiling height of mine passageway (m)
H _A	actual heat of combustion (kJ/g)
HFP	heat flow parameter [Eq (28)]
I	current signal
ΔI	change in current signal
k	convective loss coefficient
ℓ	distance (m)
\dot{m}	mass loss rate ($g/m^2 \text{ s}$)
OD	optical density base e (m^{-1})
p	exponent of power law fire
POC	product of combustion
\dot{q}_e	external heat flux (kW/m^2)
Q _A	actual heat release rate (kW)
RTI	Response Time Index ($m \cdot s$) ^{1/2}
t	time (s)
v	gas velocity (m/s)
V	voltage signal
\dot{V}	ventilation rate (m^3/s or cfm)
W	width of mine passageway (m)
X	safety parameter [Eq (16)]
Y	fractional mass yield of fire product (g/g)



Greek

α	proportionality constant of power law fire (kW/s^p)
ξ	mass attenuation coefficient (m^2/g)
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-11} \text{ kW/m}^2 \text{ K}^4$)
ρ	gas density (kg/m^3)
τ	time constant (s)
χ_A	combustion efficiency

Subscripts

avg	average
CO	carbon monoxide
CO ₂	carbon dioxide
D	detection
E	effective
f	fire growth or flow
h	height
H	hazard
H ₂ O	water
i	individual products (CO, CO ₂ , H ₂ O, THC)
l	lag
o	ambient air or reference
P	product of combustion
r	residual
s	sensor
t	transit
T	thermal
THC	total hydrocarbons
w	walls

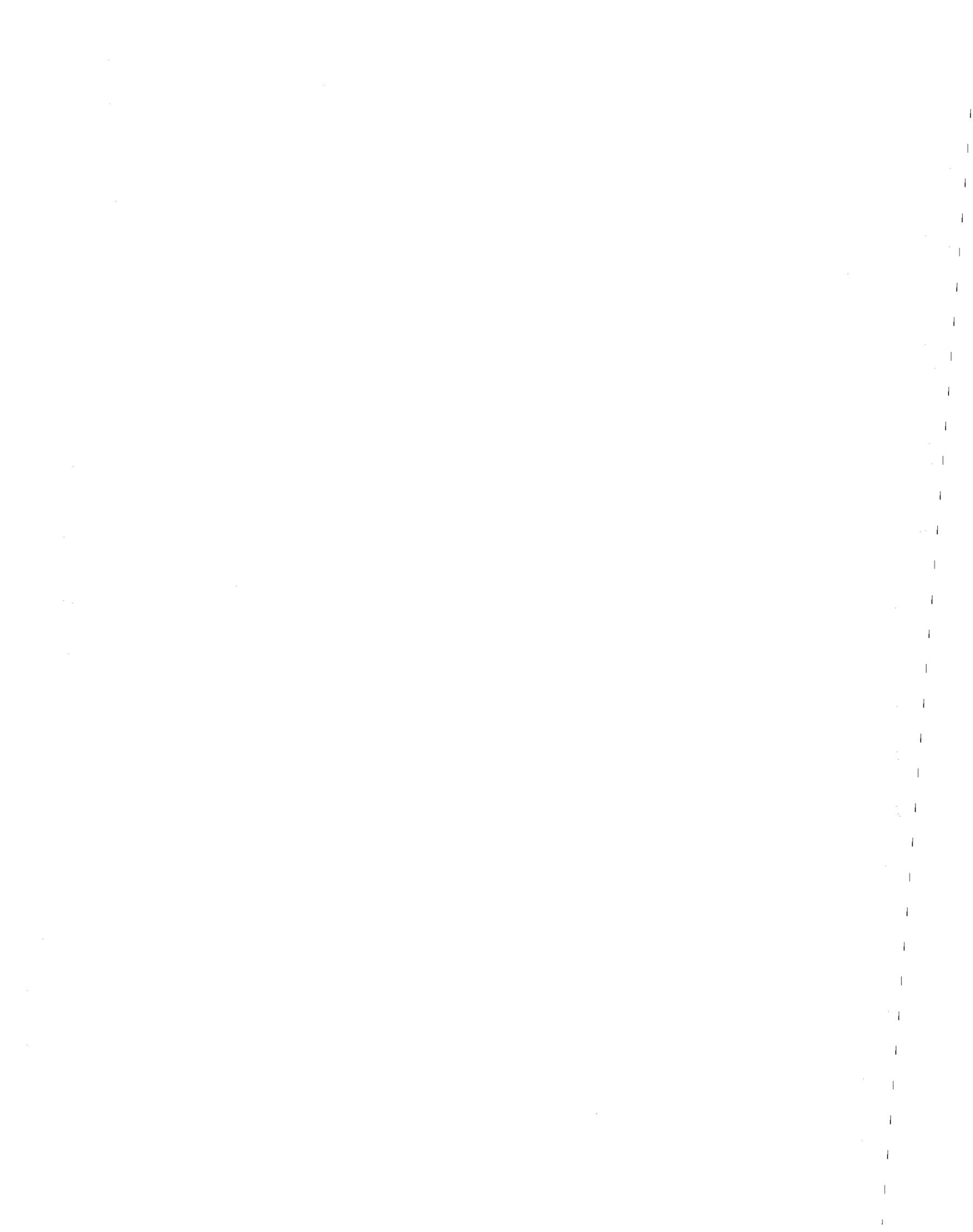


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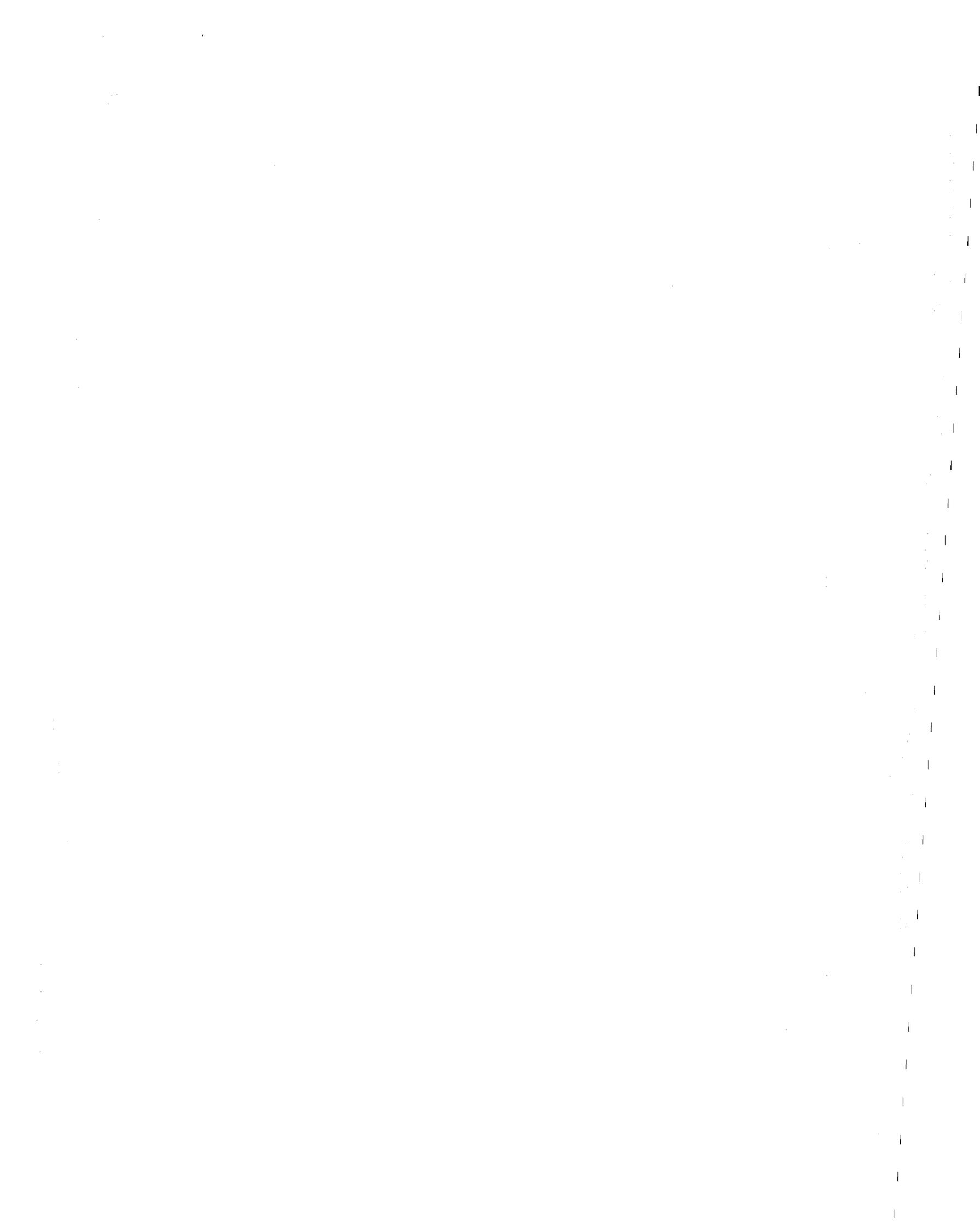
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APPENDIX A

PROGRAM FOR APPLICATION OF SPACING CRITERIA

A program has been developed to assist in the application of the developed spacing criteria through the use of a programmed hand-held calculator. This program called "SPACING" is designed for use on a Hewlett-Packard (HP) 41CX, 41CV, or 41C (with a quad memory module). The program listing is given in Table A.1. The following set of instructions is provided for the use of "SPACING" with some examples.

A.1 GENERAL INSTRUCTIONS

The program requires an allocation of 20 data registers for program memory. The initial allocation of the HP-41CX and 41CV is already sufficient. However, if the HP-41C plus quad memory is being used, execute the function "SIZE 020" to change the data register allocation. The program operates from the "USER" keyboard and execution begins by pressing the A (Σ +) key. The program prompts with questions as numerical input information is required. This information is keyed in by using the numeric keypad, i.e., keys *, and 0-9. Execution is continued by pressing the Run/Stop (R/S) key. The required input information is of three types: 1) ambient condition specifications; 2) yes (designated by "0") or no (designated by "1") decisions for selection of the appropriate fire scenario; and 3) input data for X (the safety parameter) and T_d (the detection time) or L_d (the spacing between detectors).

Finally, values calculated for L_d are rounded off by the program such that only two significant digits are given. For instance 870 ft is displayed in Example 1 instead of 868 ft.

Ambient Conditions

The following questions must be answered:

- 1) What is the ambient velocity in fpm?
- 2) What is the ambient temperature in °F?
- 3) What is the average passageway height in ft?
- 4) What is the average passageway width in ft?

TABLE A.1 - Program Spacing

01+LBL A	48 "I1)?"	94 STO 08
02+LBL "SPACING"	49 TONE 5	95 GTO 02
03 "DETECTOR SPAC"	50 PROMPT	
04 "RING PROGRAM"	51 X=0?	96+LBL "BELT"
05 RVIEW	52 GTO 03	97 1 E-04
06 PSE	53 XEQ "POC"	98 STO 07
07 "V= ? FT/MIN"		99 2700
08 TONE 5	54+LBL 03	100 STO 08
09 PROMPT	55 XEQ "HEAT"	101 RTN
10 197		
11 /	56+LBL "WOOD"	102+LBL "POC"
12 STO 01	57 1 E-03	103 "CO<0>, CO2<1>, "
13 "T= ? DEG.F"	58 STO 07	104 "PO<2>?"
14 TONE 5	59 1/X	105 TONE 5
15 PROMPT	60 1.2	106 PROMPT
16 32	61 *	107 X=0?
17 -	62 350	108 GTO "CO"
18 1.8	63 *	109 1
19 /	64 RCL 01	110 X=Y?
20 273	65 *	111 GTO "CO2"
21 +	66 RCL 03	112 GTO "OD"
22 STO 02	67 *	
23 "H= ? FT"	68 RCL 04	113+LBL "CO"
24 TONE 5	69 *	114 RCL 00
25 PROMPT	70 SQRT	115 X=0?
26 3.28	71 STO 08	116 GTO "COc"
27 /	72 RTN	117 54000
28 STO 03		118 GTO 05
29 "W= ? FT"	73+LBL "COAL"	
30 TONE 5	74 "BELTWAY? Y<0> 0"	119+LBL "COc"
31 PROMPT	75 "R N<1>?"	120 30000
32 3.28	76 TONE 5	121 GTO 05
33 /	77 PROMPT	
34 STO 04	78 X=0?	122+LBL "CO2"
35 "COAL<0> OR WOOD"	79 GTO "BELT"	123 RCL 00
36 "I<1>?"	80 1 E-04	124 X=0?
37 TONE 5	81 STO 07	125 GTO "CO2c"
38 PROMPT	82 1/X	126 2300
39 STO 00	83 1.6	127 GTO 05
40 X=0?	84 *	
41 GTO 01	85 350	128+LBL "CO2c"
42 XEQ "WOOD"	86 *	129 24000
43 GTO 02	87 RCL 01	130 GTO 05
	88 *	
44+LBL 01	89 RCL 03	131+LBL "OD"
45 XEQ "COAL"	90 *	132 RCL 00
	91 RCL 04	133 X=0?
46+LBL 02	92 *	134 GTO "ODc"
47 "HEAT<0> OR POC<0>"	93 SQRT	135 13000

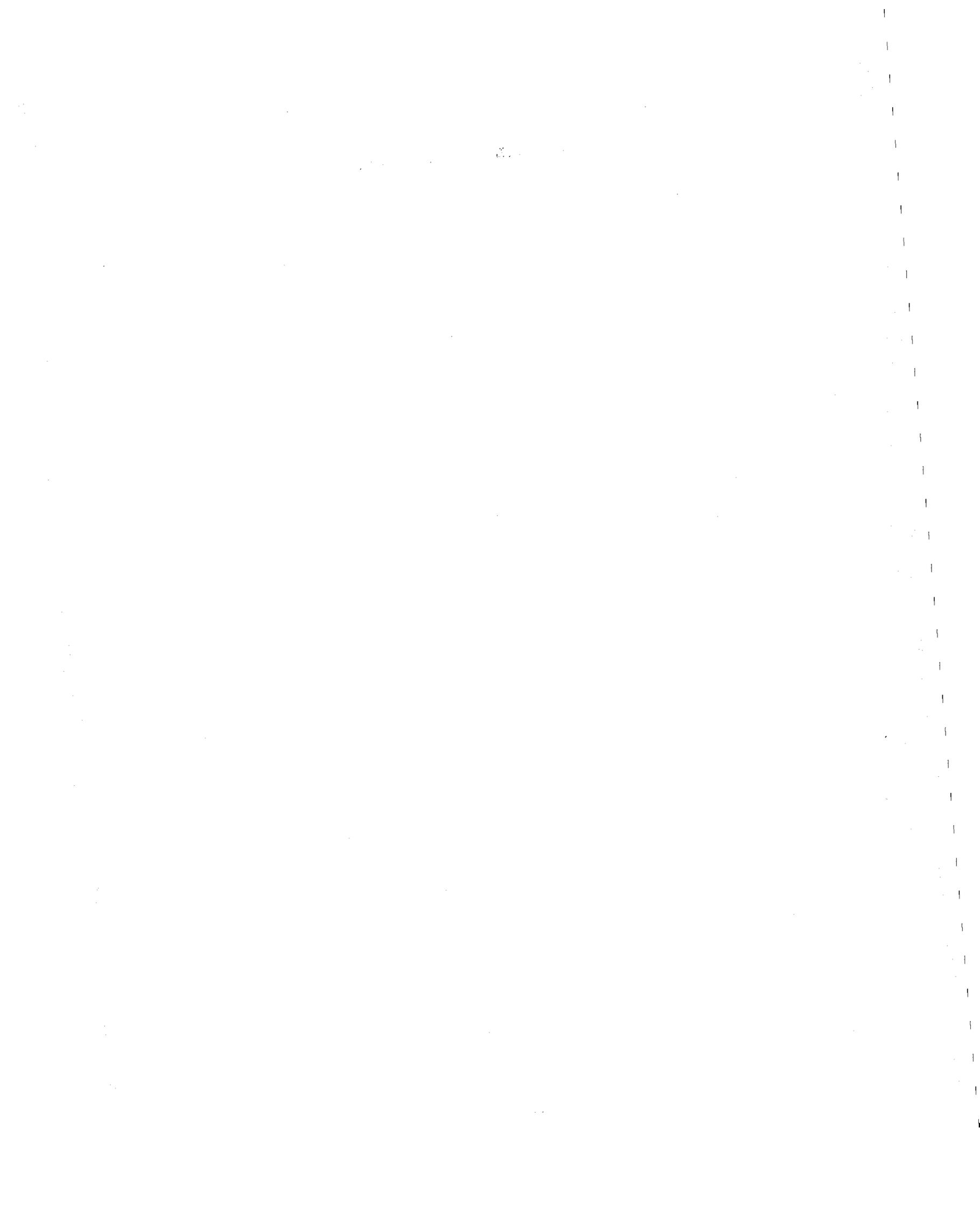


TABLE A.1 (Continued)

136 GTO 05	181 BEEP	225 -
137+LBL "0Dc"	182 PROMPT	226 RCL 08
138 6800	183 GTO "XP"	227 *
	184+LBL 06	228 RCL 14
139+LBL 05	185 "Ld>10000 FT"	229 -
140 RCL 01	186 BEEP	230 RCL 05
141 *	187 PROMPT	231 RCL 01
142 RCL 03		232 /
143 *	188+LBL 07	233 -
144 RCL 04	189 " FT"	234 X>0?
145 *	190 ASTO 16	235 GTO 08
146 SQRT	191 CLA	236 "Td < 0 SEC"
147 STO 14	192 "Ld ="	237 BEEP
	193 ARCL 15	238 PROMPT
148+LBL "XP"	194 ARCL 16	239 GTO 09
149 "X= ?(0-1)"	195 AVIEW	240+LBL 08
150 TONE 5	196 FIX 2	241 SCI 1
151 PROMPT	197 BEEP	242 RND
152 STO 09	198 STOP	243 FIX 0
	199 "NEW Td<0> OR X<"	244 STO 15
153+LBL "Td"	200 "H1>?"	245 " SEC"
154 "Td= ? SEC"	201 TONE 5	246 ASTO 16
155 TONE 5	202 PROMPT	247 CLA
156 PROMPT	203 X=0?	248 "Td = "
157 CHS	204 GTO "Td"	249 ARCL 15
158 1	205 GTO "XP"	250 ARCL 16
159 RCL 09	206 RTN	251 AVIEW
160 -		252 FIX 2
161 RCL 08	207+LBL "HEAT"	253 BEEP
162 *	208 XEQ "TAVG"	254 STOP
163 +		
164 RCL 14	209+LBL "XH"	255+LBL 09
165 -	210 "X= ?(0-1)"	256 "NEW Ld<0> OR X<"
166 RCL 01	211 TONE 5	257 "H1> ?"
167 *	212 PROMPT	258 TONE 5
168 3.28	213 STO 09	259 PROMPT
169 *		260 X=0?
170 SCI 1	214+LBL "Ld"	261 GTO "Ld"
171 RND	215 "Ld= ? FT"	262 GTO "XH"
172 FIX 0	216 TONE 5	263 RTN
173 STO 15	217 PROMPT	
174 1 E04	218 3.28	264+LBL "TAVG"
175 X<=Y?	219 /	265 RCL 01
176 GTO 06	220 STO 05	266 X12
177 X<>Y	221 XEQ "KL"	267 RCL 02
178 X>0?	222 XEQ "TFH"	268 *
179 GTO 07	223 1	269 9.81
180 "Ld < 0 FT"	224 RCL 09	270 /

TABLE A.1 (Concluded)

271 RCL 03	319 0.7	367 /
272 /	320 Y1X	368 SQRT
273 0.19	321 1	369 RCL 05
274 Y1X	322 +	370 RCL 01
275 330	323 *	371 /
276 RCL 02	324 RCL 05	372 +
277 -	325 *	373 STO 14
278 1.8	326 RCL 12	374 .END.
279 /	327 /	
280 0.81	328 STO 13	
281 Y1X	329 RTN	
282 *		
283 STO 06	330*LBL "TFH"	
284 RTN	331 RCL 06	
	332 RCL 02	
285*LBL "KL"	333 +	
286 353.4	334 X12	
287 RCL 02	335 X12	
288 /	336 RCL 02	
289 STO 10	337 X12	
290 RCL 02	338 X12	
291 273	339 -	
292 -	340 5.67 E-11	
293 3.526 E-08	341 *	
294 *	342 RCL 03	
295 1.823 E-05	343 2	
296 +	344 *	
297 STO 11	345 RCL 04	
298 /	346 2	
299 RCL 01	347 *	
300 *	348 +	
301 RCL 03	349 RCL 05	
302 RCL 04	350 *	
303 *	351 *	
304 RCL 03	352 RCL 13	
305 RCL 04	353 1	
306 +	354 +	
307 /	355 RCL 10	
308 2	356 *	
309 *	357 RCL 01	
310 STO 12	358 *	
311 *	359 RCL 03	
312 -0.2	360 *	
313 Y1X	361 RCL 04	
314 0.026	362 *	
315 *	363 RCL 06	
316 RCL 12	364 *	
317 RCL 05	365 +	
318 /	366 RCL 07	

Fire Scenario Selection

The following decisions must be made:

- 1) Is it a coal (answer 0) or wood (answer 1) fire?
- 2) If it is a coal fire (0 in 1) above), is it in a beltway (answer 0 for yes or 1 for no)?

Detector Information

- 1) Is it a heat detector (answer 0) or product of combustion, POC detector (answer 1)?
- 2) If it is a POC detector, what type is it (answer 0 for CO, 1 for CO₂, or 2 for OD, smoke)?
 - a) What is the value of X (answer between 0 and 1)?
 - b) What is the value of T_d in seconds?
 - c) The value of L_d is displayed in ft. If the value of L_d is less than zero for the conditions specified, then L_d < 0 is displayed. If the value of L_d is greater than 10,000, then L_d > 10,000 ft is displayed.
- 3) T_d (answer 0) or X (answer 1) can be changed by pressing the R/S key and providing the appropriate answer.
- 4) If the detector is a heat type (answer 0 in 1) above), then the following set of questions are asked:
 - a) What is the value of X?
 - b) What is the value of L_d in ft? Note: Due to the nature of the relations describing the local environment around the heat detector, L_d must be first specified then T_d is calculated. If the calculated value of T_d is less than the actual value of T_d for the detector, then L_d is acceptable; otherwise, either X or T_d must be changed. This is accomplished by pressing the R/S key. Either T_d (answer 0) or X (answer 1) can be changed and the process can be reiterated until T_d and L_d match.

A.2 EXAMPLES

Several examples of the use of the detector spacing program are given in Table A.2. For convenience, all these examples use the design conditions for the "typical" coal mine, i.e., v₀ = 50 fpm, T₀ = 65°F, H = 5 ft, and W = 16 ft. Detector specifications are mainly chosen to illustrate spacing values given in Table 6.

TABLE A.2 - Examples for use of spacing program

Example 1

```

XEQ A
DETECTOR SPACING PROGRAM
V= ? FT/MIN      50.00  RUN
T= ? DEG.F      65.00  RUN
H= ? FT         5.00   RUN
W= ? FT         16.00  RUN
COAL<0> OR WOOD<1>? 0.00  RUN
BELTWAY? Y<0> OR N<1>? 0.00  RUN
HEAT<0> OR POC<1>? 1.00  RUN
CO<0>, CO2<1>, OD<2>? 0.00  RUN
X= ?<0-1>      .50   RUN
Td= ? SEC      39.00  RUN
Ld =870. FT
NEW Td<0> OR X<1>? 0.00  RUN
Td= ? SEC      43.00  RUN
Ld =870. FT
    
```

Example 2

```

XEQ A
DETECTOR SPACING PROGRAM
V= ? FT/MIN      50.00  RUN
T= ? DEG.F      65.00  RUN
H= ? FT         5.00   RUN
W= ? FT         16.00  RUN
COAL<0> OR WOOD<1>? 0.00  RUN
BELTWAY? Y<0> OR N<1>? 0.00  RUN
HEAT<0> OR POC<1>? 0.00  RUN
X= ?<0-1>      .50   RUN
Ld= ? FT        50.00  RUN
Td = 570. SEC
NEW Ld<0> OR X<1> ? 0.00  RUN
Ld= ? FT       150.00  RUN
Td = 130. SEC
NEW Ld<0> OR X<1> ? 0.00  RUN
Ld= ? FT       155.00  RUN
Td = 110. SEC
    
```

Example 3

```

XEQ A
DETECTOR SPACING PROGRAM
V= ? FT/MIN      50.00  RUN
T= ? DEG.F      65.00  RUN
H= ? FT         5.00   RUN
W= ? FT         16.00  RUN
COAL<0> OR WOOD<1>? 1.00  RUN
HEAT<0> OR POC<1>? 1.00  RUN
CO<0>, CO2<1>, OD<2>? 2.00  RUN
X= ?<0-1>      .50   RUN
Td= ? SEC      0.00  RUN
Ld =240. FT
    
```

Example 4

```

XEQ A
DETECTOR SPACING PROGRAM
V= ? FT/MIN      50.00  RUN
T= ? DEG.F      65.00  RUN
H= ? FT         5.00   RUN
W= ? FT         16.00  RUN
COAL<0> OR WOOD<1>? 0.00  RUN
BELTWAY? Y<0> OR N<1>? 1.00  RUN
HEAT<0> OR POC<1>? 1.00  RUN
CO<0>, CO2<1>, OD<2>? 1.00  RUN
X= ?<0-1>      .50   RUN
Td= ? SEC      760.00  RUN
Ld =540. FT
    
```


Example 1

Selections are made for coal and a beltway. A POC detector, CO, is chosen. Spacing is first determined for $X = 0.5$ and $T_d = 39$ s (the value for the Ecolyzer CO detector), i.e., $L_d = 870$ ft. A new T_d is selected of 43 s (the value for the MSA/BUMINES CO detector) which does not change L_d .

Example 2

Selections are made for coal and a beltway. A heat detector is chosen and values for X of 0.5 and L_d of 50 ft are selected. The calculated value of T_d is 570 s. If, for example the MSA heat detector is of interest, T_d is 118 s at 0.25 m/s (50 fpm). Therefore, (570-118) or 452 s are still available which can be taken advantage of by increasing the spacing. Pressing R/S and answering 0 allows L_d to be changed. Selecting $L_d = 150$ ft results in $T_d = 130$ s which is still greater than 118 s. If a finer resolution is desired, the process can be reiterated. In this example, $L_d = 155$ ft is selected and $T_d = 110$ s is calculated, which is less than the T_d of interest of 118 s. Thus, for these conditions the maximum allowable spacing is 150 ft.

Example 3

A wood wall fire scenario is selected with a POC type detector. A smoke detector (OD) is chosen with $X = 0.50$ and $T_d = 0$ s (the value for the Becon ionization detector). The resulting spacing is 240 ft.

Example 4

A coal wall fire scenario is selected with a CO₂ detector. $X = 0.50$ and $T_d = 760$ s (the value for the Spanair CO₂ analyzer). The result is $L_d = 540$ ft.

5

APPENDIX B

PHASE I REPORT

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.
4. Title and Subtitle Standard Test Criteria For Evaluation Of Underground Fire Detection Systems Phase I		5. Report Date July 1982 (published)	
7. Author(s) Jeffrey S. Newman		6.	
9. Performing Organization Name and Address Factory Mutual Research Corporation 1151 Boston-providence Turnpike Norwood, Mass. 02062		8. Performing Organization Rept. No. J.I. OG2N4.RC	
12. Sponsoring Organization Name and Address U.S. Department of The Interior Bureau of Mines		10. Project/Task/Work Unit No.	
		11. Contract(C) or Grant(G) No. (C) H0113017 (G)	
		13. Type of Report & Period Covered Phase I Report (April 21, 1981-Feb. 21, 1982)	
15. Supplementary Notes		14.	
16. Abstract (Limit: 200 words) This report contains the results of the first phase of a multi-phase effort to establish preliminary standard test criteria for the application of fire detectors in underground mines. The major results of Phase I are: 1) the quantification and prediction of the distribution of combustion products in a mine passageway; 2) the quantification of "equivalent protection" by fire detectors as contained in Title 30 of the Code of Federal Regulations; 3) the definition of detection criteria; and 4) an outline of a preliminary acceptance plan for mine fire detectors.			
17. Document Analysis a. Descriptors Fire Detectors Mine Fire Hazards Test Criteria b. Identifiers/Open-Ended Terms c. COSATI Field/Group			
18. Availability Statement Availability Unlimited		19. Security Class (This Report) Unclassified	21. No. of Pages 61
		20. Security Class (This Page) Unclassified	22. Price

FOREWORD

This report was prepared by Factory Mutual Research Corporation, Factory Mutual System, Norwood, Massachusetts under USBM Contract No. H0113017. It was administered under the technical direction of the Pittsburgh Research Center with Dr. A. F. Cohen acting as Technical Project Officer. Mr. A.G. Young was the contract administrator for the Bureau of Mines. The report is a summary of the work recently completed as part of this contract during the period April 21, 1981 to February 21, 1982. This report was submitted by the author on March 12, 1982.

The author wishes to acknowledge gratefully the following persons who contributed to this project:

Dr. G. Heskestad and Dr. A. Tewarson for extensive contributions to the approach and development of many of the concepts contained in this report; Mr. D.L. Waters and Mr. D.W. Bryers, for their excellent technical assistance in preparing for and conducting gallery tests; Ms. J.A. Steciak and Mr. B.G. Vincent, for assistance in data analysis; Mr. J.L. Buckley, for assistance in the literature review; Dr. A.F. Cohen, for helpful suggestions, support and discussions; and Mr. L.A. Post and Mrs. H.G. Hurley for their efforts in producing this report.

STANDARD TEST CRITERIA FOR EVALUATION OF UNDERGROUND FIRE DETECTION SYSTEMS

Prepared for
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

By
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Phase I Report

Contract No. H0113017

070(A)

July 1982

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Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines or Factory Mutual Research Corporation.

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I

INTRODUCTION

1.1 SUMMARY OF PHASE I

This program consists of a four-phase multiyear approach to establishing standard test criteria and procedures for the evaluation of underground mine fire detection systems. The specific objectives of Phase I were to: 1) assess the interaction of the preignition mine environment with mine material combustion characteristics; 2) quantify "equivalent protection" or equivalency (as stated in Title 30 Code of Federal Regulations); and 3) define detection criteria to be used in the subsequent phases.

The technical approach of Phase I consisted of a review of the literature coupled with an analysis of Factory Mutual Research Corporation's (FMRC) existing experimental data in related areas. This review and analysis indicated several areas in which important data were lacking. Primarily, additional data were required to fully assess the stratification of combustion products from a fire in a mine passageway. Therefore, a test program was designed and conducted to obtain the necessary data. A total of 19 fire tests were performed in the USBM/FMRC full-scale mine gallery using, as the primary source fire either heptane, coal, neoprene conveyor belting, or coal plus neoprene belting. Ventilation velocities from 0.5 to 4.0 m/s were investigated. Heat release rates of the source fire ranged between 10 kW and 20 MW. The major results from Phase I include: 1) the quantification of the source fire; 2) the prediction to within $\pm 15\%$ of both the average gas temperature rise and gas temperature stratification downstream of the source fire; 3) the evaluation of the distribution of combustion products relative to the material combustion characteristics; 4) the quantification of equivalency; 5) the development of detection criteria both on the basis of equivalency as well as relative to a "residual time" concept; and 6) the development of an outline for a preliminary acceptance plan for mine fire detectors.

The recommendations from the work of Phase I suggest: 1) an assessment of fire growth rates for mine materials should be performed; 2) mine fire hazards should be defined; and 3) an assessment of "effective" response times relative to response to a fire detector alarm should be performed.

1.2 OBJECTIVE AND SCOPE

The objective of this project is to develop standardized test criteria and procedures which will assure that fire detectors selected for installation in mines will:

- 1) be reliable in operation;
- 2) be located in the most effective position; and
- 3) function routinely with minimal maintenance.

Since any criteria or procedures to be developed must be based on fire test conditions representative of realistic fire scenario(s) found in an underground mine, the scope of this project requires a detailed knowledge of:

- 1) preignition mine environment;
- 2) type of burning material and configuration; and
- 3) fire detector response characteristics versus the fire scenario(s) determined by 1) and 2).

1.3 TECHNICAL APPROACH

The technical approach developed to meet the objective within the scope of this project defined in Section 1.2 consists of four distinct phases. This report addresses the results from the Phase I work efforts. The following sections outline the approach followed in Phase I accompanied by a brief discussion of the work elements expected to be accomplished in Phases II through IV.

1.3.1 Phase I

The Phase I effort was primarily directed toward identification and acquisition of the data necessary to establish preliminary standard test criteria for mine fire detectors. This included: 1) review of pertinent literature; 2) gathering and analysis of FMRC's existing experimental data on fire environments and fire detector response characteristics; 3) identification of data gaps (if any); and 4) performance and analysis of additional fire tests (if required).

1.3.2 Phase II

A detailed design of a sensor evaluation test program and associated test apparatus will be prepared under this work phase. The developed test program will be capable of evaluating detector spacing requirements referenced to Title 30 Code

of Federal Regulations as influenced by fire and environmental parameters of an underground mine. Practical limits for evaluation will be used in this phase of the program. Detailed engineering drawings including suppliers will be prepared for a fire test apparatus to be developed for detector evaluation purposes. The rationale for the design of the apparatus and component selection will be provided in this work phase.

1.3.3 Phase III

The test apparatus designed by FMRC and approved by the Bureau under Phase II will be constructed. Any changes in the agreed-to design will be noted on drawing specifications and be supported with adequate discussion.

An acceptance test of the apparatus, based upon an expected worst-case set of mine conditions, will validate the performance of the test apparatus. This test will include the combination of various fuels under environmental mine conditions.

After the fire test apparatus is validated, six different types of fire detectors will be evaluated. These will include early warning devices classed as submicron particulate detectors, submicron particulate diesel-discriminating detectors, low-level CO detectors, fixed temperature units representative of devices found along conveyor beltways, and smoke detectors.

1.3.4 Phase IV

Within this phase fire and environmental performance specifications for the acceptance of mine fire detection sensors and sensing systems will be developed. The developed standards will specify optimum sensor spacing capability as related to Title 30 Code of Federal Regulations Paragraphs 75-1103-4, 75-1103-10 and will also specify the environmental conditions under which detectors used for mine applications must operate. This specification will include any special conditions and practices which should be followed by detector installers.

As a product of this investigation a response theory will be developed for the various types of detectors.

Finally, such a broad work effort will probably indicate technology gaps in the field of detector behavior and installation. These areas will be evaluated for the need of future research work. The results of this evaluation will be presented in comment form providing the rationale for the identified research and a program plan indicating the magnitude of funding and manpower required to accomplish the proposed research efforts.

II

REVIEW OF THE LITERATURE AND EXISTING DATA

2.1 LITERATURE REVIEW

The review of pertinent literature required an investigation of the following topics:

- 1) current domestic and foreign mining industry practices in regard to early warning fire detection systems for rapidly developing fires;
- 2) mine ventilation systems and practices as they affect this program;
- 3) environmental mine parameters;
- 4) equivalency tests by Mine Safety and Health Administration (MSHA); and
- 5) current Bureau efforts in early warning fire detector systems.

A survey of the literature included a review of pertinent information already available in the FMRC library plus a comprehensive, on-line, computer-based interactive literature search. The computer search resulted in approximately 170 abstracts. About 35% of these reports were considered directly applicable, were subsequently ordered and incorporated as necessary in the following review. Since it is difficult to distinguish among current domestic industry practices, current Bureau efforts in fire detection systems, and MSHA equivalency tests, items 1), 4) and 5) have been incorporated into a single review.

2.1.1 Review Of Current Domestic And Foreign Mining Fire Detector Practices

The international mining community appears to be in general agreement that, for reliable, early warning fire detection, the concentration of products of combustion, such as carbon monoxide (CO), carbon dioxide (CO₂), smoke, sub-micrometer particulates, etc., should be continuously monitored in mining operations. Considerable work has been performed on developing detection systems which will not only detect and locate a mine fire but will also perform with sufficient reliability.

Current authorized domestic practices associated with fire detection systems are contained in Title 30 Code of Federal Regulations (revised July 1, 1979), Subpart L, paragraph 75.1103-4. This paragraph delineates the location for fire detectors which are generally of the fixed-temperature, point-type. All other types of detectors must provide protection equivalent^{*} to that provided by the

*The relevance of equivalent protection or equivalency is discussed in Section IV.

fixed-temperature, point-type. National Fire Protection Association (NFPA) standard number 72A is incorporated into the requirements by reference. An examination of the Federal Register from July 1, 1979 to February 1, 1982 indicates no further changes in this law.

It appears that two different approaches to fire detection in mines are being followed by the U.S. Bureau of Mines.

The first is a short-range, immediate implementation of conventional well developed concepts, such as that followed by the Bureau's Twin Cities office. This approach utilizes off-the-shelf hardware with small modifications to achieve early installation of a detection system in a mine. Griffin⁽¹⁾ of the Twin Cities office, for example, reports on the evaluation of in-mine underground CO and smoke detectors for their use in metal and nonmetal mines. Detection modes, expected fire signatures, and environmental conditions are discussed, and preliminary results of long-term effects of in-mine tests are presented. Johnson et al⁽²⁾ and Johnson and Forshey⁽³⁾ report on other detection system implementations in work areas in metal and nonmetal mines.

It appears, however, that the Bureau's Pittsburgh office takes a longer range view of the problem. Highly sophisticated detection concepts appear to be the mission of the Bureau's Pittsburgh office, possibly requiring several years before being implemented in underground mines. Devices such as highly reliable, low-level CO gas detectors are considered for monitoring mine gases, submicron particulate detectors, and diesel discriminating submicron particulate detectors capable of discriminating background sources such as diesel-fueled internal combustion engines from potentially hazardous fire situations, tube bundle sampling procedures and advanced optical fire detector practices as discussed by Litton⁽⁴⁾.

The tube bundle concept developed in Great Britain⁽⁵⁾ appears to be gaining wide acceptance, particularly in Western Europe. This method employs a pneumatic gas sampling procedure which uses a large number of tubes to transport gas samples from several areas to a centrally located gas analysis system. This procedure has been reviewed by Fink and Adler⁽⁶⁾, and Hertzberg and Litton⁽⁷⁾ of the Bureau's Pittsburgh Research Center and found to be a feasible, competitive alternative to other methods of mine fire detection.

Considerable work has been conducted by van der Walt et al⁽⁸⁾ of South Africa in the development of CO₂ gas detection systems (Spanair) which are currently

in wide use in South African gold mines. In addition, ionization smoke detectors (Beacon Mark II) developed by van der Walt⁽⁹⁾ have recently been acquired for broad-scale evaluation by the Twin Cities Bureau office; some of these devices have been installed in mines and apparently have performed reliably over about a two-year period*.

Cooper et al⁽¹⁰⁾ and Chamberlain et al⁽¹¹⁾ report that in England CO instruments are used in the working areas, and CO sensors in conjunction with tube bundles are used in intake and upcast shafts.

The reliability of various types of detectors was evaluated in tests by Cooper et al⁽¹⁰⁾. Thermal devices were not considered due to anticipated slow response times. Optical devices were also excluded due to expected high maintenance factors. Finally, a preference for CO sensors was stated, since it was determined that the spontaneous type of fire could be more readily detected with this type of sensor.

In other test programs, Litton⁽¹²⁾ examined the spacing of thermal and CO sensors in full-scale fire tests. On this basis, Litton⁽¹³⁾ has proposed a standard for automatic fire detectors for underground coal mines. Zeidler⁽¹⁴⁾ also reports a few examples of the early detection of underground fires in German coal mines using a network of CO and CH₄ (methane) detectors. Finally, Miller⁽¹⁵⁾ of MSHA has evaluated the off-the-shelf use of low level CO monitors and found such devices to be sufficiently reliable to be widely accepted for mine environments.

2.1.2 Mine Ventilation Systems And Practices

Mine ventilation systems and practices are an important factor in providing life support to underground miners**. This factor also has a very important impact upon the transport of fire signatures and their concentrations and, consequently, upon the location of an appropriate detector. Greuer⁽¹⁶⁾ under Bureau sponsorship has treated this problem in great detail. This work contains, in addition to a computer model of ventilation systems, a comprehensive evaluation of ventilation systems and practices based on an extensive search of the open

* Personal communication, W. Pomroy, Twin Cities Bureau of Mines Office, with J.L. Buckley, FMRC (2/19/82).

** The general criteria for coal mine ventilation is contained in Title 30 of the Code of Federal Regulations, Chapter 1, Subpart D.

literature. His work cites 147 references, many of them foreign, and thus provides a ready summary of both domestic and foreign systems and procedures. Greuer* has received additional funding from the Bureau to refine his computer programs, developed under Reference 16, into real time simulations of fire situations in mines. His objectives are the evaluation of the exposure to gaseous products on a moving miner and estimation of the hazards and escape potentials. This work is apparently the most advanced effort to date (including the international community) on the simulation of the interaction of mining ventilation with potential fire hazards.

In other related efforts, the work of Casadamont⁽¹⁷⁾ in France considers a method for detecting coal mine fires by their effects on a computer-controlled ventilation system. Hansman and Mayne⁽¹⁸⁾ in Belgium describe a method of flowcharting mine ventilation networks in order to minimize risks and delays when an underground fire has been detected.

Quantitative empirical data reported in the literature on the actual interaction of a mine fire with the ventilation flow are only available from three sources: 1) the Bureau's work using model ducts to simulate coal and wood fires^(19,20); 2) the previously cited work by Litton⁽¹²⁾ of the Bureau; and 3) the Bureau's sponsored work by FMRC on full-scale fire tests using a mine gallery⁽²¹⁻³¹⁾. (FMRC's existing experimental data will be discussed in Section 2.2.)

2.1.3 Physical Mine Environmental Parameters or Environmental Test Criteria

Work efforts by FMRC⁽³²⁾ sponsored by the Bureau of Mines, have previously identified environmental test methods and associated test criteria from existing standards and modified these methods to specifically address mine conditions. These environmental test methods include:

- 1) lifetime (operation and shelf);
- 2) stability and reliability;
- 3) interference (secondary gas species and electromagnetic);
- 4) temperature (low and high);
- 5) pressure;
- 6) temperature shock;

* Personal communication with J.L. Buckley, FMRC (2/22/82)

- 7) pressure shock;
- 8) humidity;
- 9) dust and velocity;
- 10) shock; and
- 11) vibration.

In addition, other test procedures, not specifically related to environmental conditions, consider the device design, workmanship, human engineering factors, and support (device manual repair and maintenance procedures, manufacturer's quality assurance practices and procedures, etc.). Finally, the physical mine environmental conditions are being surveyed and quantified under Bureau sponsorship by Dayton T. Brown, Inc.⁽³³⁾. The quantified mine conditions can be used as a basis for selecting the test environment for the listed environmental test methods, which in turn can be used to assess the effects of the pre-ignition mine environment on fire detector performance and reliability.

2.2 EXISTING EXPERIMENTAL DATA

The review of pertinent literature was closely coupled with the gathering and analysis of a significant body of FMRC's existing experimental data. These data are associated with work in the following areas: 1) the distribution of combustion products from a fire; 2) the fundamental combustion characteristics of materials; and 3) fire detector response characteristics.

2.2.1 Distribution of Combustion Products

The previous work performed at FMRC includes research on the distribution of products from flaming and smoldering fires, in large rooms with flat ceilings or beams, in corridors and in enclosures with forced ventilation and without ventilation⁽³⁴⁻³⁸⁾. However, the major body of relevant data was obtained from the Mine Gallery Program⁽²⁴⁻³⁰⁾, which investigated the relationships between ventilation, source fire intensity and fuel loading (as related to timber sets) in a simulated full-scale mine passageway. It was concluded from an analysis of this previous work that, although major insights into the post-ignition environment for mine passageways could be obtained⁽³¹⁾, insufficient data were available to fully assess the time-dependent stratification of combustion products in passageways. These limitations are discussed in detail in Section 3.4.2. Therefore, with these data gaps identified, a fire test program was designed and conducted to

obtain the necessary additional data. This test program is described in Section III.

2.2.2 Combustion Characteristics of Materials

A number of research efforts⁽³⁹⁻⁴²⁾ have resulted in the characterization of the combustion properties for a variety of materials which could be present within an underground mine. The following characteristics are considered important in the assessment of the influence of any specific material on the post-ignition environment in a mine: 1) the actual heat of combustion of the material, H_A (defined as the net heat of combustion times the efficiency of combustion); 2) the actual heat release rate, \dot{Q}_A ; 3) the fractional yield of the combustion product species i , Y_i (defined as the mass ratio of species i to the total mass of all combustion products); and 4) the generation rate of species i , \dot{G}_i . These properties, together with the corresponding values for various materials, are given as they interact with the developments detailed in Section III.

2.2.3 Fire Detector Response Characteristics

The response characteristics of fire detectors may be initially described by the detector type. Generally, fire detectors may be classified as either: 1) product(s) of combustion type, which includes ionization detectors, photoelectric detectors and gas detectors; or 2) heat detectors, which include the fixed temperature type and the rate-of-rise type. For each detector type, the response characteristics of the detector may be measured by a combination of the following factors:

- 1) response (alarm) time;
- 2) temperature, rate of temperature rise, velocity, obscuration, gas concentration, etc. of local environment; and
- 3) repeatability (precision), reliability, etc.

Previous work⁽³⁴⁻³⁶⁾, for example, has suggested that one important parameter for the evaluation of detector response (and corresponding spacing of detectors) is the ratio of the concentration or the optical density per unit path length (related to obscuration) to the gas temperature rise above ambient. This concept is considered in the developments given in Section III. Finally, the preignition mine environment, which may be described by the ambient temperature, velocity, relative humidity, pressure, dust levels, interference levels (gas species and

electromagnetic), etc., must be considered in the fire detector response to the post-ignition fire environment. This is essential for the assessment of response characteristics, particularly in the evaluation of detector reliability and suitability for a particular mine environment application. These factors are incorporated in the outline of a preliminary acceptance plan for fire detectors described in Section 4.4.

III

TEST PROGRAM

As an integral part of Phase I, a fire test program was designed and conducted to obtain information to fill in the data gaps identified in Section 2.2.1. Additional data were necessary to fully determine the post-ignition fire environment in a mine passageway, particularly in the area of the time dependent stratification of combustion products. In addition, this information was particularly useful in treating the subject of detector equivalency. This is discussed in detail in Section 4.2.

3.1 TEST FACILITY

Figure 1 is a sketch of the large-scale mine gallery used in the tests. The gallery is a T-shaped structure with two passageways (drifts), each about 47 m long and about 2.4 x 2.4 m in cross-sectional area. The north and east drifts are horizontal, and the west drift has a slope of about 13 degrees. The ventilation air entered the gallery through an inlet orifice contained in a flow straightening section attached to the north portal and was exhausted out the east portal through a combustion product duct connected to the main air pollution control system. For all tests the fire source was placed at the location indicated by N-3 in the figure, and instrumentation stations were located at N-5, N-11, N-19, E-1, and in the combustion product duct near the orifice plate.

3.2 TYPES OF MEASUREMENTS

In the fire tests, 53 measurements were made at 3-s intervals. These measurements included: gas temperatures, gas velocities, gas concentrations (oxygen, carbon dioxide and carbon monoxide), optical densities and the mass flow rate of combustion products through the gallery.

3.3 TEST VARIABLES

The following variables were investigated in the tests: 1) fire source (both heat release rate and fuel type); and 2) ventilation air velocity. A summary of the conditions for the 19 fire tests conducted for Phase I is given in Table 1. The heat release rates from the various fire sources ranged between

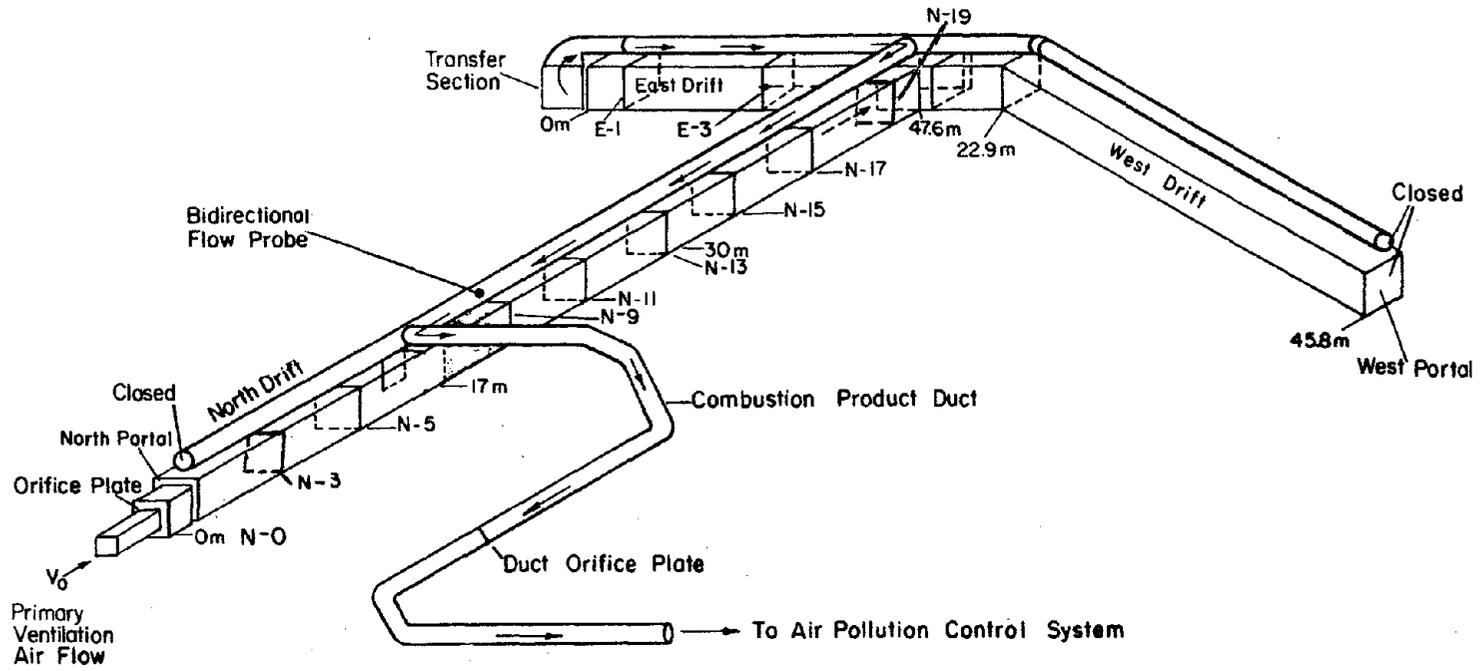


FIGURE 1. - Schematic of the simulated mine gallery

TABLE 1
SUMMARY OF FIRE TEST CONDITIONS

Test No. (Date)	Ambient Velocity (m/s)	Fuel	Quantity of Fuel (m ³)	Fuel Configuration (Dimensions)
FD001 (10/27/81)	0.5	Heptane	0.010	Square Pan (0.31 m x 0.31 m)
FD002 (10/28/81)	1.0	Heptane	0.010	Square Pan (0.31 m x 0.31 m)
FD003 (10/28/81)	2.0	Heptane	0.010	Square Pan (0.31 m x 0.31 m)
FD004 (10/28/81)	2.0	Heptane	0.040	Square Pan (0.61 m x 0.61 m)
FD005 (10/29/81)	1.0	Heptane	0.040	Square Pan (0.61 m x 0.61 m)
FD006 (10/30/81)	2.0	Heptane	0.150	Square Pan (1.2 m x 1.2 m)
FD007 (11/05/81)	3.0	Heptane	0.150	Square Pan (1.2 m x 1.2 m)
FD008 (11/06/81)	4.0	Heptane	0.150	Square Pan (1.2 m x 1.2 m)
FD009 (11/10/81)	3.0	Heptane	0.010	Square Pan (0.31 m x 0.31 m)
FD010 (11/10/81)	4.0	Heptane	0.010	Square Pan (0.31 m x 0.31 m)
FD011 (11/10/81)	3.0	Heptane	0.040	Square Pan (0.61 m x 0.61 m)
FD012 (11/10/81)	4.0	Heptane	0.040	Square Pan (0.61 m x 0.61 m)
FD013 (12/17/81)	0.5	Coal	0.035	Square Pile (0.61 m x 0.61 m)
FD014 (12/17/81)	0.5	Coal	0.035	Square Pile (0.61 m x 0.61 m)
FD015 (12/18/81)	2.0	Coal	0.035	Square Pile (0.61 m x 0.61 m)
FD016 (12/18/81)	0.5	Coal	0.035	Square Pile (0.61 m x 0.61 m)
		Neoprene Belting		
FD017 (12/21/81)	2.0	Coal	0.035	Square Pile (0.61 m x 0.61 m)
		Neoprene Belting		
FD018 (12/21/81)	0.5	Methanol	0.020	Square Pan (0.31 m x 0.31 m)
		Neoprene Belting		
FD019 (12/22/81)	2.0	Methanol	0.020	Square Pan (0.31 m x 0.31 m)
		Neoprene Belting		

10 kW and 20 MW. The ventilation air velocity was varied between 0.5 and 4.0 m/s. The heat release rates and velocities were selected to give a wider range in the ratio of the heat release rate to the mass flow rate than previous data. This ratio defined as the "heat flow parameter," is evaluated in Section 3.4.2.

A total of 12 heptane pan fires were used to quantify the post-ignition flow environments in the passageway. In addition, the following fire sources were studied: 1) 0.61 m x 0.61 m x 8-10 cm high square piles of "run of the mine" Bruceton coal, ignited with 1ℓ of kerosene sprinkled over the top; 2) coal configuration (as described in 1)) with neoprene conveyor belting (0.07-m wide x 1.52-m long x 1.27-cm thick); and 3) 0.31 m x 0.31 m methanol pan fires with neoprene conveyor belting.

3.4 TEST RESULTS

Significant test results from this program were obtained for four major parameters: 1) the source fire heat release rate; 2) the average gas temperature rise downstream of the source fire; 3) gas temperature stratification; and 4) the distribution of combustion products. The following sections discuss the quantification and/or evaluation of these parameters from the test results. In addition, it is important to note that the presented results are for flaming combustion where there is a measurable heat release rate from the source fire. For nonflaming combustion (e.g., smoldering) or pyrolysis, neither the average gas temperature rise nor the gas temperature stratification is of importance.

3.4.1 Quantification Of Source Fire Heat Release Rate

Typically, the source fire heat release rate, \dot{Q}_A can be expected to vary with time. In general, a wide range of growing fires can be treated as "power-law fires." By definition, the heat release rate of a power-law fire varies as some power of time from ignition:

$$\dot{Q}_A = \alpha t^p \quad (1)$$

where α and p are positive numbers. The coefficient α determines the fire intensity for a given power-law behavior. The heat release data for all the fire tests conducted were found to agree well with a power law fit using a value of

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$p = 1/3$. Table 2 gives the values of α for the heptane pan fire tests with $p = 1/3$. These values range from 38.9 to 2260 kW/s^{1/3} for the heptane fires investigated. By contrast, the values of α for the coal and neoprene belting fires for the conditions studied were of the order of 0.1 kW/s^{1/3}. The coal and belting tests were both slow growing and low heat release rate fires such that they were more difficult to quantify using the full-scale mine gallery. However, the temperature effects from these fires could be accurately determined and are given with the heptane results in Section 3.4.2.

3.4.2 Determination Of Average Gas Temperature Rise

Existing Data

In Figure 2 the gas temperature rise relative to ambient is plotted as a function of a heat flow parameter ($\dot{Q}_A / \rho_o c_o T_o v_o A_f$) for the full-scale timber fire tests conducted at USBM/FMRC mine gallery facility. This heat flow parameter is essentially the ratio of the source fire heat release rate (\dot{Q}_A) to the volumetric flow rate through the passageway ($v_o A_f$). The line representing the data in Figure 2 is given by the following expression:

$$\frac{\Delta T_{avg}}{T_o} = 0.525 \left(\frac{\dot{Q}_A / \rho_o c_o T_o}{v_o A_f} \right)^{0.75} \quad (2)$$

The good correlation (correlation coefficient, $r^2 = 0.943$) between eq (2) and the data from a range of test conditions (i.e., ventilation rates, materials and source fire intensities) suggests that at least the gross interaction of the major parameters affecting the average gas temperature rise has been determined. The following limitations of eq (2), however, should be noted: 1) the equation was developed under pseudo-steady state conditions and thus may not accurately reflect any time dependencies of either ΔT_{avg} or \dot{Q}_A ; 2) the equation was determined for a particular distance downstream of the source fire ($\lambda = 19.5$ m) and may not account for heat losses at other locations, i.e., the power in eq (2) of 0.75 may change with horizontal location; 3) since the equation was developed from data for primarily large fires (>3MW), the accuracy associated with any extensions to much smaller fires for detection purposes (<100kW) and correspondingly smaller values of the heat flow parameter (<0.1) is unknown; and 4) the effects of temperature stratification cannot be assessed from this data.

TABLE 2
VALUES OF α FOR THE HEPTANE PAN FIRE TESTS

Test No.	v_o (m/s)	Pan Area (m ²)	α (kW/s ^{1/3})
1	0.5	0.093	46.2
2	1.0	0.093	43.6
3	2.0	0.093	59.3
9	3.0	0.093	52.4
10	4.0	0.093	38.9
5	1.0	0.372	234
4	2.0	0.372	255
11	3.0	0.372	338
12	4.0	0.372	187
6	2.0	1.49	1710
7	3.0	1.49	2260
8	4.0	1.49	1090

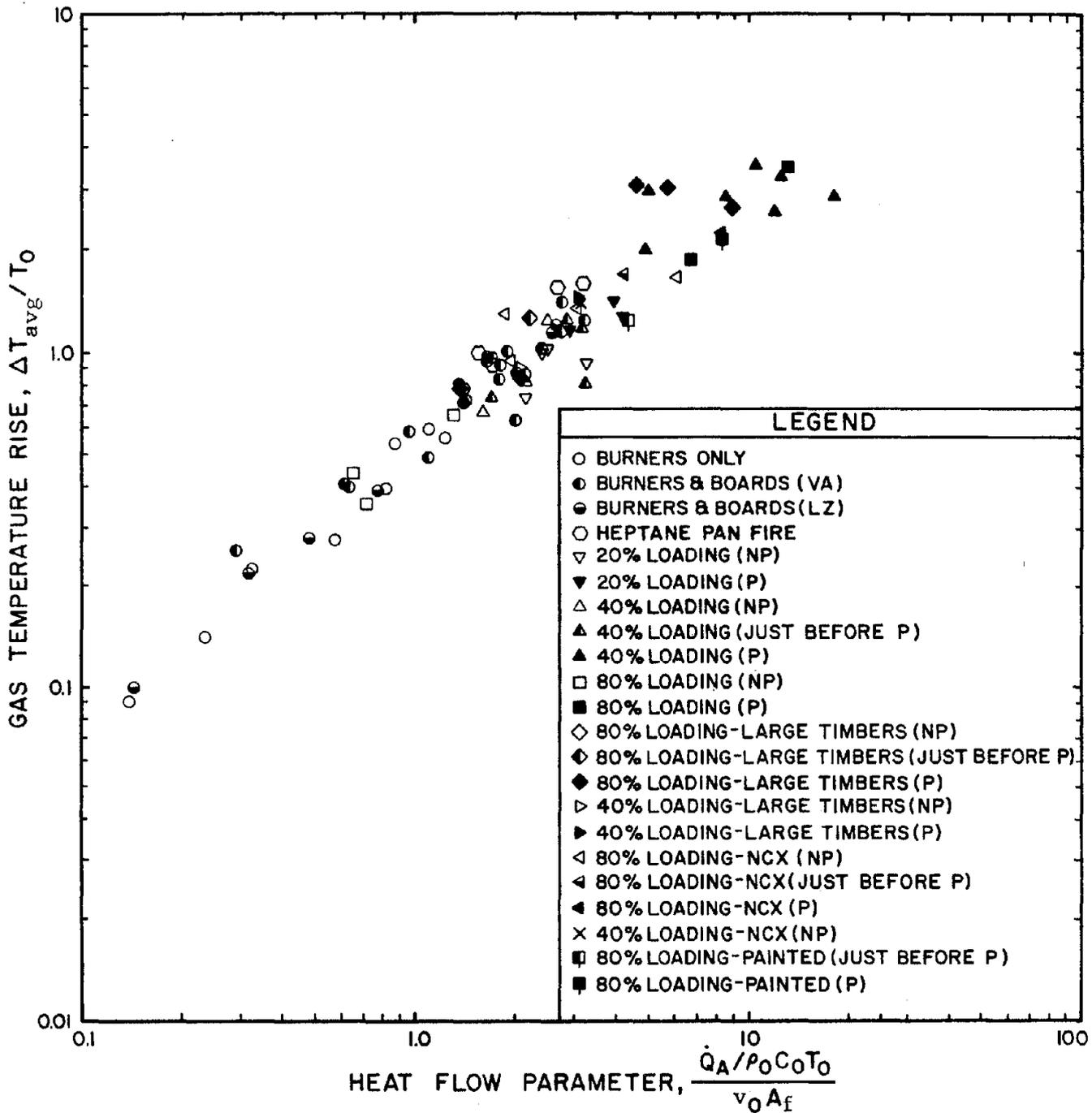


FIGURE 2. - Gas temperature rise at USBM/FMRC mine gallery facility at $\lambda = 19.5\text{m}$ vs. heat flow parameter from Reference 31; abbreviations - VA = vertical array, LZ = lagged zone, NP = nonpropagating, P = propagating and NCX refers to specific fire retardant treatment

New Test Data

In order to assess the limitations of the data presented in the previous section, a heat balance coupled with data from the current test program was developed for a fire in a mine passageway. Only the major aspects of this development are given here while the entire development is detailed in the Appendix. The heat flow rate out of a fire within a mine passageway consists of two major components: 1) one associated with the convection of heat down the passageway and 2) one associated with heat losses to the walls, ceiling and floor of the passageway. In addition the heat losses consist of two dominant components: 1) the heat loss rate to the walls from convection and 2) the radiative heat loss rate to the walls. An expression for the average gas temperature rise can be developed from generalized correlations for convective heat losses and assuming that: 1) the wall temperature is equal to the ambient temperature and 2) the radiation view factor and the wall surface emissivity are both equal to 1.0. The result from this development is the following equation (eq (A-7) Appendix):

$$\Delta T_{\text{avg}} = \frac{1}{(1+k_{\ell})} \frac{1}{\rho_o c_o v_o A_f} [\dot{Q}_A - A_w \sigma (T_{\text{avg}}^4 - T_o^4)] \quad (3)$$

where ΔT_{avg} is the average gas temperature rise downstream of the source fire at time t ; k_{ℓ} is the convective loss coefficient at distance ℓ downstream defined in the Appendix (eq (A-7b)); \dot{Q}_A is the source fire heat release rate at time $(t-\ell/v_o)$; $v_o A_f$ is the volumetric flow rate through the passageway; A_w is the area of the passageway walls, ceiling and floor; ρ_o, c_o, T_o are the ambient gas density, specific heat and temperature, respectively; and σ is the Stefan-Boltzmann constant.

The similarity between eq (3) and eq (2) given in the previous section should be noted. The primary distinction between these two expressions is that eq (3) avoids two of the limitations of eq (2) by: 1) accounting for the specific heat loss rates as a function of distance, ℓ , downstream of the source fire and the average temperature in the passageway at distance ℓ ; and 2) making no assumptions relating to steady-state conditions, i.e., eq (3) is time dependent.

Figure 3 plots the average gas temperature rise (ΔT_{avg}) as calculated by eq (3) versus the measured gas temperature rise for all the heptane pan fire tests. Calculated versus measured quantities are presented for values of ΔT_{avg} between 1 and approximately 500K. The data are for a wide range of the parameters given

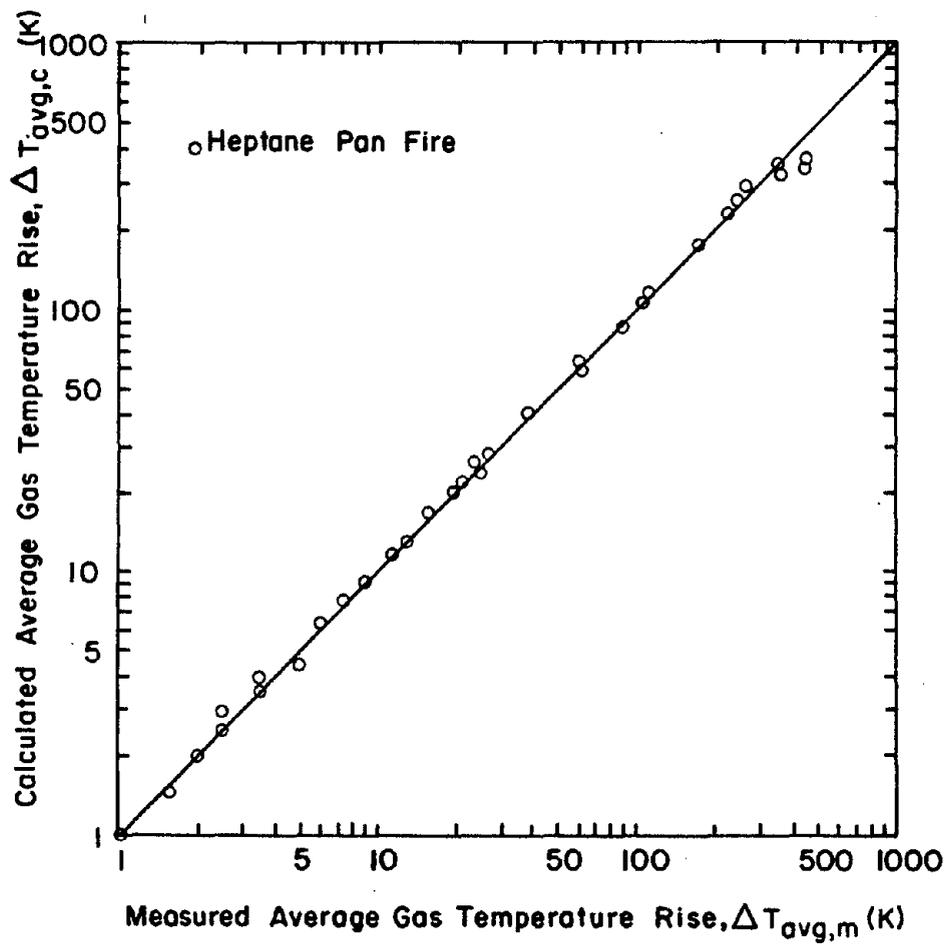


FIGURE 3. - Calculated vs. measured average gas temperature rise

directly or implied by eq (3). These parameters include v_o , ℓ , and \dot{Q}_A as a function of time. The excellent agreement between the calculated and measured average gas temperature rise as illustrated by the line in Figure 3, indicates that eq (3) can be used to accurately predict the average gas temperature rise in a mine passageway. Finally, it should also be noted that Figure 3 incorporates data for much smaller gas temperature rises than was previously available as indicated by Figure 2.

3.4.3 Determination Of Gas Temperature Stratification

One of the major limitations noted in Section 3.4.2 for existing gas temperature data was the incomplete quantification of stratification effects on the gas temperature rise (and corresponding combustion product concentrations) downstream of the source fire; i.e., the gas temperature variation in the passageway vertically from ceiling to floor. Existing data were sufficient to indicate that temperature variations from the centerline to the side walls for each vertical location were not significant at distances ≥ 0.3 m from the wall. However, the new data from the current test program were essential for evaluating the effects of \dot{Q}_A , v_o and ℓ on the vertical gas temperature (and product concentrations) stratification.

Figure 4 presents the relationship between the average gas temperature rise (ΔT_{avg}), the excess gas temperature rise (ΔT_{xs}) and the gas temperature rise near the ceiling (ΔT_h) for all the heptane pan fire tests. The excess temperature rise is a representation of the vertical temperature stratification at any point downstream of the source fire; it is the difference between the gas temperature near the ceiling (at height, $h = 0.88H$ where $H =$ the height of the passageway) and the gas temperature near the floor (at height $H-h = 0.12H$). $\Delta T_h = (T_h - T_o)$, the gas temperature rise above ambient at height h , and ΔT_{avg} is the average gas temperature rise as previously defined. The data in Figure 4 can be excellently correlated ($r^2 = 0.99$) through the following equation

$$\frac{\Delta T_{xs}}{\Delta T_h} = 0.67 \left(\frac{\Delta T_{xs}}{\Delta T_{avg}} \right)^{0.77} \quad (4)$$

for values of $\frac{\Delta T_{xs}}{\Delta T_{avg}} \leq 1.7$.

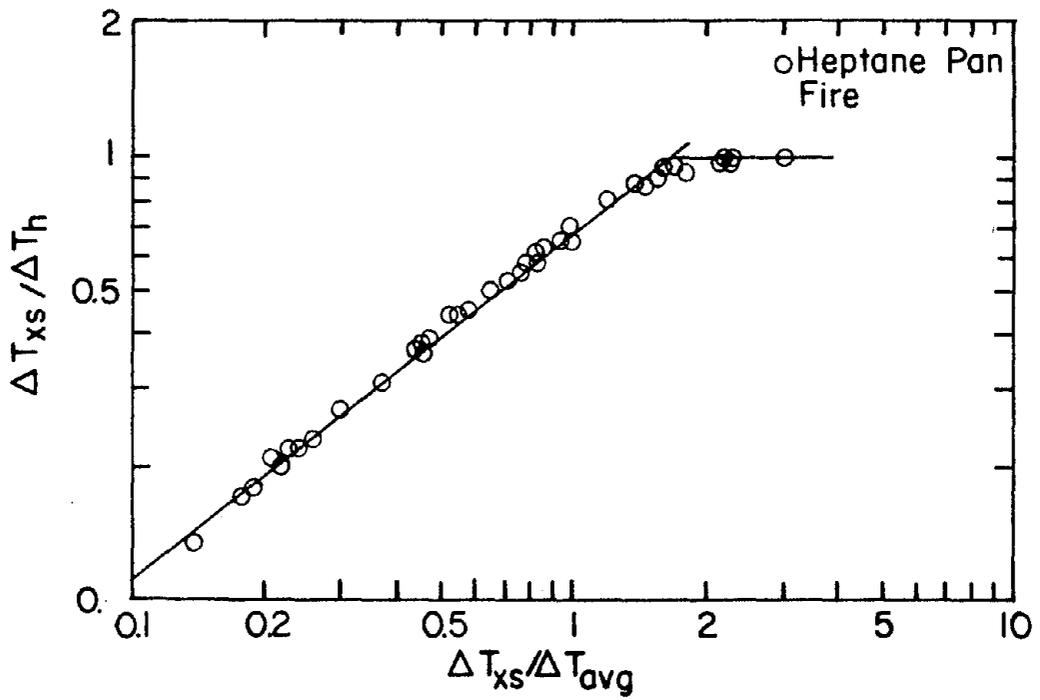


FIGURE 4. - Gas temperature stratification

For values of $\frac{\Delta T_{xs}}{\Delta T_{avg}} > 1.7$, $\frac{\Delta T_{xs}}{\Delta T_h} = 1.0$; i.e., the gas near the floor is essentially at ambient conditions. In summary, the primary usefulness of eq (4) is in relating the gas temperature rise at the ceiling (ΔT_h) where a detector might be located to the temperature stratification (ΔT_{xs}) and the gas bulk average temperature (ΔT_{avg}). Equation (4) can be used to predict ΔT_h , once ΔT_{xs} is quantified in addition to ΔT_{avg} .

In order to quantify the temperature stratification (i.e., ΔT_{xs}), a Froude number (Fr) may be used. Essentially, the Froude number is the ratio of the flow velocity (v) and the buoyancy velocity associated with the temperature stratification:

$$Fr = \frac{v_{ref}}{\left[\frac{\Delta T}{T_{ref}} g H \right]^{1/2}} \quad (5)$$

where ΔT is the temperature difference associated with the stratification; T_{ref} is the reference temperature; g is the acceleration of gravity; and H is the characteristic dimension, i.e., the height of the passageway. A very good fit to all the fire test data was found using a Froude number based upon the average velocity across the passageway (v_{avg}), the excess temperature (ΔT_{xs}) and the average gas temperature (T_{avg}) as the reference temperature. Figure 5 plots $\Delta T_{xs}/\Delta T_{avg}$ versus this Froude number for the heptane, kerosene/coal, coal, coal/belting and methanol/belting fire tests. (The specific conditions and intermediate data for each of the plotted points in the figure are given in Table 3.) The curve representing the data in the figure is given by the following equation:

$$\frac{\Delta T_{xs}}{\Delta T_{avg}} = 1.5 \left\{ \frac{v_{avg}}{\left[\frac{\Delta T_{xs}}{T_{avg}} g H \right]^{1/2}} \right\}^{-1} \quad (6)$$

where $v_{avg} = \left(\frac{T_{avg}}{T_o} \right) v_o$

Equation (6) fits the data well ($r^2 = 0.90$) and when combined with eq (4) allows the prediction of the gas temperature rise near the ceiling of a mine passageway (ΔT_h) downstream of a fire source as a function of the average gas temperature

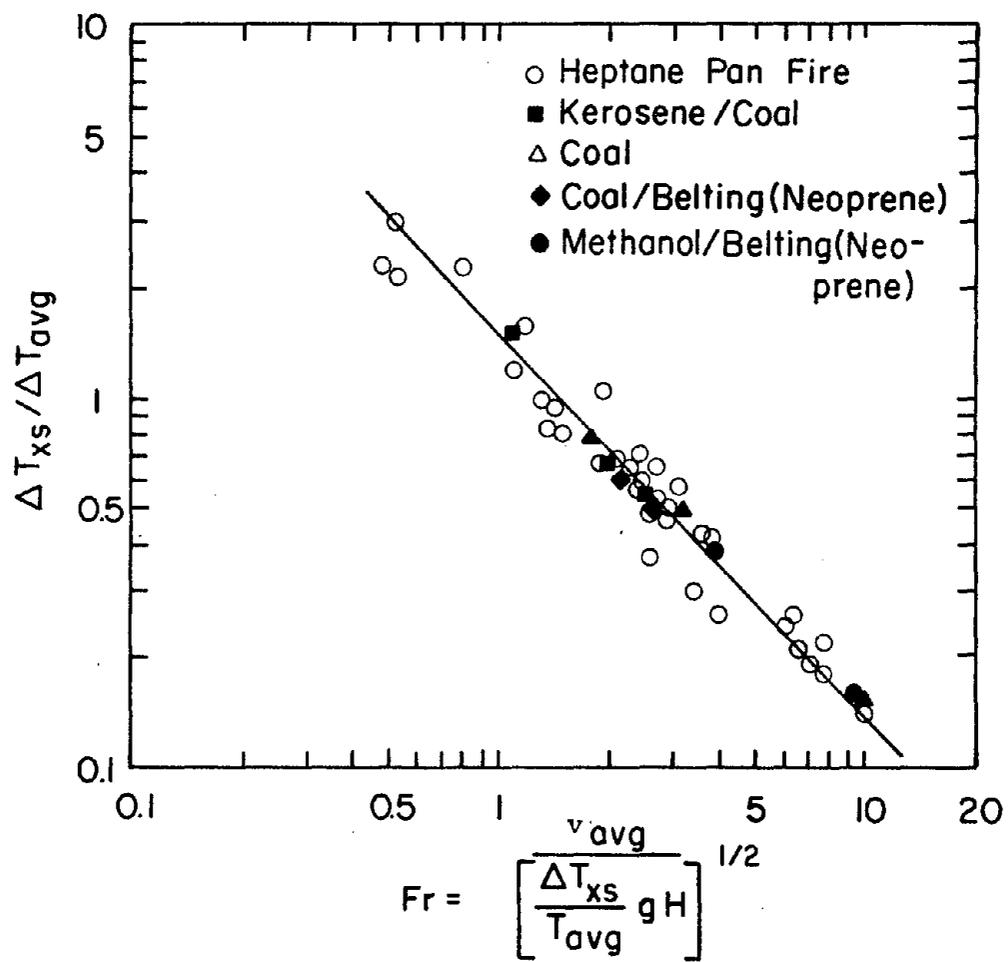


FIGURE 5. - Gas temperature stratification vs. Froude number

TABLE 3
DATA FOR FROUDE NUMBER COMPUTATION

Fr	$\Delta T_{xs} / \Delta T_{avg}$	Test No.	Fuel	ℓ/H	T_o (K)	v_o (m/s)	v_{avg} (m/s)	ΔT_h (K)	ΔT_{xs} (K)	ΔT_{avg} (K)
0.48	2.33	1	Heptane	8	287	0.61	0.63	21	21	9.0
0.52	2.15	5	Heptane	12	283	1.1	1.2	73	71	33
0.53	3.0	1	Heptane	16	287	0.58	0.59	15	15	5.0
0.79	2.29	6	Heptane	12	282	2.1	2.6	163	160	70
1.12	1.20	2	Heptane	8	286	1.1	1.1	15	12	10
1.14	1.5	14	Kerosene/Coal	2	274	0.64	0.65	4.0	3.75	2.5
1.25	1.58	2	Heptane	12	286	1.1	1.1	10.5	9.5	6
1.32	0.99	4	Heptane	12	288	2.2	2.7	86.5	61.5	62
1.35	0.82	6	Heptane	12	282	2.3	3.8	253	154	186
1.42	0.94	4	Heptane	16	288	2.1	2.4	60.5	39.5	42
1.50	0.80	4	Heptane	8	288	2.4	3.3	136	80	100
1.8	0.80	13	Coal	16	274	0.53	0.53	0.75	1.0	1.25
1.83	0.67	6	Heptane	12	282	2.6	5.1	378	185	276
1.97	1.08	12	Heptane	12	278	3.6	4.4	104	71.5	66.5
1.97	0.71	14	Kerosene/Coal	12	274	0.65	0.65	2.5	1.25	1.75
2.15	0.60	16	Coal/Belting	12	274	0.55	0.55	1.75	0.75	1.25
2.22	0.68	3	Heptane	2	290	2.0	2.1	22	11.5	17
2.37	0.71	3	Heptane	12	290	2.0	2.1	19	10	14
2.37	0.65	3	Heptane	8	290	2.0	2.1	20	10	15.5
2.48	0.58	11	Heptane	16	281	3.3	4.1	90.5	41	71
2.51	0.60	14	Kerosene/Coal	16	274	0.64	0.64	1.75	0.75	1.25
2.56	0.71	3	Heptane	16	290	2.0	2.1	16	8.5	12
2.61	0.37	6	Heptane	12	282	2.7	5.6	351	114	305
2.61	0.48	11	Heptane	12	281	3.3	4.4	112	43.5	91
2.64	0.50	16	Coal/Belting	16	274	0.55	0.55	1.25	0.50	1.0
2.69	0.53	11	Heptane	22	281	3.3	4.0	75	31.5	60
2.80	0.65	12	Heptane	16	278	3.8	4.6	76	38	58.5
2.83	0.47	3	Heptane	12	290	2.0	2.1	18	7.0	15
2.92	0.65	3	Heptane	22	290	2.0	2.1	13	6.5	10
2.94	0.52	8	Heptane	16	289	3.6	7.4	370	156	302
3.12	0.50	14	Coal	8	274	0.65	0.65	1.25	0.5	1.0
3.15	0.57	8	Heptane	12	289	4.3	7.7	305	131	231
3.40	0.30	6	Heptane	12	282	2.8	7.1	486	132	436
3.63	0.43	7	Heptane	22	290	4.2	8.0	309	112	262
3.81	0.42	7	Heptane	16	290	3.8	8.2	337	121	286
3.9	0.40	19	Methanol/Belting	12	274	2.0	2.0	10	3.0	7.5
4.0	0.26	6	Heptane	12	282	3.0	7.9	515	124	470
6.12	0.24	7	Heptane	12	290	4.4	11	470	102	434
6.40	0.26	9	Heptane	8	276	3.1	3.2	13	3.0	11.5
6.63	0.21	9	Heptane	16	276	3.1	3.3	15	3.0	14
7.14	0.19	9	Heptane	12	276	3.1	3.2	14	2.5	13
7.81	0.22	9	Heptane	22	276	3.1	3.2	10	2.0	9.0
7.81	0.18	7	Heptane	8	290	4.1	12	595	101	559
9.6	0.17	19	Methanol/Belting	16	274	2.0	2.0	3.0	0.5	3.0
10	0.14	7	Heptane	8	290	4.9	15	623	82	602
10	0.14	10	Heptane	12	278	3.9	4.1	14	2.0	14
10	0.15	15	Coal	16	272	2.1	2.1	3.5	0.5	3.25

downstream, the average velocity, the ambient temperature and the passageway

height. A closed form solution for $\frac{\Delta T_h}{\Delta T_{avg}}$ is possible for the region defined by $\frac{\Delta T_{xs}}{\Delta T_{avg}} \leq 1.7$ in eq (4).

3.4.4 Evaluation Of The Distribution Of Combustion Products

Up to this point, considerable emphasis has been placed on the determination of how the gas temperature is distributed downstream of a source fire. Although distribution of combustion products is of particular interest in detection, the temperature distribution is a far more difficult problem due to the loss of heat to the passageway surfaces (walls, ceiling and floor) while combustion products can be considered to be conserved. In addition, it has been shown both previously⁽³⁶⁾ and in this work that the concentration of any species i follows the local gas temperature rise. This means that once the temperature distribution is known, the distribution of any combustion product is also known.

The generation rate from flaming combustion of a species i (\dot{G}_i) for a given material can be expressed by the following equation:

$$\dot{G}_i = Y_i \frac{\dot{Q}_A}{H_A} \quad (7)$$

where Y_i is the fractional yield of species i (kg/kg); \dot{Q}_A is the actual heat release rate (kW); and H_A is the actual heat of combustion of the material (kJ/kg). Table 4 gives the fractional yields of carbon dioxide (Y_{CO_2}) carbon monoxide (Y_{CO}) and hydrocarbons (Y_{HC}) as well as the actual heats of combustion of a variety of materials that may be found in mines. To determine the concentration of a combustion product i ($G_{i,avg}$) in a mine passageway, eq (7) must be divided by the mass flow rate ($\rho_o v_o A_f$):

$$G_{i,avg} = \frac{\dot{G}_i}{\rho_o v_o A_f} = \frac{Y_i \dot{Q}_A}{\rho_o v_o A_f H_A} \quad (8)$$

For detection purposes, for example, $G_{i,h}$ (G_i at the ceiling) can now be determined by multiplying $G_{i,avg}$ from eq (8) with $\frac{\Delta T_h}{\Delta T_{avg}}$, a ratio which may be determined from eqs (3), (4) and (6). In other words, $G_{i,h}$ is related to $G_{i,avg}$ through the following expression:

TABLE 4
COMBUSTION PROPERTIES FOR VARIOUS MATERIALS*

Material	H_A (kJ/kg)	Y_{CO_2} (kg/kg)	$Y_{CO} \times 10^2$ (kg/kg)	$Y_{HC} \times 10^3$ (kg/kg)
Rubber (neoprene)				
Untreated	12,000	0.99	3.7	4.7
Treated	10,000	0.60	4.0	10
Red Oak				
Untreated	13,000	1.2	0.23	0.02
Treated	6,500	0.66	<0.01	0.05
Douglas Fir				
Untreated	13,000	1.4	<0.01	0.24
Treated	7,500	0.66	<0.01	<0.01
Cellulose	12,000	1.2	0.48	0.15
Polyvinyl Chloride	6,000	0.46	5.7	28
Polyethylene	31,000	2.1	3.6	8.7
Polyurethane Foam (GM-25)	15,000	1.4	2.7	2.7
Heptane	38,000	2.6	5.2	18
Acetone	22,000	1.7	0.20	<0.01
Methanol	20,000	1.0	0.03	<0.01
Hydrocarbon Transformer Fluid	38,000	2.0	3.3	-

* Compiled from References 39-42

$$\frac{G_{i,h}}{G_{i,avg}} = \frac{\Delta T_h}{\Delta T_{avg}} \quad (9)$$

Combining eqs (8) and (9) and rearranging yields:

$$G_{i,h} = \frac{Y_i \dot{Q}_A}{\rho_o v_o A_f H_A} \left[\frac{\Delta T_h}{\Delta T_{avg}} \right] \quad (10)$$

It should be noted from eq (10) that $G_{i,h}$ approaches the average concentration of i ($G_{i,avg}$) as heat is lost from the gas and temperature stratification is reduced ($\Delta T_h / \Delta T_{avg} \rightarrow 1$). In summary, the distribution of any combustion product may be determined from knowledge of the corresponding temperature distribution and generation rate of product i .

IV

APPLICATION OF RESULTS

The intent of this section is to develop, from the results described in Section III, a format for a preliminary acceptance plan for the application of fire detectors in underground mines. This format development is approached from a consideration of the following aspects: 1) an assessment of the predictive capability for the interaction of the preignition mine flow field, post-ignition fire field and mine material properties (combustion characteristics); 2) a quantification of equivalency; and 3) a definition of essential detection criteria. The following sections address these aspects in conjunction with any limitations in their application.

4.1 ASSESSMENT OF PREDICTIVE CAPABILITY

The following discussion assesses predictive capability of the test results given in Section III for each of the previously identified parameters: 1) source fire heat release rate; 2) average gas temperature rise downstream of the source fire; 3) gas temperature stratification; and 4) combustion product distribution.

4.1.1 Source Fire

The results of the series of heptane fire tests indicate that the heat release rate may be correlated using a power-law relationship of the form of eq (1):

$$\dot{Q}_A = \alpha t^{1/3} \quad (11)$$

Examination of Table 2 shows that the values of α for the same pan area vary significantly with the ambient ventilation velocity, v_o . For example, for the 0.093 m² pan fires over the velocity range of 0.5 to 4.0 m/s, α varies from 38.9 to 59.3 kW/s^{1/3} with a mean of 48.1 ± 7.9 kW/s^{1/3}. In other words, for these conditions α varies ±17%. The variation in α with v_o for the heptane fires becomes larger with increasing fire size (i.e., pan area) with $\alpha = 254 \pm 63$ kW/s^{1/3} (±25%) for the 0.372 m² pan and $\alpha = 1690 \pm 590$ kW/s^{1/3} (±35%) for the 1.49 m² pan. However, in terms of predictive capability for these fires, the following should be noted: 1) for detection purposes, these are all "large" fires, i.e., relatively simple to detect; and 2) even an uncertainty of ±35% in the heat release

rate is still expected to be within the uncertainty of estimating the potential fire, i.e., determining the fire configuration and fuel contribution (in this case, the spill area and the quantity of fuel spilled).

For the coal and conveyor belt fire tests, as noted in Section 3.4.1, the growth rates were such that, for the conditions investigated, only an order of magnitude estimate can be made for the heat release rate, where the α determined for these tests was $0.1 \text{ kW/s}^{1/3}$. Thus, it is difficult to assess the degree to which the actual heat release rate from these fires can be predicted. Again, however, it is expected that the major uncertainty still lies in the determination of the actual fuel configuration, fuel type(s), and potential quantity of fuel that can be contributed to the fire. It is worthwhile noting here that Litton⁽¹²⁾ of the Bureau has apparently had some degree of success in correlating the growth rates for coal fires using the data of Miller⁽¹⁵⁾ and the following expression:

$$\dot{Q}_A = 7.0 \times 10^{-6} (v_o t)^2 \quad (12)$$

where \dot{Q}_A is the actual heat release rate in kW, v_o is the ventilation velocity in m/s, and t is the time in seconds from the initiation of flaming of the coal. As will be shown in later discussions, any expression such as given by eq (11) or eq (12) for the actual heat release rate can be used in the derived correlations for predicting gas temperatures or gas species concentrations. The following estimates of predictive capability assume that \dot{Q}_A is accurately known.

4.1.2 Average Gas Temperature Rise

The average gas temperature rise (ΔT_{avg}) downstream of the source fire can be predicted using eq (3) given in Section 3.4.2 with an estimated error of not more than $\pm 10\%$ (typically less than $\pm 5\%$) for values between ~ 1 and 500 K. Thus, the accuracy of predicting the average gas temperature rise depends largely on the accuracy of estimating the actual heat release rate.

4.1.3 Gas Temperature Stratification

The gas temperature rise (ΔT_h) near the ceiling of a mine passageway is given by eqs (4) and (6) in Section 3.4.3. "Near the ceiling" is defined for the purposes

of these correlations by the limits of the following expression:

$$0.970 \leq \frac{h}{H} \leq 0.875 \quad (13)$$

where h is the vertical location of the detector, and H is the height of the passageway. For example, for a 2.44 m (8 ft) high passageway, the detector can be located between 2.37 m and 2.14 m off the floor (i.e., between 3 and 12 in. from the ceiling). For detector locations outside the limits defined by eq (13), the correlations for gas temperature stratification do not strictly apply. Near the center of the passageway, the gas temperature rise is close to the average gas temperature rise predicted by eq (3), while locations closer to the ceiling than those given by eq (13) would have a gas temperature rise between that predicted by eqs (4) and (6) and the ceiling temperature rise. Therefore, it is estimated that the gas temperature rise (relative to the average gas temperature rise) within the limits imposed by eq (13) can be predicted to $\pm 15\%$ (typically $\pm 10\%$).

4.1.4 Combustion Products Distribution

The prediction of concentration of any combustion product, i , near the ceiling in a mine passageway, as given by eq (10), is primarily dependent upon knowledge of the heat release rate, \dot{Q}_A , the ratio of the gas temperature rise near the ceiling to the average gas temperature rise, $\Delta T_h / \Delta T_{avg}$, and the fractional yield of combustion product i , Y_i . Therefore, the accuracy of the prediction of combustion product at a detector location is a function of the combined errors in estimating \dot{Q}_A , $\Delta T_h / \Delta T_{avg}$, and Y_i . The error in Y_i in Table 4 is given in Reference 42 as $\pm 5\%$. The error in $\Delta T_h / \Delta T_{avg}$ as previously mentioned is $\pm 15\%$. The errors in \dot{Q}_A , as before, are undetermined. Thus, it appears that the limiting error in the estimation of combustion products distribution is associated with the uncertainty in the prediction of gas temperature rise.

4.1.5 Summary

From the previous discussion, it appears that the interaction of: 1) the pre-ignition mine flow field (defined by ρ_o, c_o, v_o, T_o in eq (3) and the mine passageway geometry); 2) the post-ignition fire field (defined by ΔT_{avg} and \dot{Q}_A in eq (3), ΔT_{xs} and ΔT_h in eq (4) and v_{avg} in eq (6)); and 3) the mine material

combustion characteristics (given by H_A , $G_{i,h}$ and Y_i in eq (10)) can be estimated with an error of approximately $\pm 15\%$. This assumes that the heat release rate, \dot{Q}_A , is known with at least the same degree of certainty. Thus, with a knowledge of the mine materials properties, the potential source fire size and configuration, and the preignition mine environment, detection criteria based upon ΔT_h (or ΔT_{avg}) and $G_{i,h}$ (or $G_{i,avg}$) can now be determined. This will be addressed in Section 4.3.

4.2 QUANTIFICATION OF EQUIVALENCY

"Equivalent protection" or equivalency has been previously stated in general terms in the summary of Title 30 CFR 75.1103 in Section 2.1.1 of the literature review. However, in order to actually determine what the law physically means, it is useful to summarize the spacing requirements for automatic fire sensors using the following interpretations:

- 1) Spacing Specifications For Point-Type Thermal Sensors
 - a) For $v_o \leq 0.5$ m/s (100 ft/min) and fire resistant belting,
 $\ell = 38$ m (125 ft)
 - b) For $v_o > 0.5$ m/s or nonfire resistant belting,
 $\ell = 15$ m (50 ft)
- 2) Equivalency For Other Than Thermal Sensors

$$t_\ell + t_T \geq t_{\ell'} + t_p \quad (14)$$

where $t_\ell = \ell/v_o =$ transit time to thermal sensor with spacing ℓ ;
 $t_T =$ alarm time for a thermal sensor after t_ℓ has occurred;
 $t_{\ell'} = \ell'/v_o =$ transit time to combustion product sensor with spacing ℓ' ;
 $t_p =$ alarm time for a combustion product sensor after $t_{\ell'}$ has occurred.

In 2) equivalency has been defined relative to the sum of two times: $t_\ell + t_T$. As long as the sum of the transit time and alarm time of any other type of sensor is less than or equal to $t_\ell + t_T$ (with the specifications given in 1)), then that sensor provides equivalent protection. The following discussion and associated figures attempt to further quantify both what the spacing specifications in 1) imply and what is the corresponding equivalent protection as defined by eq (14). The relationships defined by eqs (3), (4), (6) and (10) have been used to generate the values plotted in the accompanying figures for mine passageways with square cross-sectional areas.

Figure 6 illustrates the relationship between the source fire size, \dot{Q}_A , and the passageway ceiling height, H , for the spacing specifications previously stated in 1a) for a point type thermal sensor with an activation temperature of 330 K (135°F) and no thermal inertia; i.e., $v_o = 0.5$ m/s (100 ft/min) and $\ell = 38$ m (125 ft). Three curves are presented to indicate the effect of the ambient temperature, T_o , which is not considered in the CFR spacing specifications. These curves represent the typical range in ambient temperature within underground mines (273-313 K). As expected, the lower the ambient temperature the larger is the source fire necessary to heat the ambient air to the specified thermal activation temperature, T_h , of 330 K. For example, with a 5-m ceiling height, the fire size could vary between 140 and 380 kW. This variation is further illustrated by Figure 7, which plots the same conditions as Figure 6 except that $\ell = 15$ m (50 ft), i.e., the borderline spacing specifications for 1b). Selecting the same 5-m ceiling height, \dot{Q}_A ranges from 120 to 320 kW, which is not significantly different from the variation previously found at $\ell = 38$ m. The primary difference between the two sets of values of \dot{Q}_A found in Figures 6 and 7 is that some additional heat has been lost to the walls, ceiling and floor between 15 and 38 m downstream of the fire source.

Another important parameter in addition to the ambient temperature, T_o , is the height of the passageway ceiling, H (also not considered in the CFR spacing specifications). For example, a variation in H from 2 to 5 m with $T_o = 293$ K gives values of \dot{Q}_A from 50-220 kW (Figure 7) or 70-270 kW (Figure 6). The significant effects of T_o and H on the required \dot{Q}_A to meet CFR spacing requirements, thus raise a serious question: exactly what size source fire should be used to determine the generation rate of combustion products necessary to determine equivalency? The answer in simplistic terms is that there is no single size source fire that can be used. So far, it has been demonstrated that T_o and H must be specified. In addition, Figure 8 illustrates that the ambient velocity, v_o , must be stated more specifically than either ≤ 0.5 m/s or > 0.5 m/s. In this figure, the source fire size is plotted versus v_o at constant H for the conditions of Figure 7 except that T_o has been fixed at 293 K. Referring to the curve for $H = 5$ m on the figure, for example, the range in \dot{Q}_A from $v_o = 0.5$ m/s to $v_o = 5$ m/s is 110 to 450 kW, respectively.

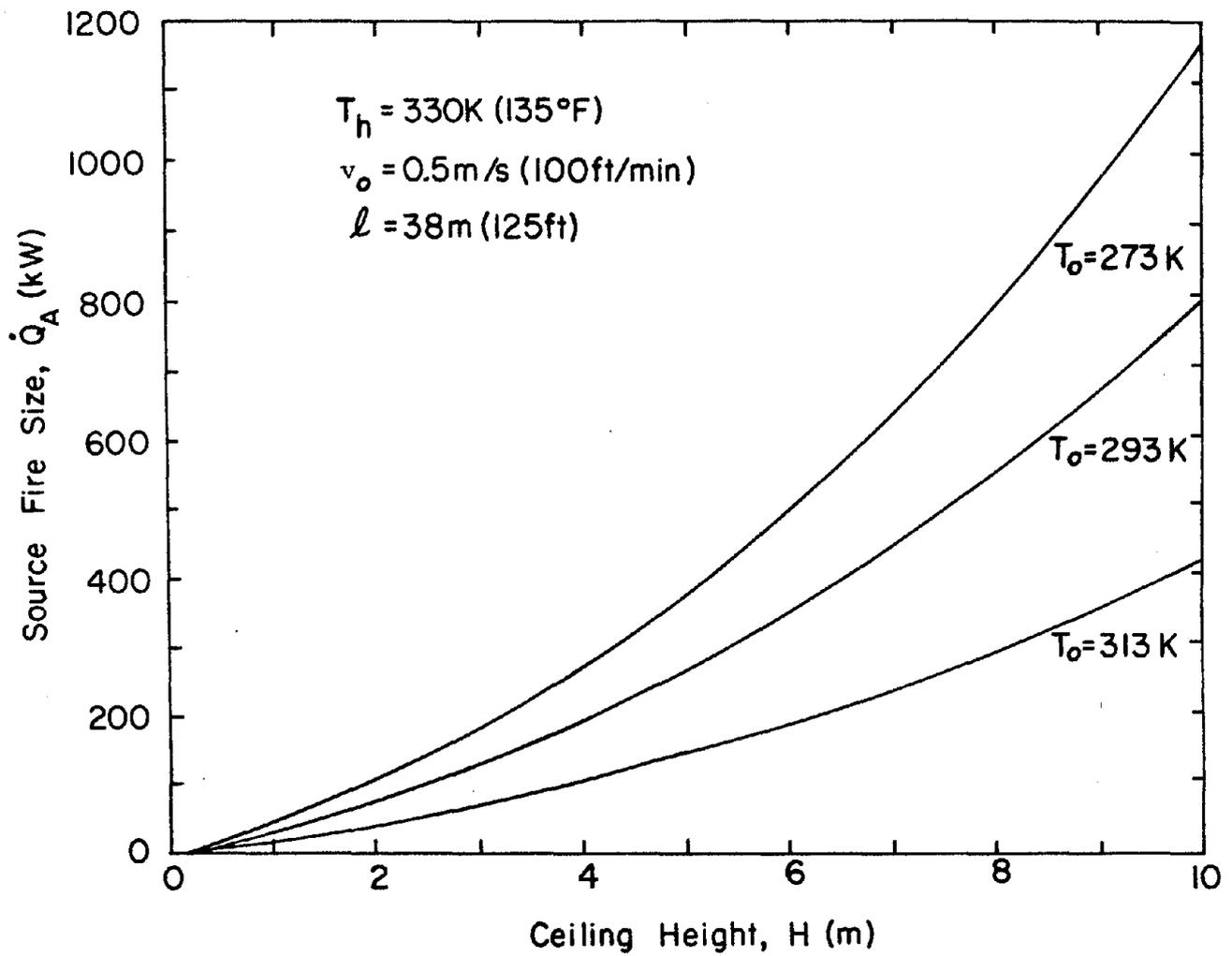


FIGURE 6. - Source fire size vs. ceiling height ($l = 38\text{m}$)

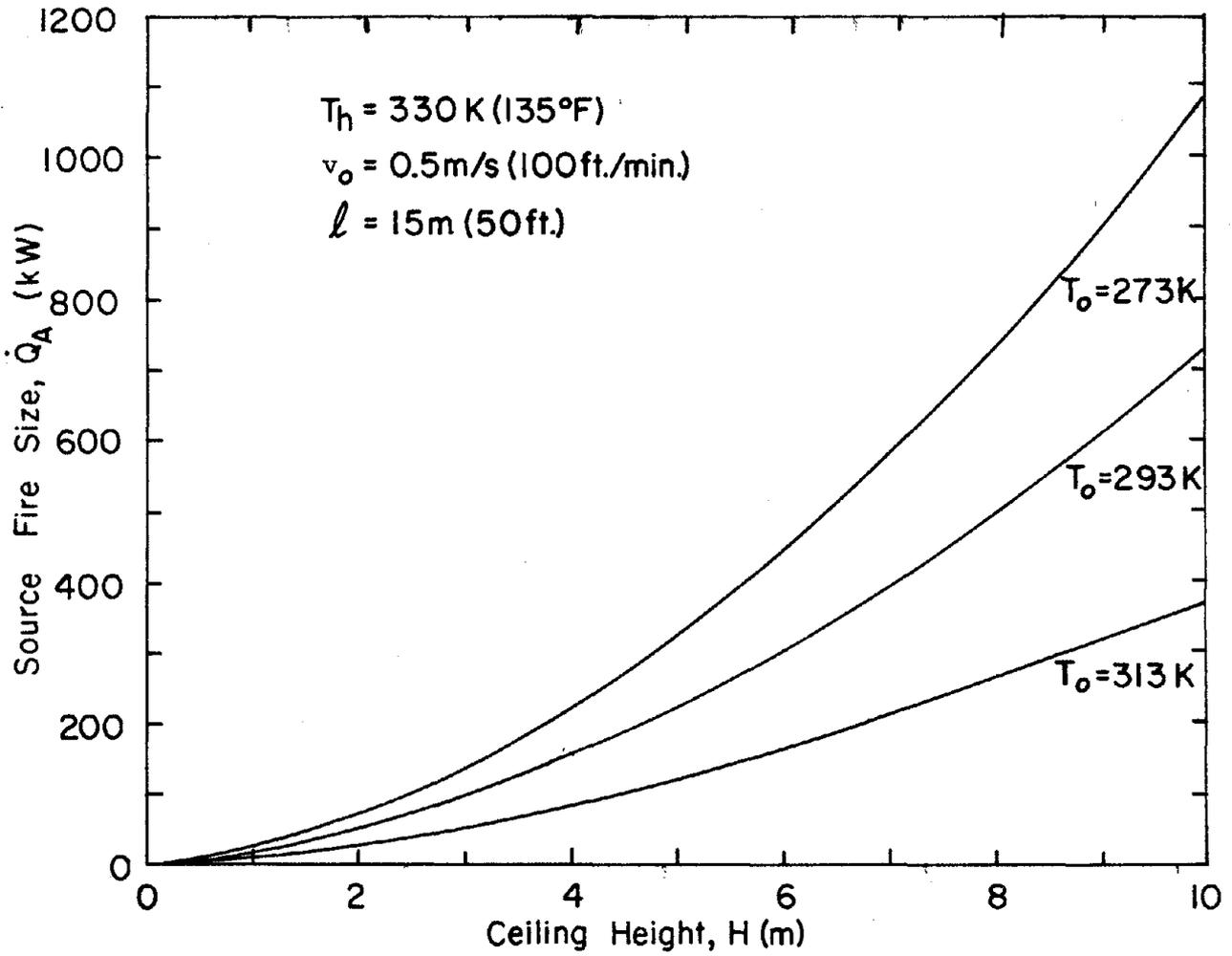


FIGURE 7. - Source fire size vs. ceiling height ($l = 15\text{m}$)

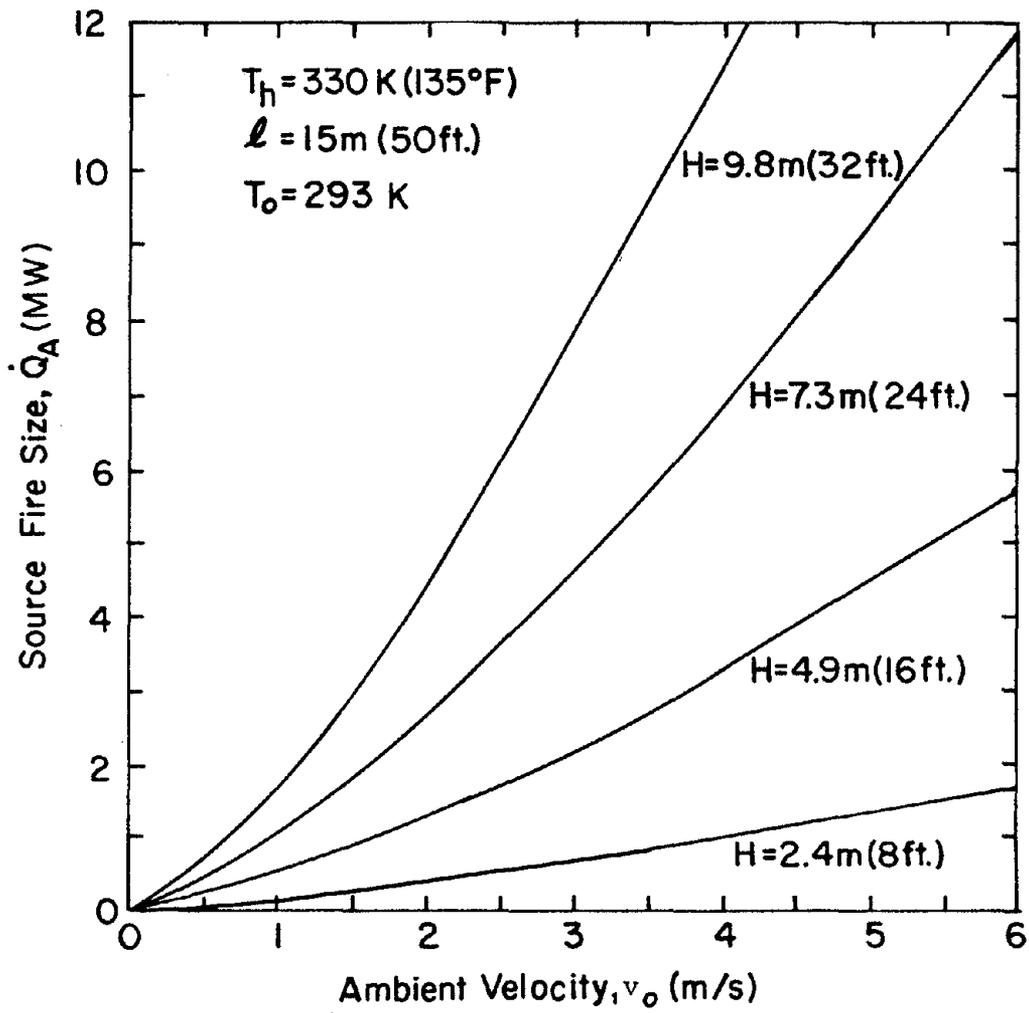


FIGURE 8. - Source fire size vs. cold velocity

Once T_o , H and v_o are specified, the CFR spacing specifications can be used to determine \dot{Q}_A . However, in order to quantify equivalency an additional parameter is required: the growth rate of the source fire. Referring to eq (14), the transit time to the thermal sensor, t_ℓ , is determined by the ambient velocity, i.e., $t_\ell = v_o/\ell$, with ℓ either 15 or 38 m. The thermal sensor alarm time, t_T , is a function of how rapidly the temperature is rising at the sensor, which in turn is a function of how rapidly the source fire is growing. The equivalent sum of t_ℓ and t_p in eq (14), therefore, can only be determined through a knowledge of this growth rate. Figure 9 illustrates one example of the application of this relationship. In the figure, the CO_2 concentration rise at the ceiling for untreated neoprene rubber, $\Delta C_{CO_2,R}$, at alarm of a thermal sensor spaced at $\ell = 15$ m is plotted versus the distance downstream of the source fire, ℓ' . H is fixed at 2.44 m (8 ft), T_o at 293 K and $t_\ell = v_o/15$ m. The fire growth parameters from eq (1) are $\alpha = 100 \text{ kW/s}^{1/3}$ and $p = 1/3$, which define a rapidly growing fire. Three curves are presented for $v_o = 1, 2$ and 4 m/s. For each of these curves it has been assumed that t_T is negligible compared to t_ℓ and that t_p is negligible compared to t_ℓ . While this is generally not the case, these assumptions are unavoidable without quantifying t_T and t_p for the specified conditions. Therefore, the curves give, for each equivalent time defined by eq (14), the CO_2 concentration rise at spacing, ℓ' . The distance downstream where $\Delta C_{CO_2,R}$ drops to zero for a given v_o is the maximum distance that the combustion products have reached when the thermal sensor alarms. Thus, for example, with the stated conditions the maximum spacing based upon $\Delta C_{CO_2,R}$ at $v_o = 1$ m/s is approximately 20 m.

Table 5 gives the product yields in ratio to $\Delta C_{CO_2,R}$ for carbon dioxide, carbon monoxide and hydrocarbons (HC), using the materials and properties from Table 3. In Figure 9, Table 5 may be used to determine the product concentration rise at the ceiling for CO, CO_2 and HC for any of the other materials listed by multiplying the values of $\Delta C_{CO_2,R}$ in the figure by the relative product yield from the table.

Figure 10 is similar to Figure 9, where $\Delta C_{CO_2,R}$ has been plotted versus ℓ' for a moderately growing fire with $\alpha = 10 \text{ kW/s}^{1/3}$ and $p = 1/3$. In addition, the curve for $v_o = 0.5$ m/s and slow growing fire with $\alpha = 1 \text{ kW/s}^{1/3}$ is shown.

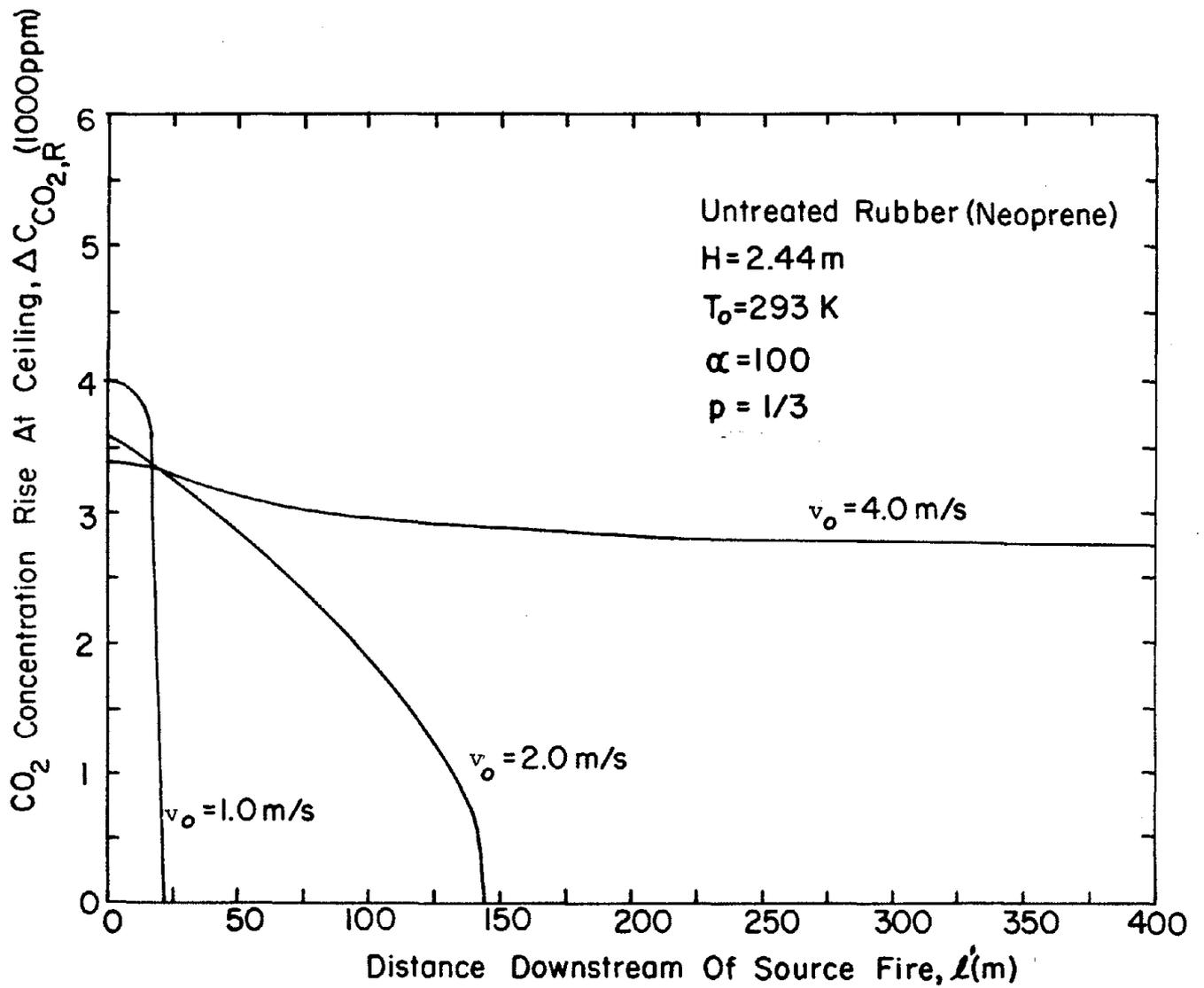


FIGURE 9. - CO₂ concentration rise vs. distance downstream ($\alpha = 100$) at alarm of a thermal sensor spaced at $\ell = 15 \text{ m}$

TABLE 5
RELATIVE PRODUCT YIELDS FOR VARIOUS MATERIALS

Material	$\frac{\Delta C_{CO_2}}{\Delta C_{CO_2,R}}$	$\frac{\Delta C_{CO}}{\Delta C_{CO_2,R}} \times 10^2$	$\frac{\Delta C_{HC}}{\Delta C_{CO_2,R}} \times 10^3$
Rubber (neoprene)			
Untreated	1.0	3.7	4.8
Treated	0.73	4.9	12
Red Oak			
Untreated	1.1	0.21	0.02
Treated	1.2	<0.01	0.09
Douglas Fir			
Untreated	1.3	<0.01	0.22
Treated	1.1	<0.01	<0.01
Cellulose	1.2	0.48	0.15
Polyvinyl Chloride	0.93	12	57
Polyethylene	0.82	1.4	3.4
Polyurethane Foam (GM-25)	1.1	2.2	2.2
Heptane	0.83	1.7	5.7
Acetone	0.94	0.11	<0.01
Methanol	0.61	0.02	<0.01
Hydrocarbon Transformer Fluid	0.64	1.1	-

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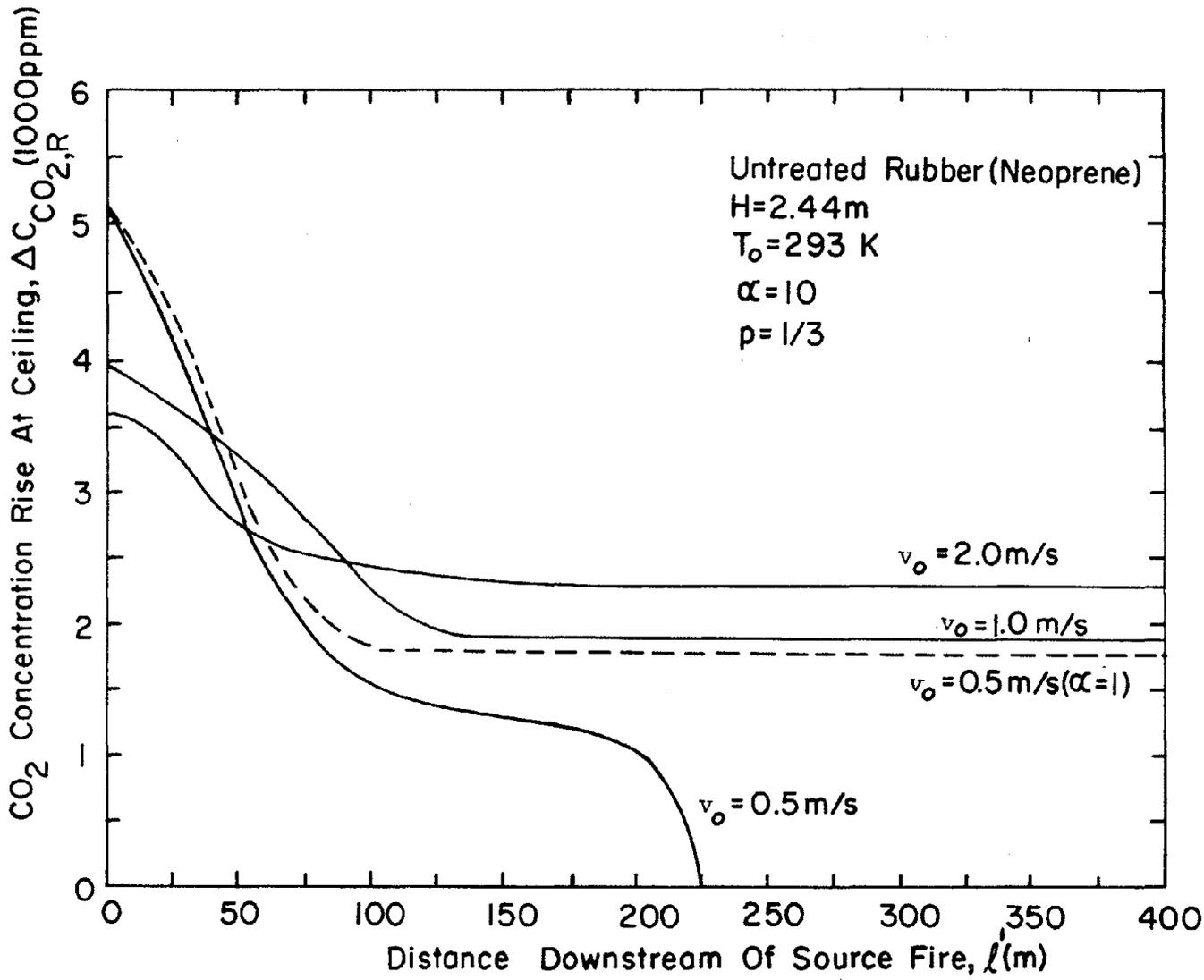


FIGURE 10. - CO₂ concentration rise vs. distance downstream ($\alpha = 10$) at alarm of a thermal sensor spaced at $\ell = 15\text{m}$

(The curves for $v_o = 1$ and 2 m/s do not significantly change for α between 1 and 10.) For example, with $v_o = 1$ m/s for all practical purposes there is no defined maximum spacing based upon $\Delta C_{CO_2,R}$ (assuming that the specified sensor can detect the concentration level given by the curve).

In summary, the spacing specifications given by Title 30 of the Code of Federal Regulations are insufficient for a general quantification of equivalency. The ambient temperature, T_o , ceiling height of the passageway, H , the ambient velocity, v_o , and the combustion characteristics of the fire to be detected (i.e., growth rate and fractional yields of products) must also be specified.

4.3 DEFINITION OF DETECTION CRITERIA

Two sets of detection criteria may be defined relative to the application of fire detectors in underground mines: 1) criteria based upon equivalency and 2) criteria based upon hazard-detection-response time relationships.

4.3.1 Detection Criteria for Equivalency

The fundamental relationship defining equivalency, as previously defined by eq (14) in Section 5.2 is

$$t_l + t_T \geq t_{l'} + t_p .$$

This relationship essentially defines detection requirements on the basis of equivalency. The left hand side of the equation specifies the total detection time of a thermal sensor, while the right hand side specifies the required total detection time of any type of product-of-combustion sensor. Implicit in this relationship is the relative spacing requirements for product-of-combustion versus thermal sensors. Finally, as previously discussed, the limitation on eq (14) is that it cannot be quantified without the specification of the preignition mine environment and the fire to be detected.

4.3.2 Detection Criteria for Residual Time

An alternative and intrinsically preferable method to defining detection criteria based on equivalency is based upon the relationship between the time to detect a fire, the time to "effectively" respond after detecting a fire, and the

time after the initiation of a fire to reach a defined hazard, i.e., a fire which becomes seriously life or property threatening. This relationship is defined by the following expression:

$$t_r \equiv t_H - t_\ell - (t_D + t_E) \geq 0 \quad (15)$$

where $t_r \equiv$ residual time;

$t_H =$ time to defined hazard;

$t_\ell =$ transit time to distance ℓ ;

$t_D =$ alarm time (t_T or t_p); and

$t_E =$ "effective" response time once fire has been detected.

Equation (15) states that the residual time, which must be zero or positive, is a function of four individual times: a hazard time, a transit time, a detection time, and a response time. In addition, for these detection criteria to have significance, the sum of transit, detection and response times must be less than or equal to the hazard time. The results of Phase I can be applied to accurately determine t_ℓ ; t_D will be quantified for a variety of detector types in Phase III. However, t_H and t_E are still somewhat unknown quantities; t_H depends on the defined hazard which is a function of the material properties and configuration. For example, previous work⁽³¹⁾ has defined the propagation hazard for timber sets in mines relative to the heat flow parameter given in eq (2). When this parameter is greater than or equal to 3 or 5 a fire will propagate for untreated or treated timbers, respectively. However, in this example the "smoke" hazard might be defined as either more important for human escape or occurring more quickly than the propagation hazard. Thus, the time to the smoke hazard would be used for t_H . Table 6 gives some examples of tentative critical values for human escape. These critical values, therefore, could be used to define the level of the hazard. However, the characteristics of the material(s), the fire configuration, and growth rate must also be specified to determine the time to this level, t_H . This, however, has not been included in the scope of Phase I.

The effective response time, t_E , is more difficult than t_H to assess. t_E depends on the individual mine configuration, the location of the fire, and primarily on the method of response to the fire, such as automatic or manual fire fighting, ventilation control (e.g., fire doors), or simply evacuation.

TABLE 6
 TENTATIVE CRITICAL VALUES FOR HUMAN ESCAPE FROM FIRES
 OR TOLERABLE SHORT TERM EXPOSURE TO FIRE PRODUCTS

Compound	Tentative Critical Values for Human Escape (ppm) ^a
HCN	30 ^b
HCl	50
Benzene	1,500
CO	1,500
CO ₂	40,000
O ₂	<60,000
Temperature (°F)	280
Smoke	0.07 ft ⁻¹

^aData from References 44, 45

^bData from Reference 43

Thus, t_E could vary from the order of seconds, as in the case of automatic sprinklers, to the order of hours as in the case of the evacuation of deep mines. In conclusion, t_E could probably best be quantified on the basis of mine experience, practice and procedures.

4.4 PRELIMINARY ACCEPTANCE PLAN

Figure 11 presents an outline of a preliminary acceptance plan for underground mine fire detectors. This plan is based upon the application of test results from Phase I and information obtained from the literature review. The figure follows a format similar to that given in Reference 32 and considers the determination of detector response characteristics (e.g., alarm time, repeatability and reliability) versus the preignition and post-ignition mine environment (e.g., source fire and ventilation rate). It is intended that Figure 11 serve as a starting point for a detailed sensor evaluation test program to be prepared in Phase II and later refined in Phase IV following the sensor testing program in Phase III (see Section 1.3, Technical Approach).

PRELIMINARY ACCEPTANCE PLAN FOR UNDERGROUND MINE FIRE DETECTORS

- I. PRELIMINARY EVALUATION OF DETECTOR**
 - A. Manufacturer's Specifications (operational manual)**
 - B. Detector Classification**

- II. DETECTOR RESPONSE UNDER STANDARD CONDITIONS**
 - A. Calibration (if required by manufacturer)**
 - B. Response Characteristics vs. Source Fire and Ventilation Rate**
 - 1. Response (Alarm) Time**
 - 2. Temperature, Obscuration, Gas Concentration(s) at Alarm**
 - 3. Repeatability (Precision), Reliability, etc.**

- III. DETECTOR RESPONSE UNDER MINE ENVIRONMENT
CONDITIONS**
 - A. Specification of Mine Environment - Temperature, Humidity,
Other (Dust, Interferences, Pressure, etc.)**
 - B. Response Characteristics vs. Source Fire and Ventilation Rate**

- IV. OTHER DETECTOR PERFORMANCE TESTS**
 - A. Durability - Stability, Operation Lifetime, Shock, Vibration,
Intrinsic Safety, Other**
 - B. Detector Support**

- V. EVALUATION OF TEST DATA RELATIVE TO ACCEPTANCE/
APPLICATION STANDARDS**
 - A. Statistical Analysis of Data**
 - B. Evaluation Sheet**
 - C. Acceptance/Application Decision**

FIGURE 11

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

On the basis of the test results and analysis of the Phase I work effort, several conclusions were made relating to the development of standardized test criteria and procedures for mine fire detectors.

1. The interaction of the preignition and post-ignition underground mine environment was effectively assessed in Phase I through the following:

- a) a quantification of source fire heat release rates;
- b) the prediction to within $\pm 10\%$ of the average gas temperature and to within $\pm 15\%$ of the effects of temperature stratification downstream of a source fire; and
- c) the determination of the distribution of products of combustion downstream of the source fire as a function of the predicted fire environment and the combustion characteristics of the materials comprising the source fire.

2. "Equivalent protection" or equivalency as defined by Title 30 of the Code of Federal Regulations was determined to be inadequately specified in order to be quantified for general applications. However, equivalency can be quantified if the following additional parameters are specified:

- a) the mine ambient temperature, T_0 ;
- b) the ceiling height of the mine passageway, H ;
- c) the mine ambient average velocity, v_0 ;
- d) the growth rate of the source fire; and
- e) the materials comprising the source fire.

3. Detection criteria for mine fire detectors were defined based upon:

- a) the concept of a "residual" time which is related to the time to reach a specified mine fire hazard, the spacing between fire detectors, the detector response time, and the time for "effective" response to the fire hazard once the detector has alarmed; and
- b) the concept of "equivalent protection" or equivalency which is a function of both spacing and response time of a product of combustion detector and is defined relative to the spacing and response time of a fixed-temperature, point-type thermal detector.

4. An outline for a preliminary acceptance plan for underground mine fire detectors was developed to be used in subsequent phases.

5.2 RECOMMENDATIONS

It is recommended that: 1) an assessment of the growth rates for mine materials (particularly coal) be performed in order to specify the heat release rate of the source fire for a given "realistic" mine fire scenario; 2) mine fire hazards be defined, which are essential for the quantification of hazard times used in the developed detection criteria; and 3) an assessment of "effective" response times relative to fire detection times be made which also is necessary for quantifying detection criteria.

NOMENCLATURE

A	area of mine passageway (m^2)
c	specific heat ($kJ/kg \cdot K$)
ΔC	concentration rise (ppm)
Fr	Froude number
g	acceleration of gravity (m/s^2)
G	concentration of combustion product (kg/kg)
\dot{G}	generation rate of combustion product (kg/s)
h	height for position of interest (m)
H	ceiling height of mine passageway (m)
H_A	actual heat of combustion (kJ/kg)
k	convective loss coefficient
ℓ, ℓ'	distance downstream of source fire (m)
p	exponent of power law fire
\dot{Q}	heat release rate (kW)
t	time (s)
T	temperature (K)
ΔT	excess temperature or temperature rise (K)
v	gas velocity (m/s)
Y	mass yield of combustion product (kg/kg)

Greek

α	proportionality constant of power law fire (kW/s^p)
ρ	gas density (kg/m^3)
σ	Stefan-Boltzmann constant ($kW/m^2 \cdot K^4$)

Subscripts

A	actual
avg	average
CO	carbon monoxide
CO ₂	carbon dioxide
D	detection
E	effective
f	flow

h height
H hazard
HC hydrocarbons
i individual products (CO,CO₂,HC)
l,l' horizontal distance
o ambient air
p product of combustion
r residual
ref reference
R rubber (untreated neoprene)
T thermal
w walls
xs excess

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APPENDIX

DEVELOPMENT OF THE HEAT BALANCE FOR A FIRE IN A MINE PASSAGEWAY

The heat flow rate out of a fire within a passageway is comprised of two terms, one associated with convection and the other associated with thermal losses to the walls, i.e.,

$$\dot{Q}_A = \dot{Q}_C + \dot{Q}_\ell \quad (A-1)$$

where \dot{Q}_A = heat release rate of the fire source (kW) at time $(t - \ell/v_o)$;
 \dot{Q}_C = convective heat flow rate down the passageway at time t and distance ℓ from fire source (kW); and
 \dot{Q}_ℓ = heat loss rate through the passageway walls at time t and over distance ℓ from fire source (kW).

The convective heat flow rate can be written as:

$$\dot{Q}_C = \rho_o c_o v_o A_f (T_{avg} - T_o) \quad (A-2)$$

where ρ_o = ambient gas density (kg/m^3);
 c_o = ambient specific heat ($\text{kJ/kg}\cdot\text{K}$);
 v_o = ambient velocity (m/s);
 A_f = cross-sectional area of the passageway (m^2);
 T_{avg} = average temperature in passageway at distance ℓ (K); and
 T_o = ambient gas temperature (K).

The heat loss term in eq (A-1) also consists of two major components:

$$\dot{Q}_\ell = \dot{Q}_{\ell,C} + \dot{Q}_{\ell,R} \quad (A-3)$$

where $\dot{Q}_{\ell,C}$ = heat loss rate to walls due to convection (kW); and
 $\dot{Q}_{\ell,R}$ = heat loss rate to walls due to radiation (kW).

The convective and radiative loss terms can be approximated by the following equations:

$$\dot{Q}_{\ell,C} = h_{\ell} A_w (T_{avg} - T_w) \quad (A-4)$$

$$\dot{Q}_{\ell,R} = \bar{F}_{ws} \epsilon_w A_w \sigma (T_{avg}^4 - T_w^4) \quad (A-5)$$

where h_{ℓ} = average convective heat transfer coefficient to the walls over distance ℓ ($\text{kW}/\text{m}^2 \cdot \text{K}$);

A_w = total area of walls (including ceiling and floor) to distance ℓ (m^2);

T_w = temperature of wall (K);

\bar{F}_{ws} = view factor between walls and fire source;

ϵ_w = emissivity of walls; and

σ = Stefan-Boltzmann constant ($5.67 \times 10^{-11} \text{ kW}/\text{m}^2 \cdot \text{K}^4$).

Nusselt/Reynolds number correlations for convective heat transfer from a fluid flowing inside a rectangular duct give the following expression (McAdams, W.H., "Heat Transmission," 3rd ed., McGraw-Hill, New York, 1954) for h_{ℓ} :

$$h_{\ell} = 0.026 [\text{Re}]^{-0.2} \left\{ 1 + \left[\frac{D_H}{\ell} \right]^{0.7} \right\} \rho_o c_o v_o \quad (A-6)$$

where $\text{Re} = \text{Reynolds number} = \frac{\rho_o D_H v_o}{\mu_o}$; and

D_H = hydraulic diameter of the passageway (m)

$$= \frac{4 A_f}{P} \quad (\text{where } P = \text{perimeter of the passageway, m}).$$

Combining and rearranging eqs (A-1), (A-2), (A-4), (A-5) and (A-6) with the following assumptions: 1) $T_w = T_o$; 2) $\bar{F}_{ws} = 1$; and 3) $\epsilon = 1$, yields the following result:

$$\Delta T_{avg} = \left(\frac{1}{1+k_{\ell}} \right) \frac{1}{\rho_o c_o v_o A_f} [\dot{Q}_A - A_w \sigma (T_{avg}^4 - T_o^4)] \quad (A-7)$$

where

$$\Delta T_{avg} = T_{avg} - T_o \quad (A-7a)$$

$$k_{\ell} = 0.026 [\text{Re}]^{-0.2} \left\{ 1 + \left[\frac{D_H}{\ell} \right]^{0.7} \right\} \frac{A_w}{A_f} \quad (A-7b)$$

In summary eq (A-7) gives the average temperature rise in a passageway at distance l downstream from a fire source as a function of the ambient gas properties, gas velocity, passageway dimensions, source fire heat release rate and heat losses to the passageway walls.

NOMENCLATURE FOR APPENDIX

A	area of mine passageway (m^2)
c	specific heat ($kJ/kg \cdot K$)
D	diameter of mine passageway (m)
\bar{F}	view factor
h	average convective heat transfer coefficient ($kW/m^2 \cdot K$)
k	convective loss coefficient
ℓ	horizontal length of passageway from source fire (m)
P	perimeter of passageway (m)
\dot{Q}	heat release or flow rate (kW)
Re	Reynolds number
T	temperature (K)
ΔT	temperature rise (K)
v	gas velocity (m/s)

Greek

ϵ	surface emissivity
μ	viscosity ($Pa \cdot s$, i.e., $kg/m \cdot s$)
ρ	gas density (kg/m^3)
σ	Stefan-Boltzmann constant ($kW/m^2 \cdot K^4$)

Subscripts

A	actual
avg	average
C	convective
f	flow
H	hydraulic
ℓ	horizontal distance
o	ambient air
R	radiative
w	walls
ws	walls and fire source



APPENDIX C

PHASE II REPORT

STANDARD TEST CRITERIA FOR EVALUATION OF UNDERGROUND FIRE DETECTION SYSTEMS

Prepared for
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

By
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Phase II Report

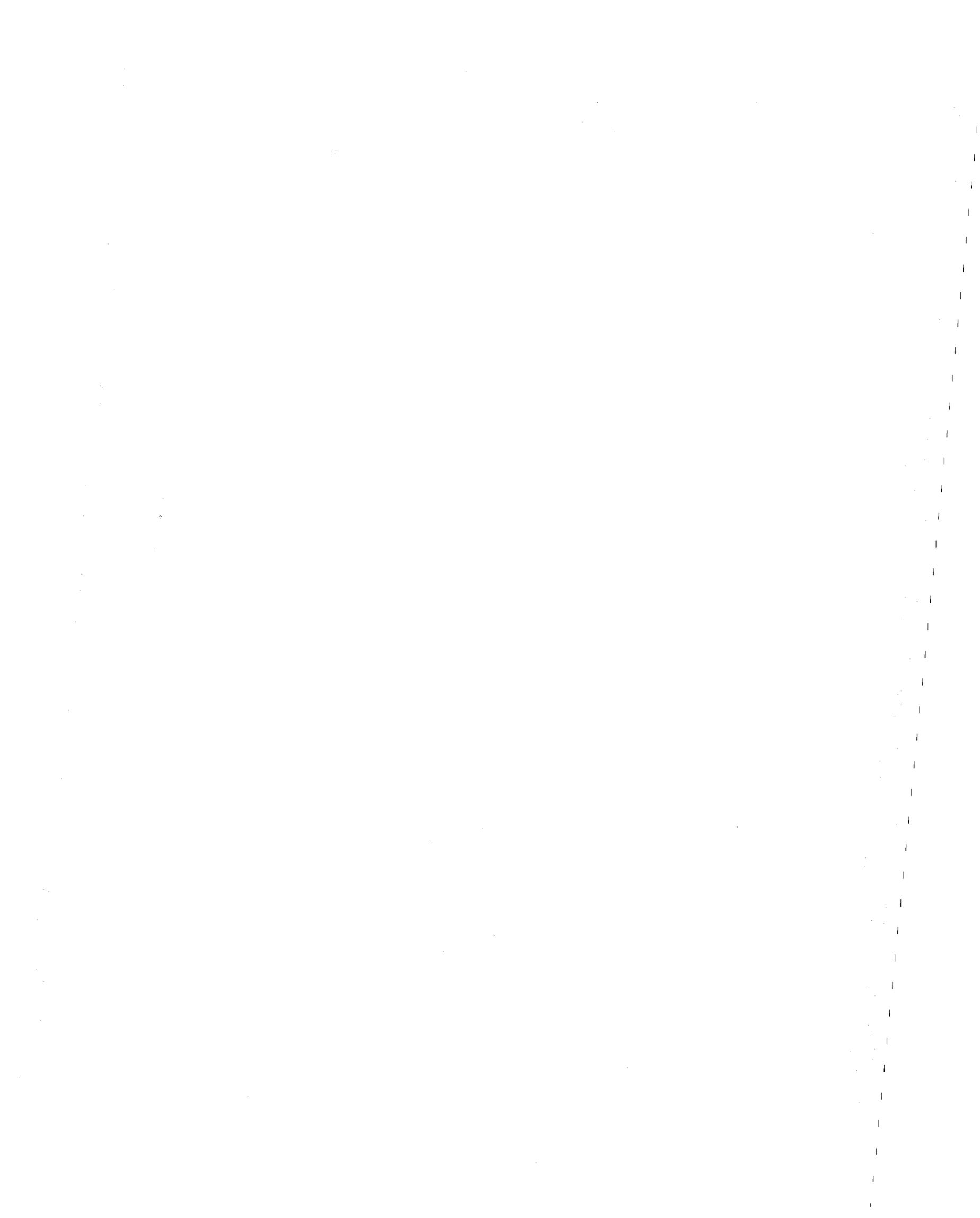
Contract No. H0113017

December 1982

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Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines, or Factory Mutual Research Corporation.



REPORT DOCUMENTATION PAGE		1. REPORT NO.	2.	3. Recipient's Accession No.
4. Title and Subtitle Standard Test Criteria For Evaluation Of Underground Fire Detection Systems-Phase II			5. Report Date December 1982	
7. Author(s) Jeffrey S. Newman and James R. Brown			8. Performing Organization Rept. No. J.I. OG2N4.RC	
9. Performing Organization Name and Address Factory Mutual Research Corporation 1151 Boston-Providence Turnpike Norwood, Mass. 02062			10. Project/Task/Work Unit No.	
			11. Contract(C) or Grant(G) No. (c) H0113017 (G)	
12. Sponsoring Organization Name and Address U.S. Department of The Interior Bureau of Mines			13. Type of Report & Period Covered Phase II Report (Feb. 22, 1982-Nov. 20, 1982)	
14.				
15. Supplementary Notes				
16. Abstract (Limit: 200 words) This report presents the results of the second of a four-phase effort conducted for the Bureau of Mines to evaluate underground mine fire detection systems. The major results of Phase II are the design of: 1) a sensor test program for determining detector spacing requirements, and 2) an apparatus for testing fire detector systems under simulated mine fire environments.				
17. Document Analysis a. Descriptors Fire Detectors Mine Fire Hazards Test Criteria b. Identifiers/Open-Ended Terms c. COSATI Field/Group				
18. Availability Statement Availability Unlimited		19. Security Class (This Report) Unclassified		21. No. of Pages 37
		20. Security Class (This Page) Unclassified		22. Price



FOREWORD

This report was prepared by Factory Mutual Research Corporation (FMRC), Factory Mutual System, Norwood, Massachusetts under USBM Contract No. H0113017. It was administered under the technical direction of the Pittsburgh Research Center with Dr. A.F. Cohen acting as Technical Project Officer. Mr. A.G. Young was the contract administrator for the Bureau of Mines. The report is a summary of the work recently completed as part of this contract during the period February 22, 1982 to November 20, 1982. This report was submitted by the authors on December 30, 1982.

The authors wish to acknowledge gratefully the following persons who contributed to this project: Mr. W.R. Brown for extensive contributions to the design of the test apparatus; Dr. A.F. Cohen, Dr. G. Heskestad and Dr. A. Tewarson, for valuable contributions; and Mr. L.A. Post and Mrs. H.G. Hurley for their efforts in producing this report.

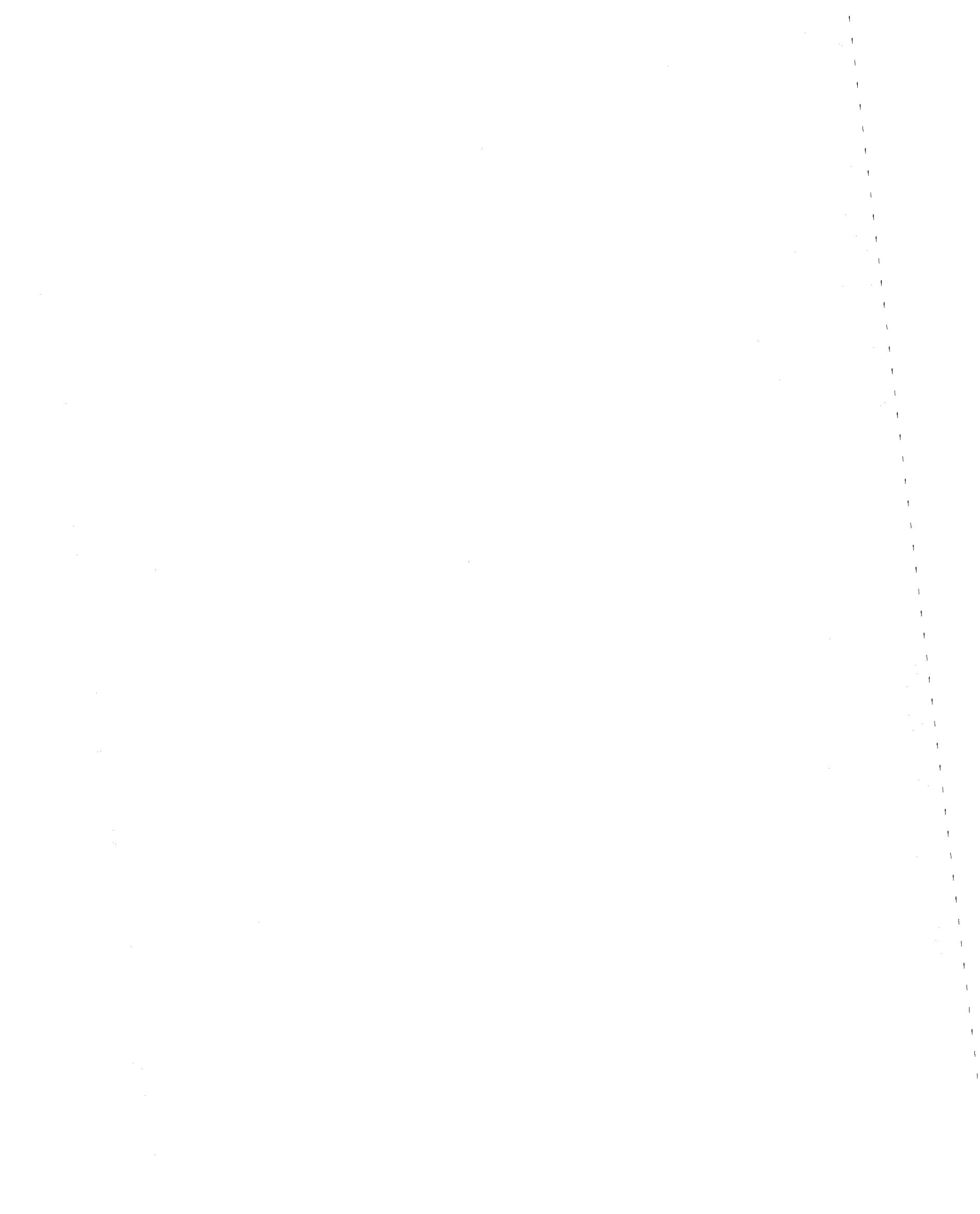
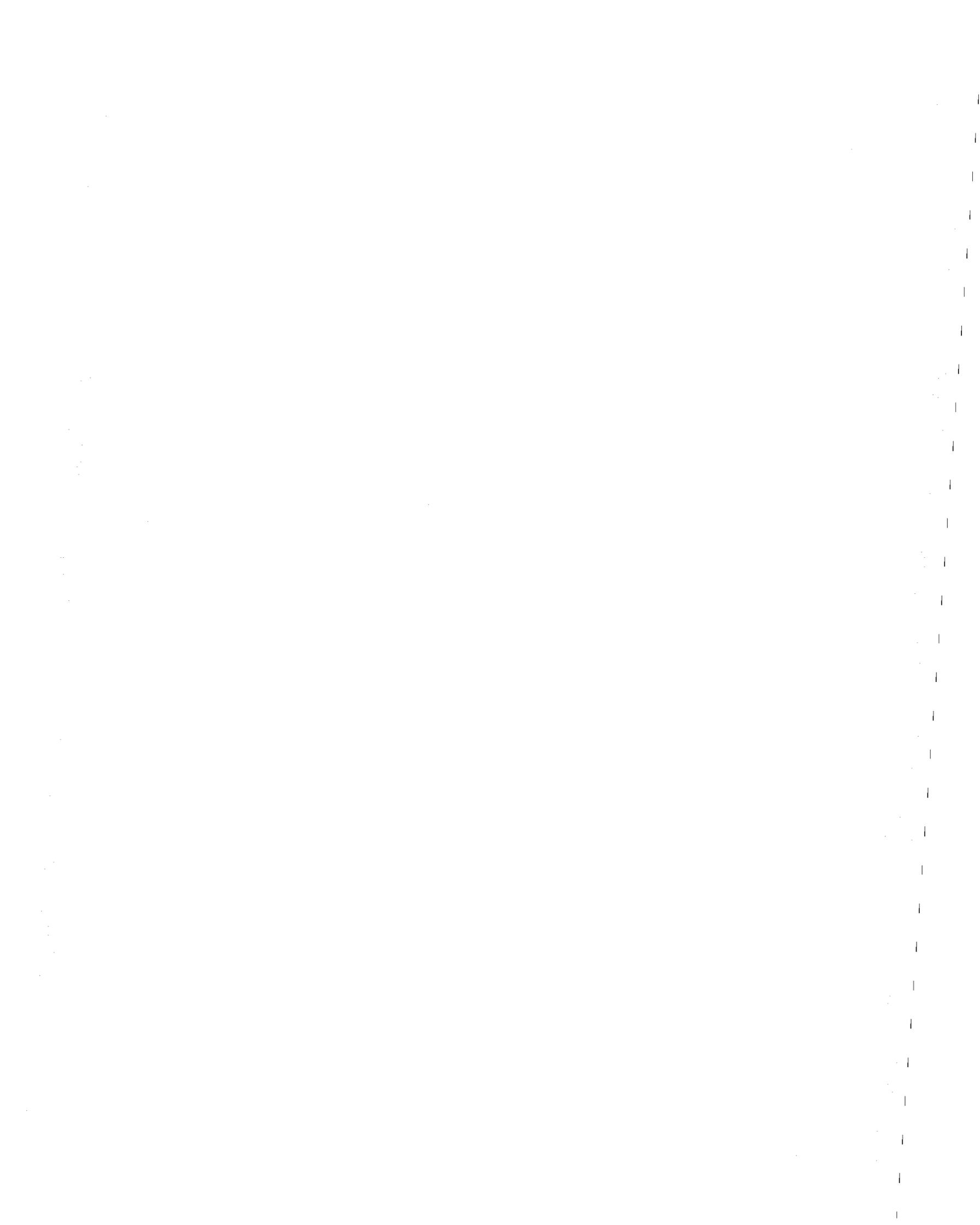


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I

INTRODUCTION

1.1 SUMMARY OF PHASE II

This report details the efforts of Phase II of a four-phase approach to establishing standard test criteria and procedures for the evaluation of underground mine fire detection systems. The objectives of Phase II were to:

1) develop a test program design capable of evaluating detector spacing requirements as specified in, but not limited to, Title 30 Code of Federal Regulations; and 2) provide a detailed design for the necessary test apparatus to evaluate fire detector systems under simulated mine fire environments.

The fire detector evaluation test program design primarily considers the following effects on detector response characteristics: 1) fire source intensity and material (coal, wood, flammable liquid, conveyor belting, etc.); and 2) ventilation air velocity. In addition, provisions are made to consider detector performance relative to: 1) calibration; 2) ranges in mine environment ambients, i.e., temperature, humidity, dust, electromagnetic and gas interferences, pressure, etc.; 3) durability, i.e., stability, operation lifetime, shock, vibration, intrinsic safety, etc.; and 4) detector support, i.e., detector documentation, repair and maintenance procedures, quality assurance practices and procedures.

The test apparatus is a wind tunnel arrangement capable of directly evaluating detector response versus simulated mine fire environments for up to four detectors simultaneously with: 1) variable fire source intensity up to a maximum of 100 kW; 2) a variety of materials in configurations up to 0.3 m x 0.3 m x 0.15 m high; and 3) ventilation air velocities up to 6.1 m/s (1200 ft/min).

Finally, further results are reported on the quantification of mine fire environments assessed initially in Phase I. These results will have direct application to the quantification of fire hazards, which is necessary for specifying detection criteria in Phase IV.

1.2 OBJECTIVE AND SCOPE

The objective of this project is to develop standardized test criteria and procedures which will assure that fire detectors selected for installation in mines will:



- 1) be reliable in operation;
- 2) be located in the most effective position; and
- 3) function routinely with minimal maintenance.

1.3 TECHNICAL APPROACH

The technical approach developed to meet the objective within the scope of this project consists of four distinct phases. This report addresses the results from the Phase II work efforts. The following paragraphs outline the approach followed in Phases I and II accompanied by a brief discussion of the work elements expected to be accomplished in Phases III and IV.

Phase I

The Phase I effort (1) was primarily directed toward identification and acquisition of the data necessary to establish preliminary standard test criteria for mine fire detectors. This included: 1) review of pertinent literature; 2) gathering and analysis of FMRC's existing experimental data on fire environments and fire detector response characteristics; 3) identification of data gaps (if any); and 4) performance and analysis of additional fire tests (if required).

Phase II

A detailed design of a sensor evaluation test program and associated test apparatus was prepared under this work phase. The developed test program will be capable of evaluating detector spacing requirements referenced to Title 30 Code of Federal Regulations as influenced by fire and environmental parameters of an underground mine. Practical limits for evaluation were defined in this phase of the program. Detailed engineering drawings including suppliers were prepared for a fire test apparatus to be developed for detector evaluation purposes. In addition, the rationale for the design of the apparatus and component selection was provided in this work phase.

Phase III

The test apparatus designed by FMRC and approved by the Bureau under Phase II will be constructed. Any changes in the agreed-to design will be noted on drawing specifications and be supported with adequate discussion.

An acceptance test of the apparatus, based upon an expected worst-case set of mine conditions, will validate the performance of the test apparatus. This test will include the combination of various fuels under environmental mine conditions.

After the fire test apparatus is validated, six different types of fire detectors will be evaluated. These will include early warning devices classed as particulate detectors, low-level CO detectors, fixed temperature units representative of devices found along conveyor beltways, and smoke detectors.

Phase IV

Within this phase fire and environmental performance specifications for the acceptance of mine fire detection sensors and sensing systems will be developed. The developed standards will specify optimum sensor spacing capability as related to Title 30 Code of Federal Regulations Paragraphs 75-1103-4, 75-1103-10 and will also specify the environmental conditions under which detectors used for mine applications must operate. This specification will include any special conditions and practices which should be followed by detector installers.

As a product of this investigation a response theory will be developed for the various types of detectors.

Finally, such a broad work effort will probably indicate technology gaps in the field of detector behavior and installation. These areas will be evaluated for the need of future research work. The results of this evaluation will be presented in comment form providing the rationale for the identified research and a program plan indicating the magnitude of funding and manpower required to accomplish the proposed research efforts.

II

DESIGN OF SENSOR EVALUATION TEST PROGRAM

2.1 SUMMARY

The design of a sensor evaluation test program for underground mine fire detectors has been completed. The test program is capable of evaluating detector spacing requirements referenced to Title 30 Code of Federal Regulations as influenced by fire and environmental parameters of an underground mine. In Phase III the test apparatus (Section III) will be calibrated (Section 2.2) for an expected worst-case set of mine fire conditions. Six different types of fire detectors will then be evaluated according to readout and use classifications (Section 2.3). The response of each selected detector will be determined under fire environment conditions before and, if required, after conditioning under mine environment conditions (Sections 2.4 through 2.6). After performing other detector performance tests (Section 2.7), an evaluation of the test data relative to acceptance/application standards will be completed as part of Phase IV efforts.

2.2 TEST APPARATUS CALIBRATIONS

An acceptance test of the apparatus, based upon an expected worst-case set of mine conditions will be conducted to validate the performance of the test apparatus. These tests will include the combination of various fuels (e.g., coal, conveyor belting, wood, flammable liquids, etc.) under ambient ventilation conditions simulating mine environments (e.g., 0.5-6.1 m/s). It will be necessary to evaluate the operational characteristics of the apparatus at these test conditions. The time for temperature stabilization of the apparatus will be determined. Also, the time for temperature stabilization for a given set of test conditions will be determined by use of gas and wall temperature data from the thermocouples located at key locations throughout the device. In addition, uniformity of gas temperature profiles will be determined by temperature traverses across the test section. Similarly, pitot-static probe traverses will be performed for the purpose of determining velocity uniformity across the test section. For this purpose, the average velocity in the test section will be set by use of the pressure differential across the upstream orifice plate and its associated gas temperature.

2.3 PRELIMINARY EVALUATION OF DETECTORS

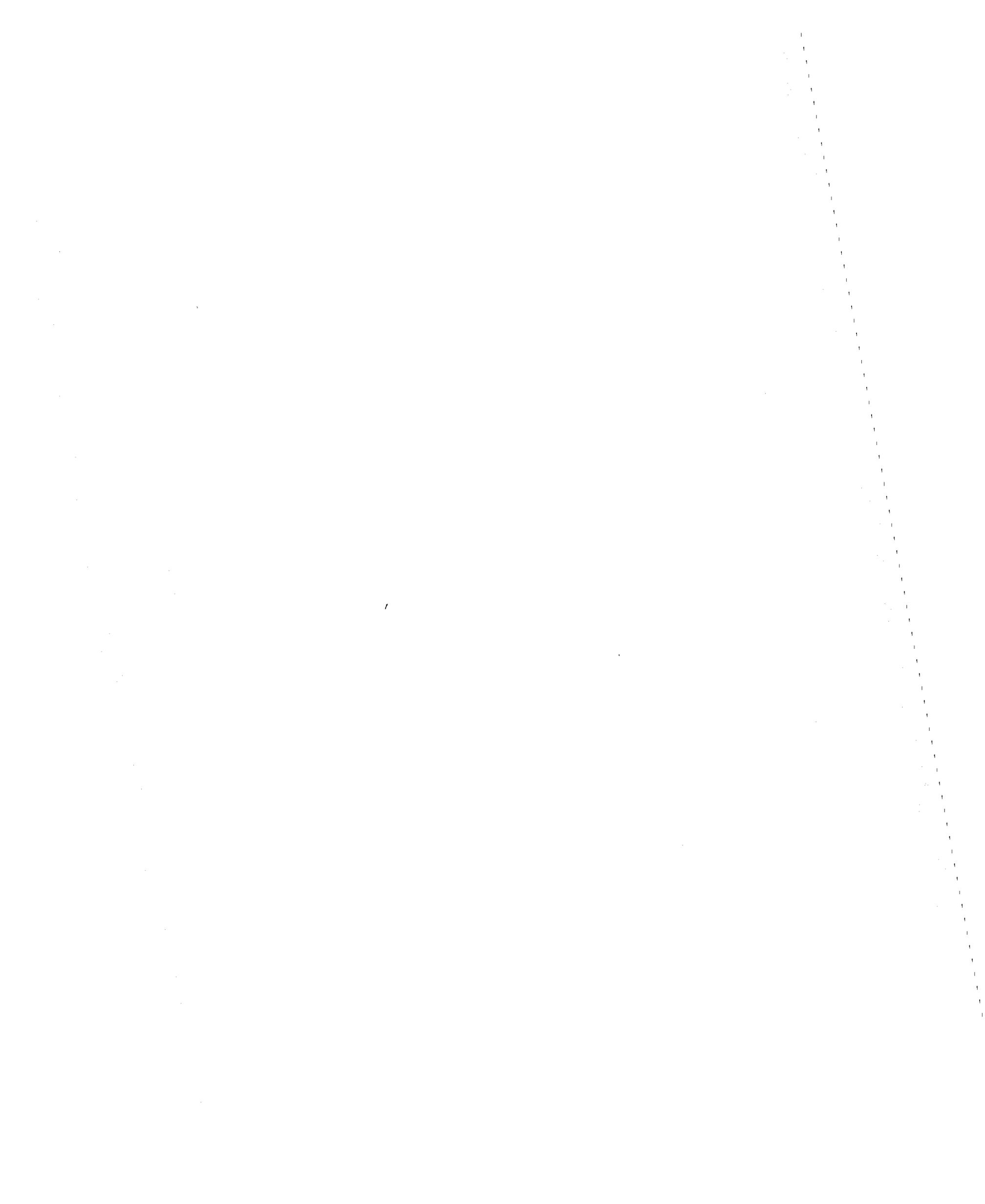
A comprehensive evaluation structure for all types of gas detectors was previously presented (2) to serve as the basis for eventual certification of gas detection devices for mine situations. This structure is directly applicable in a simplified form to fire detectors and considers a method of classifying all detectors based upon: 1) the type of readout which provides information to the user; and 2) the intended use or application of the device. The results of this classification scheme define a precise path to certification by determining: 1) a set of optimum test requirements resulting in definitive test results; 2) a statistical level of confidence in the evaluation; 3) a device quality rating; and 4) an assessment of the support for the device (i.e., device manual, device repair and maintenance procedures, and quality assurance practices and procedures). Also, the method is structured such that a specific aspect for device evaluation is covered by: 1) formats for an evaluation sheet, a manufacturer's data sheet and necessary evaluation standards; 2) details for detector classification; 3) step-by-step test procedures; 4) test apparatus specifications; and 5) an extensive glossary with operational definitions.

2.4 DETECTOR RESPONSE UNDER FIRE ENVIRONMENT CONDITIONS

Selected fire detectors for underground mines will be evaluated using the test apparatus (Section III) under laboratory ambient conditions with simulated mine fire environments (Section 2.2). Tests to measure detector characteristics will consist of baseline tests and use tests. Baseline tests provide information necessary for the evaluation of the detector characteristics under fire environment conditions. These tests measure:

- 1) calibration (if required);
- 2) warm-up (if required);
- 3) noise/drift (if required);
- 4) characteristic time; and
- 5) characteristic response.

Use tests specify testing conditions which provide information to extend the baseline evaluation of the device characteristics to field ambient environments. Use tests could consist of:



- 1) interference (secondary gas species, electromagnetic); and
- 2) environment (temperature, pressure, humidity, dust, orientation, velocity, shock, vibration, etc.).

2.5 DETECTOR CONDITIONING UNDER MINE AMBIENT ENVIRONMENT CONDITIONS

After evaluation in the test apparatus, it is suggested that the selected detectors be installed, in the field, within an existing underground mine to test for the effects of: temperature, humidity, pressure, dust, shock, vibration, etc. Alternatively, some of these effects could be simulated using environmental testing procedures as suggested in Reference 2.

2.6 DETECTOR RESPONSE AFTER CONDITIONING VERSUS FIRE ENVIRONMENT

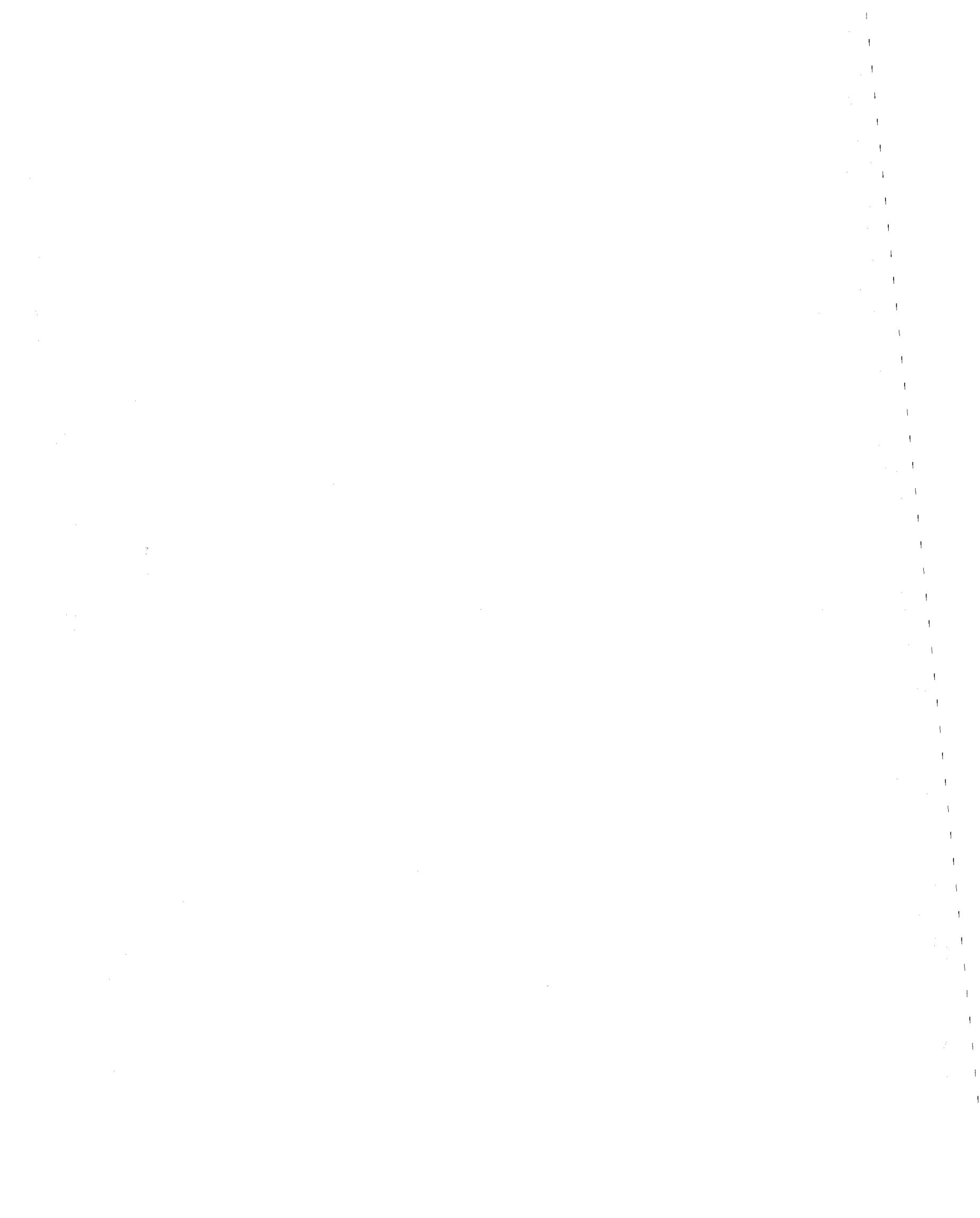
After the in-field underground mine conditioning, or simulated environmental conditioning, the fire detectors will be further tested in the test apparatus to determine response characteristics versus source fire and ventilation rate.

2.7 OTHER DETECTOR PERFORMANCE TESTS

In addition to the above described tests, other possible use tests could consider: durability (stability, operation and shelf lifetime); human factors (safety, information transfer, workmanship, special features); and support (device manual, repair and maintenance procedures, quality assurance practices and procedures).

2.8 EVALUATION OF TEST DATA RELATIVE TO ACCEPTANCE/APPLICATION STANDARDS

The statistical methods previously developed (consistent with MIL-STD-414) (2) will be applied where possible to the evaluation of the device test sample group. In this manner an acceptance/application decision can be made for the selected devices.



III
DESIGN OF THE TEST APPARATUS

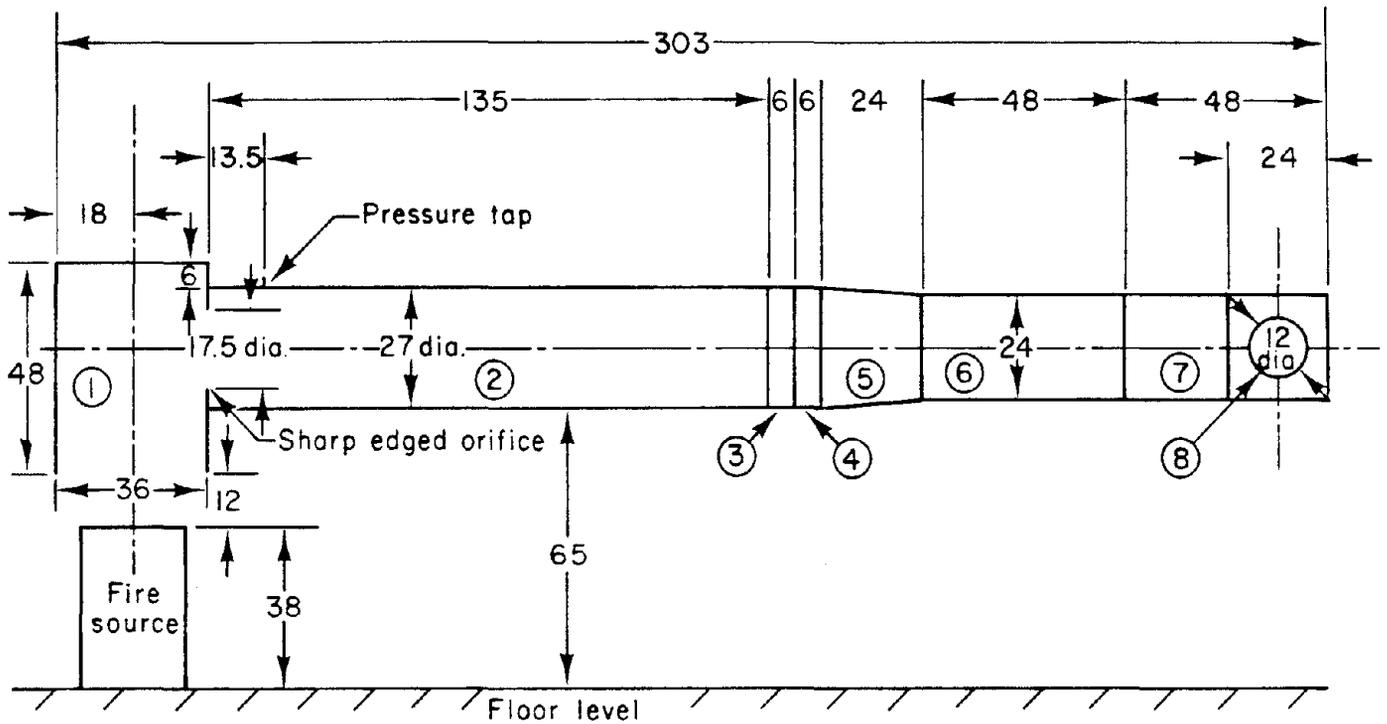
3.1 DESIGN SUMMARY

The test apparatus configuration is shown in Figures 1 and 2. Detailed design drawings are given in the Appendix. This apparatus consists of essentially two parts: 1) a fire source, and 2) a duct work for combustion product collection and distribution. The fire source apparatus will be capable of generating products of combustion from a variety of fuels typical of those found in an underground mine environment, e.g., coal, wood, conveyor belting, flammable liquids, etc. The overall size of the duct work will be determined by considering:

- 1) the cross-sectional flow area necessary to accurately test both current and anticipated mine fire detector designs (i.e., 24 in. x 24 in.);
- 2) the minimum duct length (coupled with an appropriate orifice opening) required to adequately mix the flow, i.e., 5 duct diameters; and
- 3) a smooth constant-area transition between the round duct mixing section and the square test section. The ductwork will: 1) be fabricated from 18 B&S gage monel 400 metal; 2) have a test section 2 ft x 2 ft x 4 ft long; and 3) have an operating range to include gas temperatures of about 100°C (212°F) and gas velocities to about 6.1 m/s (1200 ft/min). Test data will be collected for analysis through use of appropriate instrumentation together with a computerized data acquisition system.

In operation, all of the combustion products (i.e., materials typical of a mine environment) generated by the fire source together with room air will be drawn into the intake section (item 1 in Figure 1) by a downstream exhaust blower. After passing through the intake section, the total mass flow of combustion products and room air mixture will, in proportion to the setting of the blast gate (item 8), flow through the orifice plate positioned at the upstream end of the mixing section (item 2). Optical density and particle size of gaseous products will be determined by a smoke turbidimeter (item 3). Data for mass generation rate of CO, CO₂, and total hydrocarbons, together with associated temperatures, will be collected at the measuring section (item 4) while gas velocity will be determined by measuring the differential pressure across the upstream orifice plate. Measurements of gas as well as duct wall



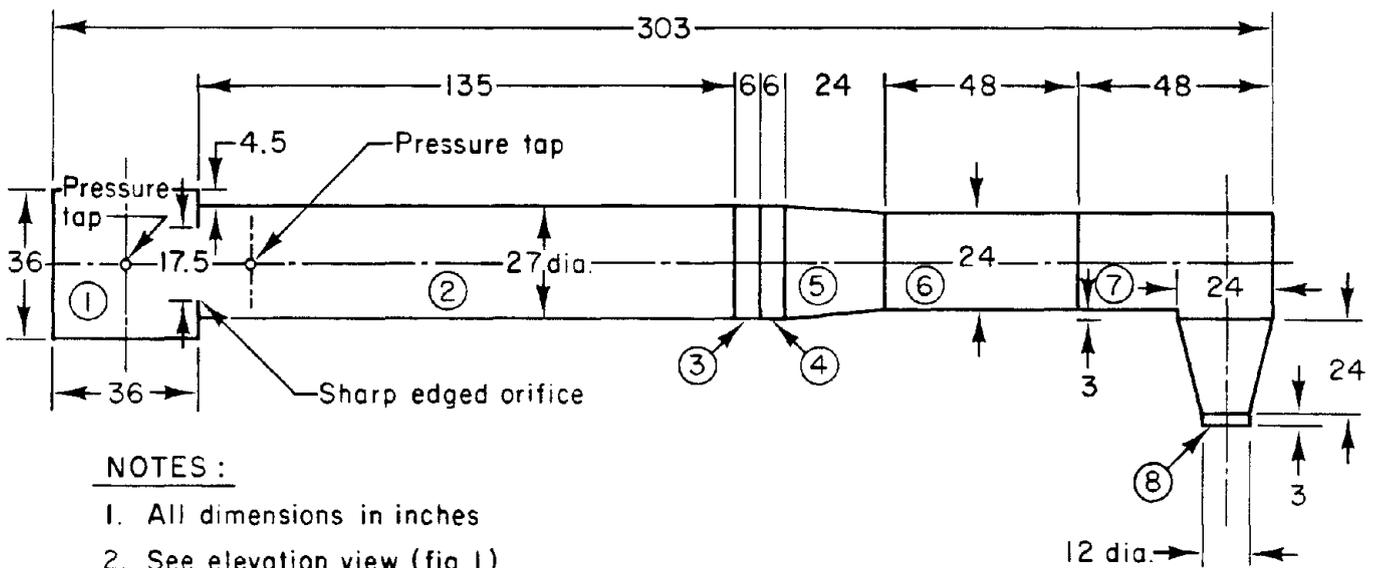


NOTES :

All dimensions in inches

- | | |
|-------------------------------------|--|
| ① Intake section (square duct) | ⑤ Transition section (round to square) |
| ② Mixing section (round duct) | ⑥ Test section (square duct) |
| ③ Turbidimeter section (round duct) | ⑦ Transition ell (square to round) |
| ④ Measuring section (round duct) | ⑧ Blast gate (stock type 12 in.) |

FIGURE 1.- Test apparatus schematic (elevation view)



NOTES :

1. All dimensions in inches
2. See elevation view (fig.1) for description of components

FIGURE 2.- Test apparatus schematic (plan view)

temperatures will also be obtained. The test section (item 6) is suitable for testing up to four fire detectors at one time. Test section view ports will be provided for visual observation, and separate ports for gas flow velocity and temperature probes are also included. After passing through the test section, the gas will flow through the transition ell (item 7) and be exhausted through the blast gate (item 8) and outlet duct to the exhaust blower.

3.2 FIRE SOURCE APPARATUS

The fire source, as shown in Figure 3, will be placed beneath the intake section of the ductwork. Four high-density radiant heaters, mounted on a support frame (20 in. x 20 in. cross section), will provide external heating. In addition, the position of each heater will be adjustable to provide uniform radiant heating to the fuel surface. Electrical power to the heaters from about 20 to 60 kW will be controlled by use of a phaser power controller (not shown). The amount of combustion products generated by a specific fuel will be adjustable by two means: 1) varying the surface area of the fuel up to a maximum of 0.3 m x 0.3 m (12 in. x 12 in.) and 2) varying the external heat flux received by the fuel surface. Finally, a load cell system will be included as part of the fire source apparatus to measure the mass loss rate of the fuel.

3.3 DUCT INSTRUMENTATION

As summarized in Section 3.1, the duct will be instrumented to provide measurements of:

- 1) gas temperatures;
- 2) duct wall temperatures;
- 3) gas velocities;
- 4) total mass and volumetric flow rates;
- 5) gas species concentrations including CO, CO₂, O₂ and THC (total hydrocarbons); and
- 6) optical densities and smoke particle sizes.

The specific locations of these instruments are shown in Figure 4.

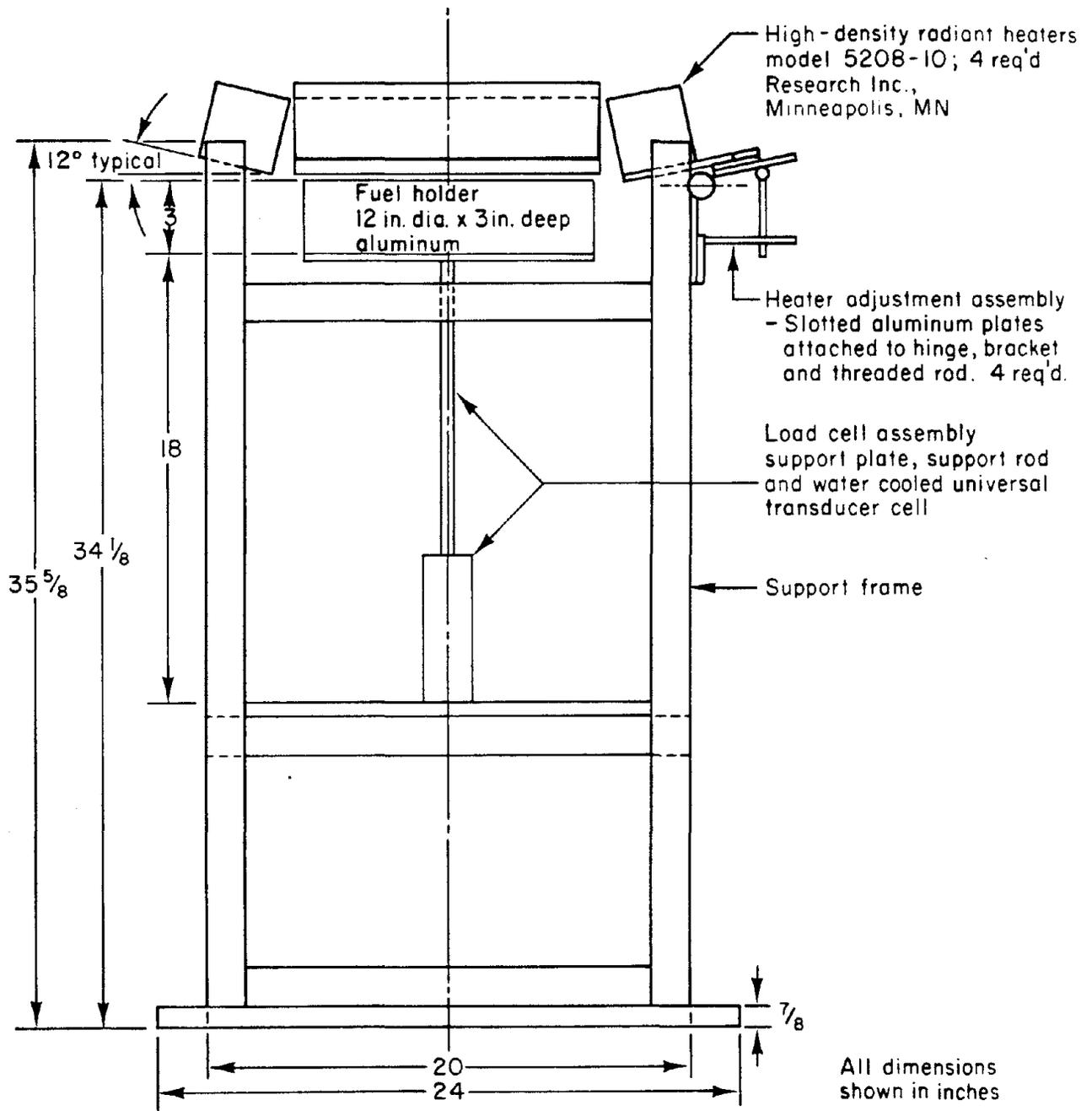
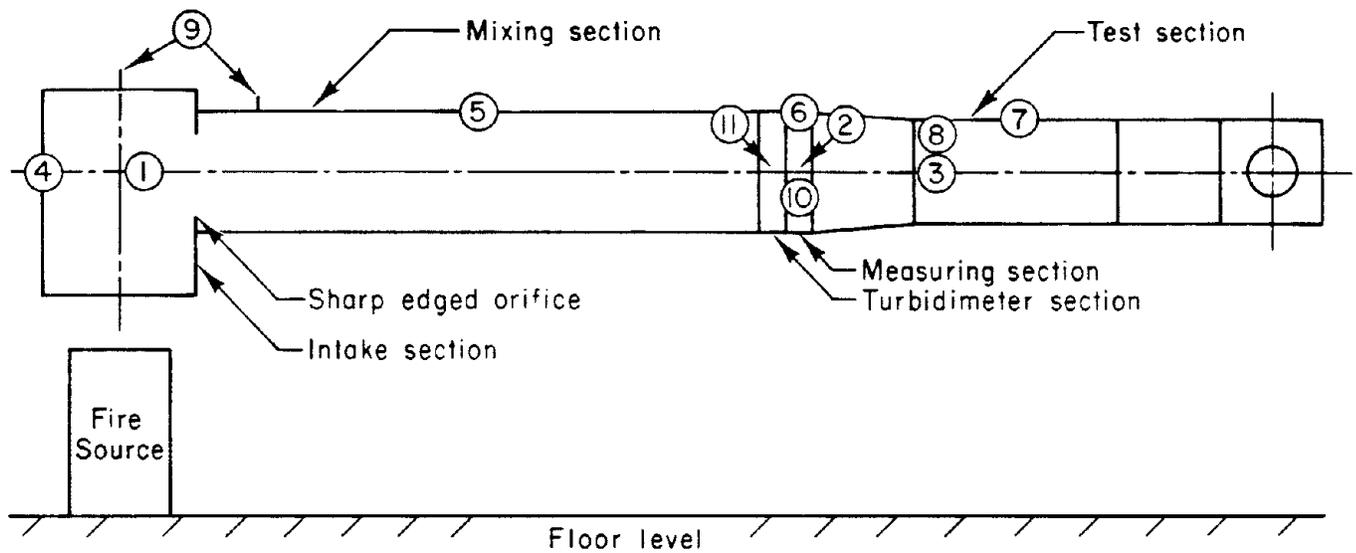


FIGURE 3.- Fire source apparatus



<u>LOCATION</u>	<u>INSTRUMENTATION DESCRIPTION</u>
① - ③	Gas temperatures
④ - ⑦	Wall temperatures
⑧	Pitot - static probe
⑨	Differential pressure transducer
⑩	Gas sampling probe
⑪	Smoke turbidimeter

FIGURE 4.- Duct instrumentation

3.3.1 Gas Temperatures

Gas temperature probes will be located in the intake, measuring and test sections. These probes will be unshielded bare-bead (chromel/alumel type thermocouples) with an inconel sheath.

3.3.2 Wall Temperatures

Wall temperature measurements will be made on the duct surface at four locations - the intake, mixing, measuring and test sections. Ribbon thermocouples (chromel/alumel) will be used for this purpose.

3.3.3 Gas Velocities

The gas velocity profile entering the test section will be determined just upstream of the location of the fire detectors under evaluation. These measurements will be made with a pitot-static probe.

3.3.4 Total Mass And Volumetric Flow Rates

Measurement of the differential pressure across the sharp-edged orifice in the intake section in conjunction with the test section gas temperature will provide a means to determine the total mass and volumetric flow of combustion products through the duct. This will require the pressure measurement to be calibrated against the pitot static tube in the test section.

3.3.5 Gas Species Concentrations

Gas species concentrations will be monitored by a gas sampling probe located in the measuring section. CO and CO₂ will be measured by continuous infrared analyzers; O₂, by a continuous paramagnetic analyzer; and THC, by a continuous flame ionization analyzer. In addition, it is anticipated that H₂O will be measured by a continuous hygrometer.

3.3.6 Optical Densities And Smoke Particle Sizes

Optical densities will be measured by a three-wavelength smoke turbidimeter located in the turbidimeter section. Smoke particle sizes can be assessed by applying Mie-scattering theory to the data obtained from the smoke turbidimeter.



IV

FURTHER RESULTS ON QUANTIFICATION OF MINE FIRE ENVIRONMENTS

Based upon the test results and concepts developed in Phase I, additional analysis has been performed on the quantification of mine fire environments. The major results previously reported in Phase I (1) include: 1) the quantification of the source fire; 2) the prediction to within $\pm 15\%$ of both the average gas temperature rise and gas temperature stratification downstream of the source fire; and 3) the evaluation of the distribution of combustion products relative to the material combustion characteristics. Additional analyses, presented in detail in Reference 3, have extended the Phase I work to provide predictive capabilities necessary to: 1) define the conditions for initiation of flame propagation in materials lining duct (i.e., mine) walls, e.g., wood and coal; and 2) assess the extent of flame propagation. These capabilities are particularly important for determining fire hazard times which are an essential part of the detection criteria defined in Phase I (1).

These analyses use the concept of a nondimensional heat flow parameter (3) $(\dot{Q}_A / \rho_o c_o T_o) / v_o A_f$, abbreviated as HFP, which is essentially the ratio of the heat generation rate of the fire source, \dot{Q}_A , to the volumetric flow rate through the mine cross section, $v_o A_f$. (ρ_o, c_o, T_o are the ambient air density, specific heat and temperature respectively.)

4.1 CONDITION FOR IGNITION

The condition necessary for the ignition of a material can be defined in terms of a critical heat flux for piloted ignition (4,5) which represents the lower limit of the heat flux needed for ignition. The data available in the literature for critical heat flux for a variety of fuels are listed in Table 1.

For mine fires, if it is assumed that, once the critical heat flux condition for ignition has been satisfied, flame propagation processes will be initiated (without specifying the time dependency of the process) then it is possible to predict the initiation of flame propagation in mines. In Reference 3 the condition for material ignition has been analyzed as a function of critical heat flux, \dot{q}_{cr}'' , heat flow parameter, and nondimensional distance downstream of the fire source, l/D_H (where l is the distance downstream and D_H is the hydraulic

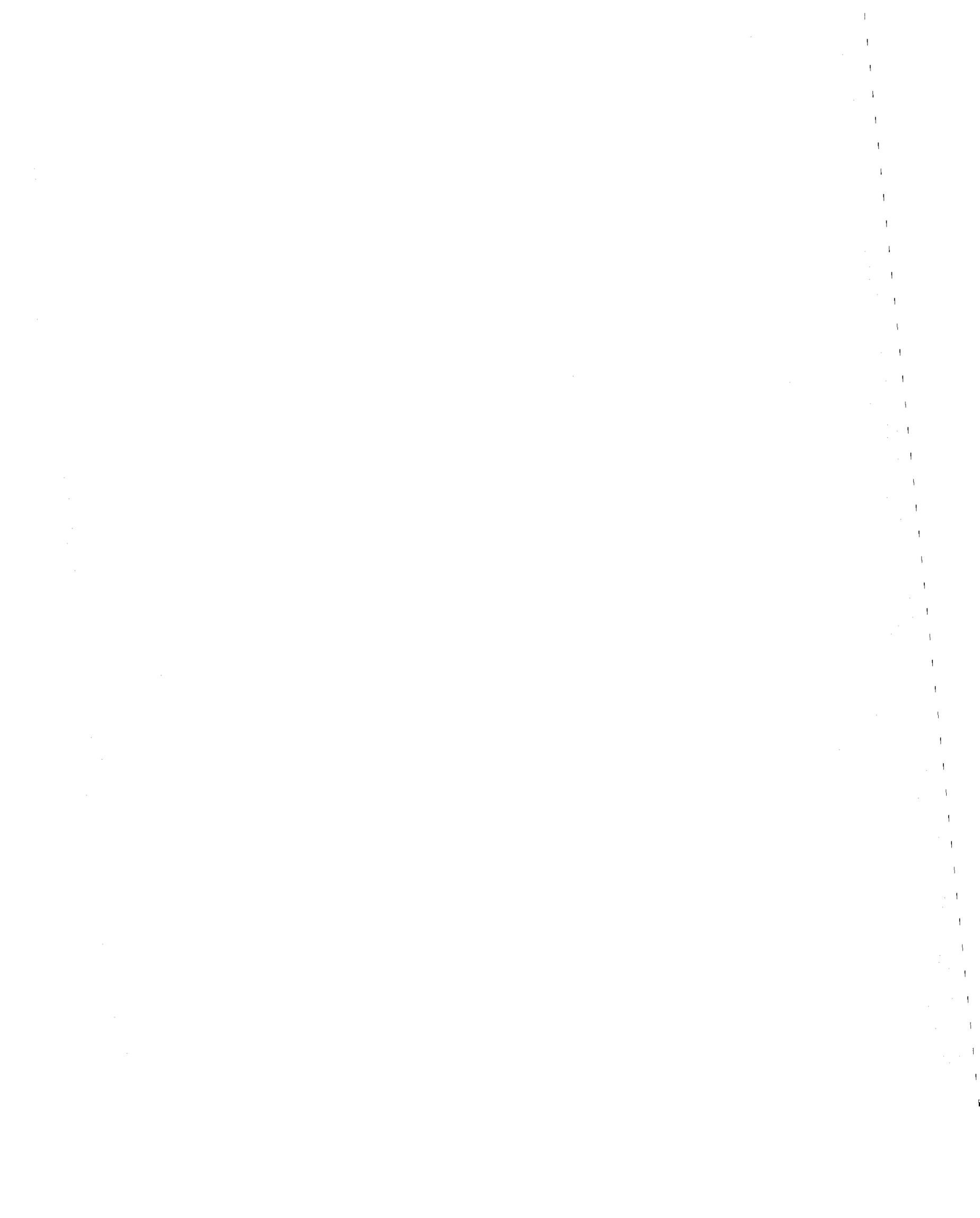


TABLE 1 CRITICAL HEAT FLUX AND TEMPERATURE
FOR IGNITION OF VARIOUS MATERIALS ^a

Material	\dot{q}_{cr}'' (kW/m ²)	T _{cr} (K) ^b
<u>Solid</u>		
Red Oak	16	730
Douglas Fir - Untreated	11	660
NCX	19	760
Intumescent Paint	16	730
Coal	18 ^c	750
<u>Nonaromatic, Granular</u>		
POM	13	690
PMMA	11	660
PP	18	750
PE	15	720
PE/25% C ₂	12	680
PE/36% C ₂	12	680
PE/42% C ₂	10	650
PVC	10	650
<u>Polyurethane Foams</u>		
I-A	16	730
GM-21	16	730
GM-23	19	760
GM-25	19	760
GM-27	19	760
GM-29	22	790
GM-31	22	790
GM-37	22	790
<u>Polystyrene</u>		
Granular	13	690
<u>Foams</u>		
GM-47	12	680
GM-49	13	690
GM-51	12	680
GM-53	13	690

^a data taken from Reference [4]; ^b calculated from $\dot{q}_{cr}'' = \sigma T_{cr}^4$

^c data taken from Reference [6]



diameter of the mine cross section). This relationship is shown in Figure 5. In this figure, the conditions are specified for ignition of a material at a given distance ℓ/D_H from a fire source (with no intervening fuel contribution). The solid lines in the figure represent predicted conditions, while the symbols are the average experimental results with a variation of $\pm 10\%$. An excellent agreement between predictions and measurements can be noted. Table 1, which summarizes critical heat flux and temperature data for ignition of various materials, can be used in conjunction with Figure 5 to predict the ignition of other materials in a mine configuration.

4.2 EXTENT OF FLAME PROPAGATION

Once the condition for ignition has been satisfied, the extent of flame propagation is governed by the heat balance between wall heat losses and heat contributed by the lining materials as a function of distance downstream of the fire source, ℓ/D_H , i.e.,

$$(\text{HFP})_{\text{net}} = \Sigma(\text{HFP}) - (\text{HFP})_{\text{fs}} - (\text{HFP})_{\text{ls}} \quad (1)$$

where HFP is the heat flow parameter; Σ represents the sum of the contributions of the duct lining materials and fire source; subscripts fs and ls indicate the contribution of the fire source and the losses, respectively. An example of the use of eq (1) to determine the extent of flame propagation for timber sets is illustrated in Figure 6, where the ignition of the first timber set occurs via the fire source and propagation then depends upon the relative spacing of timber sets and the heat losses between them. In this figure the net heat flow parameter is plotted versus ℓ/D_H from the fire source for various Douglas fir timber loading densities* and fire-retardant treatments. It is implicit in Figure 6 that the condition for ignition (the minimum heat flow parameter required to obtain the critical heat flux as given in Figure 5) has been met for each specified value of ℓ/D_H . In the figure, the lines represent the flame propagation behavior of the timber sets for complete propagation to the end of the duct, while the symbols are for partial propagation. $(\text{HFP})_{\text{net}}$ was calculated as follows:

* Timber loading density is defined as the ratio of the exposed surface area of the timbers to the surface area of the walls plus ceiling times 100%.

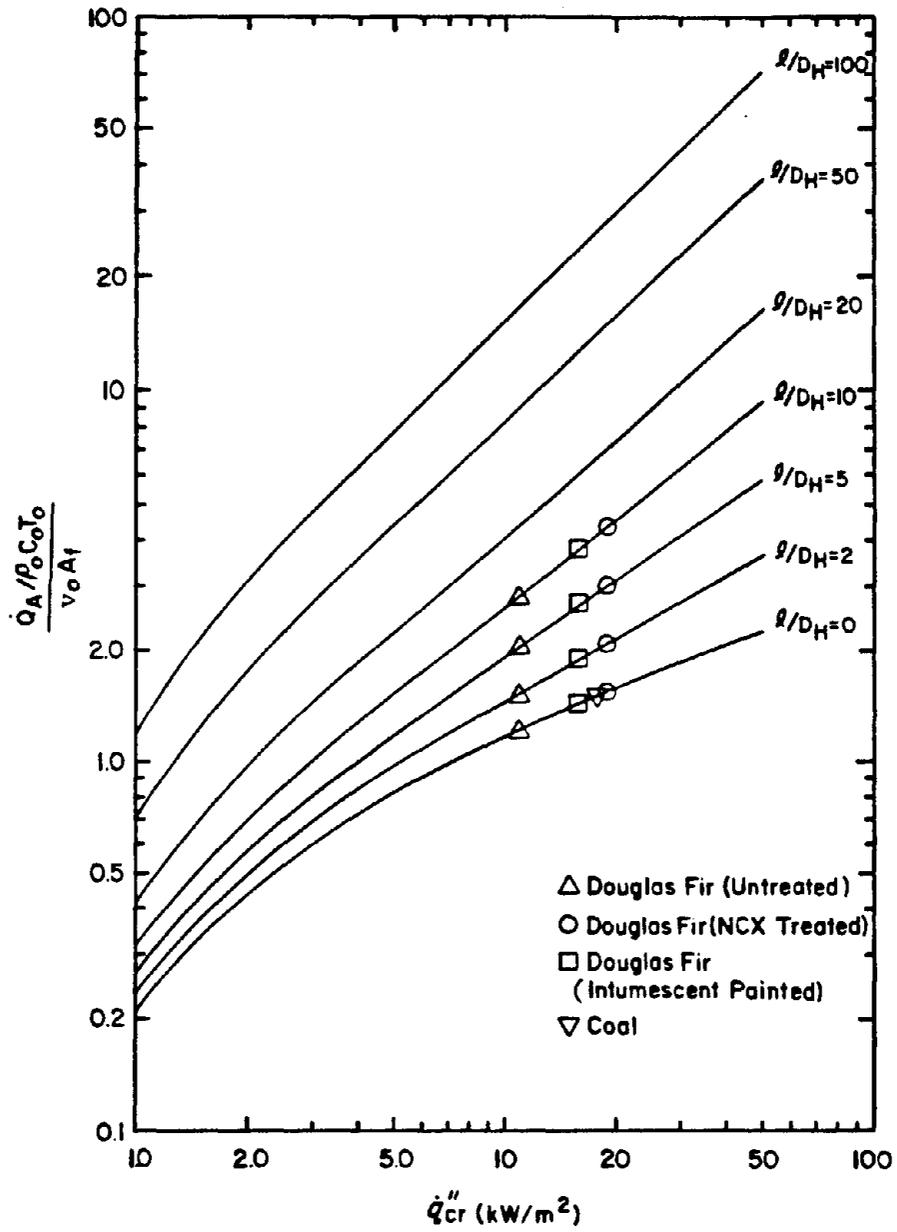


FIGURE 5.- Heat flow parameter versus critical heat flux (from reference 3)

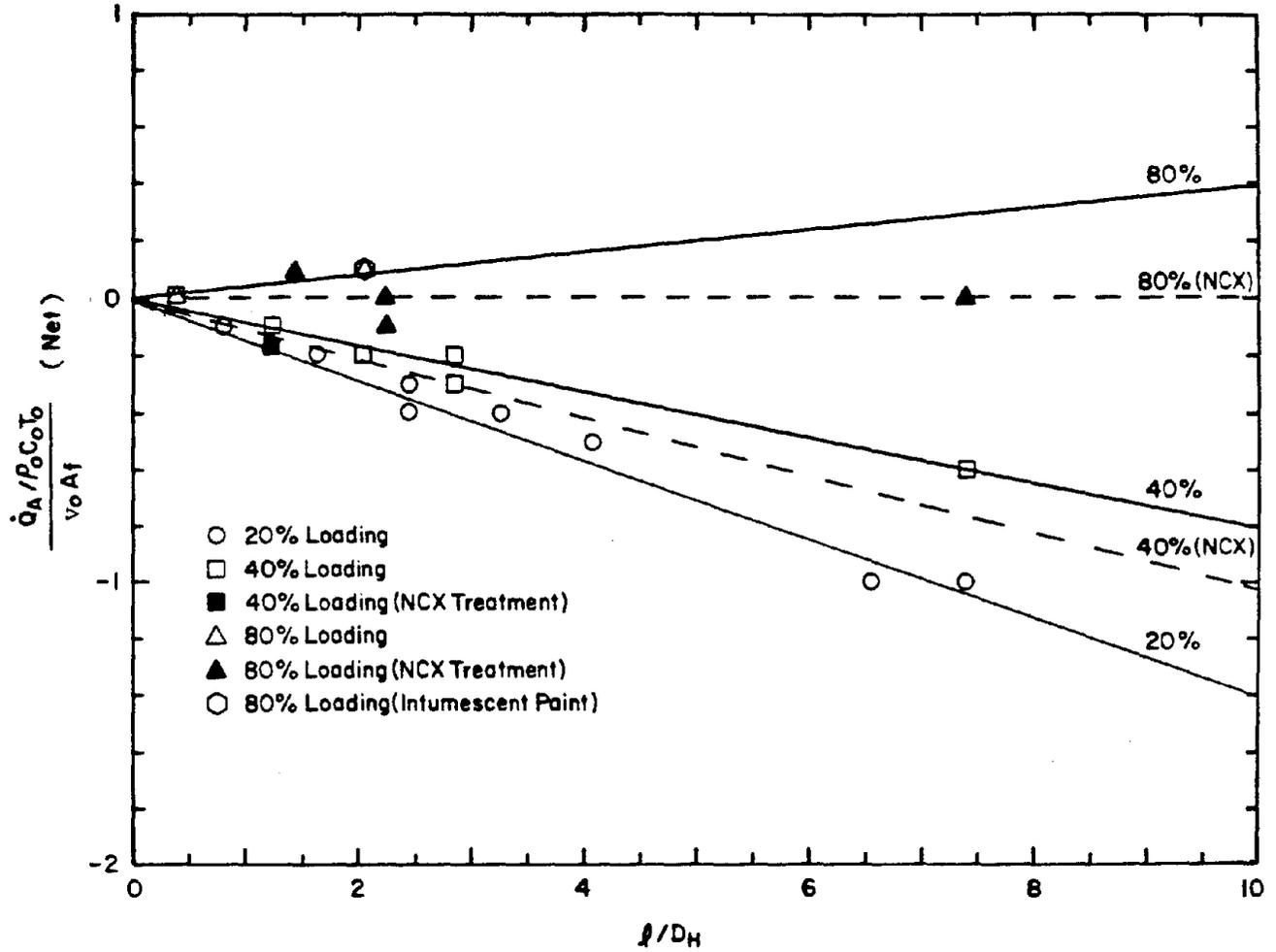


FIGURE 6.- Net heat flow parameter versus nondimensional distance downstream of fire source (from reference 3)

- 1) $\Sigma(\text{HFP})$ was measured for partially as well as completely propagating timber set fires;
- 2) $(\text{HFP})_{fs}$ was separately measured (without timber sets);
- 3) $(\text{HFP})_{1s}$ was obtained from Figure 5 at the critical heat flux values for treated and untreated timber sets as a difference between various l/D_H values.

Both positive and negative values for $(\text{HFP})_{net}$ can be noted in Figure 6. The positive values show self-sustained flame propagation for timber sets, while the negative values are due to source-fire-assisted propagation. Only the 80% loading condition shows self-sustained propagation. However, it should be emphasized that this analysis pertains only to the first propagation. In certain cases, even if the first propagation is partial, subsequent propagations could be complete due to reduced wall losses.

In summary, additional analysis has been performed on the quantification of mine fire environments. The analysis suggests that the condition for ignition or extent of flame propagation for various materials in mines can be defined by the critical heat flux for ignition of the material, a heat flow parameter, and a nondimensional distance downstream of the fire source. The time to reach a fire hazard, previously identified but not quantified as a part of the detection criteria defined in Phase I, can now be assessed from this latest analysis.

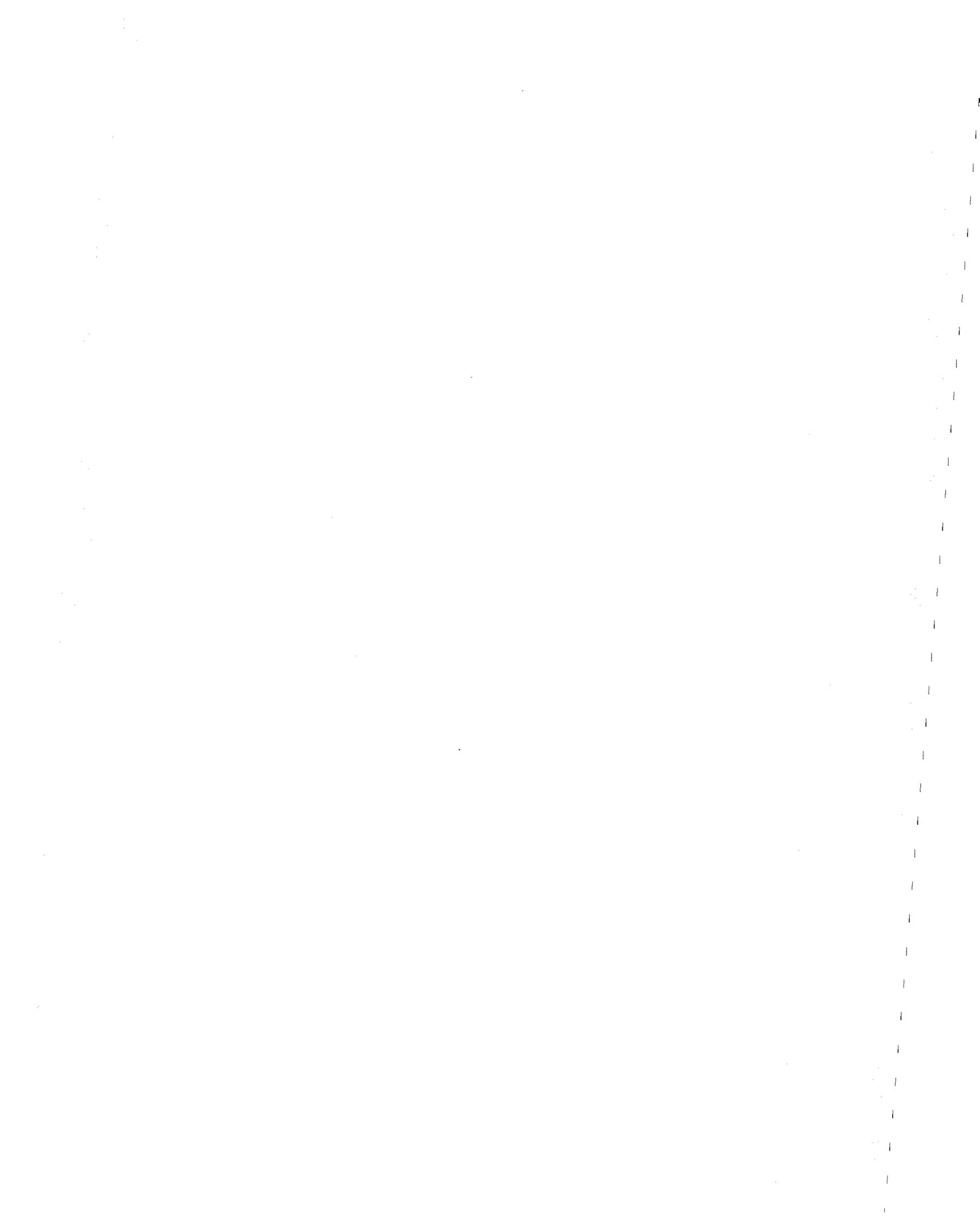
NOMENCLATURE

A_f	flow area of mine passageway (m^2)
c_o	ambient air specific heat ($kJ/kg \cdot K$)
D_H	hydraulic diameter of mine passageway (m)
ℓ	horizontal length of mine passageway from fire source (m)
\dot{Q}_A	actual heat release rate from fire source (kW)
\dot{q}_{cr}''	critical heat flux (kW/m^2)
T_{cr}	critical temperature (K)
T_o	ambient air temperature (K)
v_o	ambient air velocity (m/s)
<u>Greek</u>	
ρ_o	ambient air density (kg/m^3)
σ	Stefan-Boltzmann constant ($56.703 \text{ nW/m}^2 \cdot K^4$)



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2. Newman, J.S., "Procedures For The Performance Evaluation Of Gas Detection Devices Including Preliminary Test Methods," Factory Mutual Research Corporation, Norwood, Mass., Technical Report RC79-T-52, Serial J.I. OC2N4.RC, May 1980.
3. Newman, J.S. and Tewarson, A., "Flame Propagation in Ducts," paper to be published.
4. Tewarson, A., "Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials," Factory Mutual Research Corporation, Norwood, Massachusetts, Serial J.I. OEON6.RC, November 1980.
5. Quintiere, J., "A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus," Fire and Materials 5:52 (1981).
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APPENDIX A

DETAILED DESIGN DRAWINGS

This appendix contains the detailed design drawings for the Test Apparatus (Section III). The component parts of the apparatus are listed in Table A-1 with associated figure numbers.

TABLE A-1
LIST OF DESIGN DRAWINGS

Item No.	Description Of Component	Figure No.
1	Fire Source Apparatus	A-1
2	Intake Section	A-2
3	Mixing Section	A-3
4	Saddle Hanger	
5	Turbidimeter Section	A-4
6	Measuring Section	A-5
7	Transition Section	
8	Test Section Plan And Elevation Views	A-6
	Test Section End View, Window Detail	A-7
9	Transition Ell	A-8

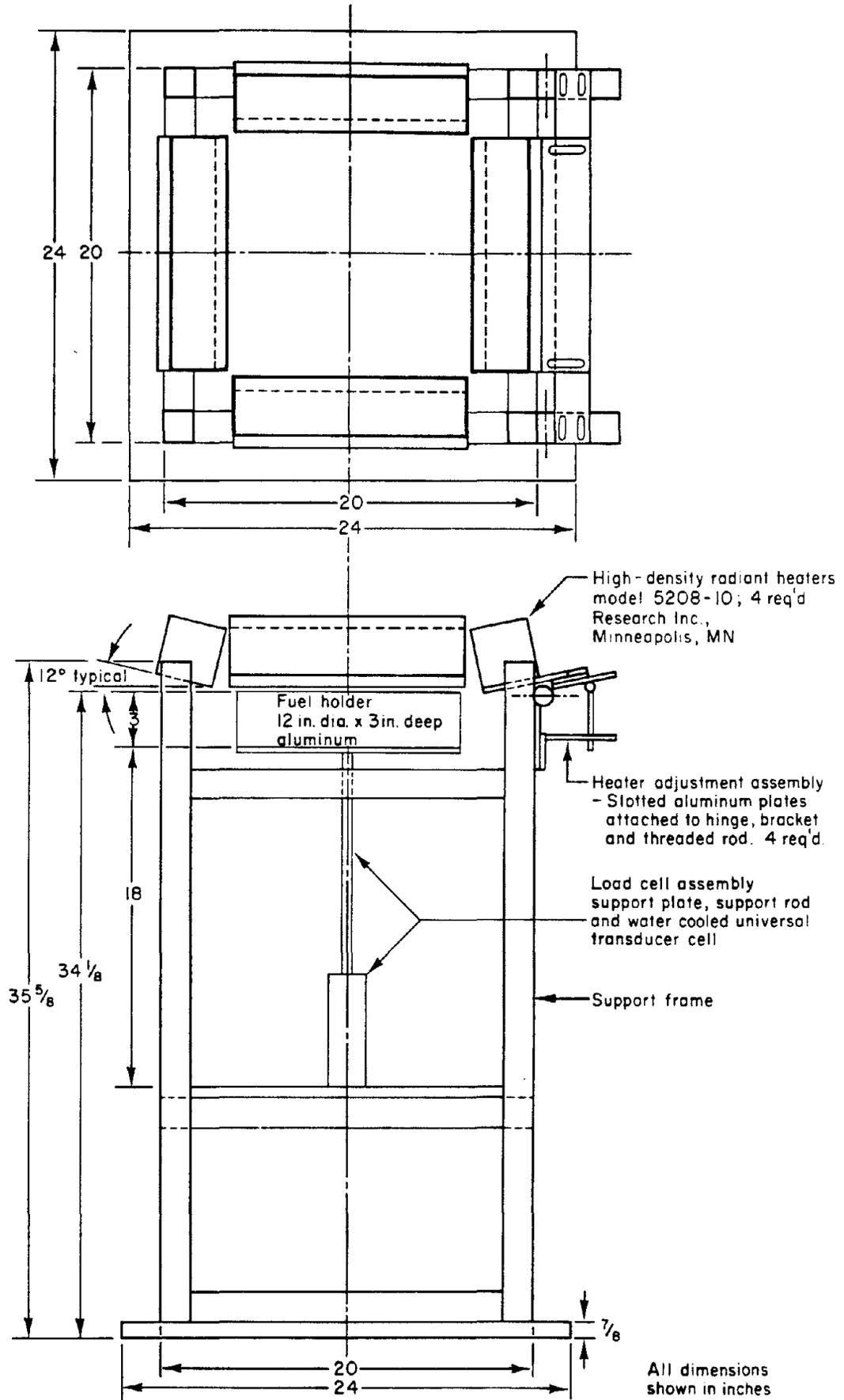
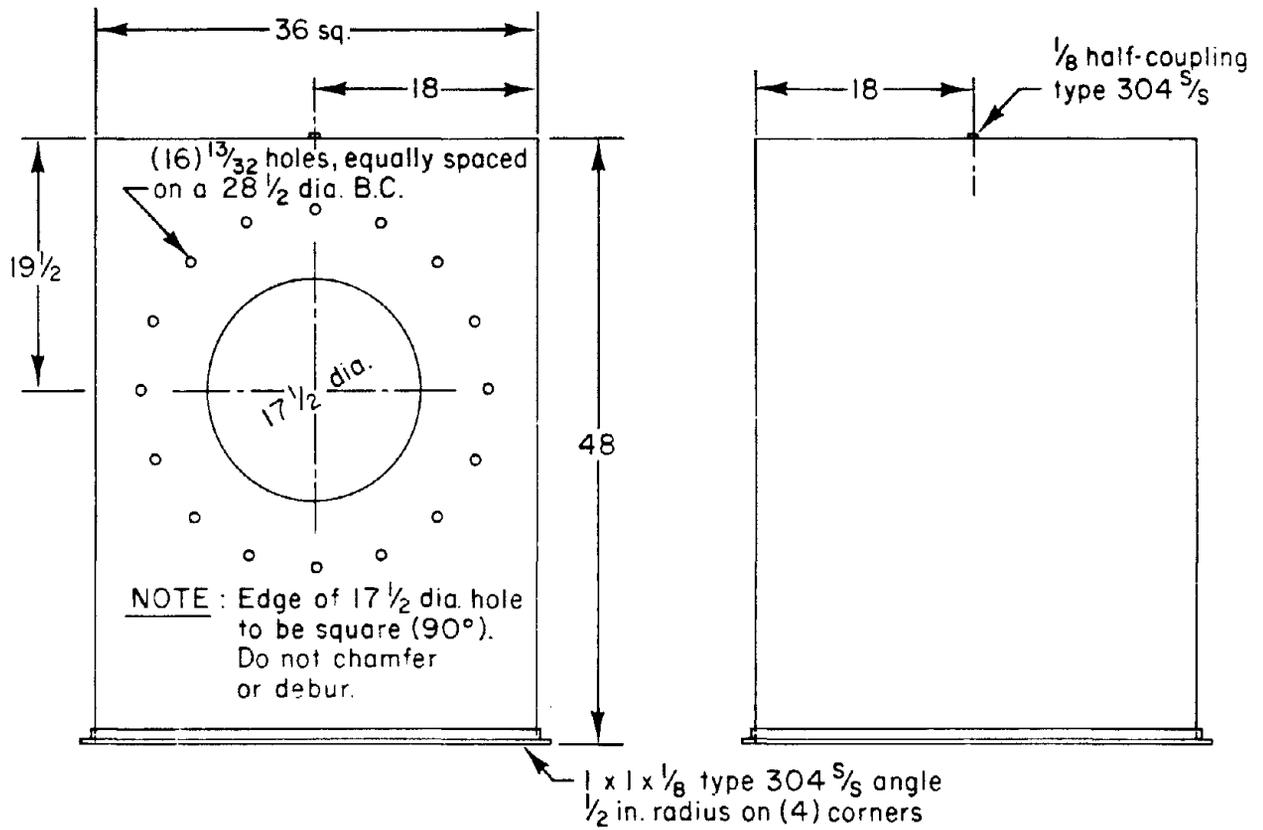


FIGURE A-1.- Fire source apparatus



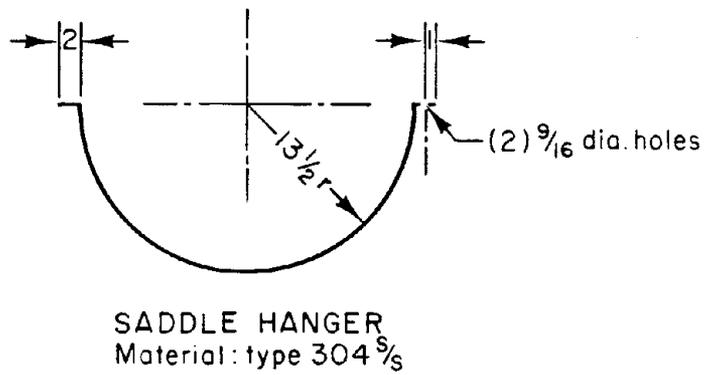
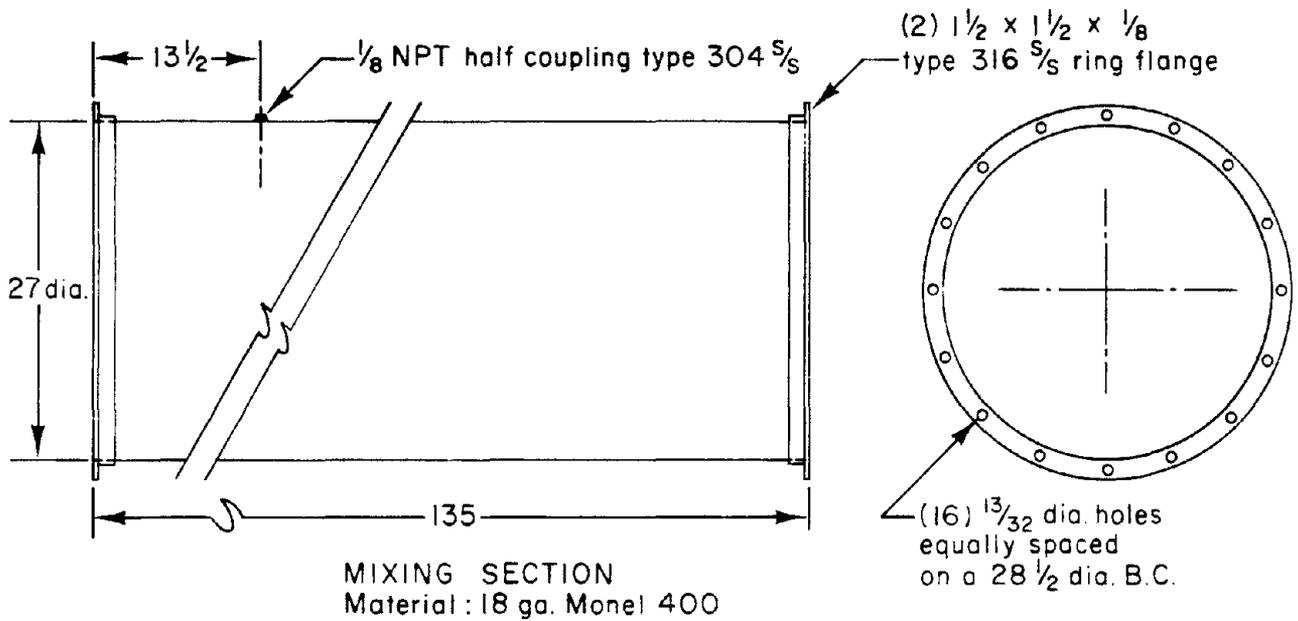


Material : 18 ga. Monel 400

NOTE: All dimensions in inches

FIGURE A-2.- Intake section

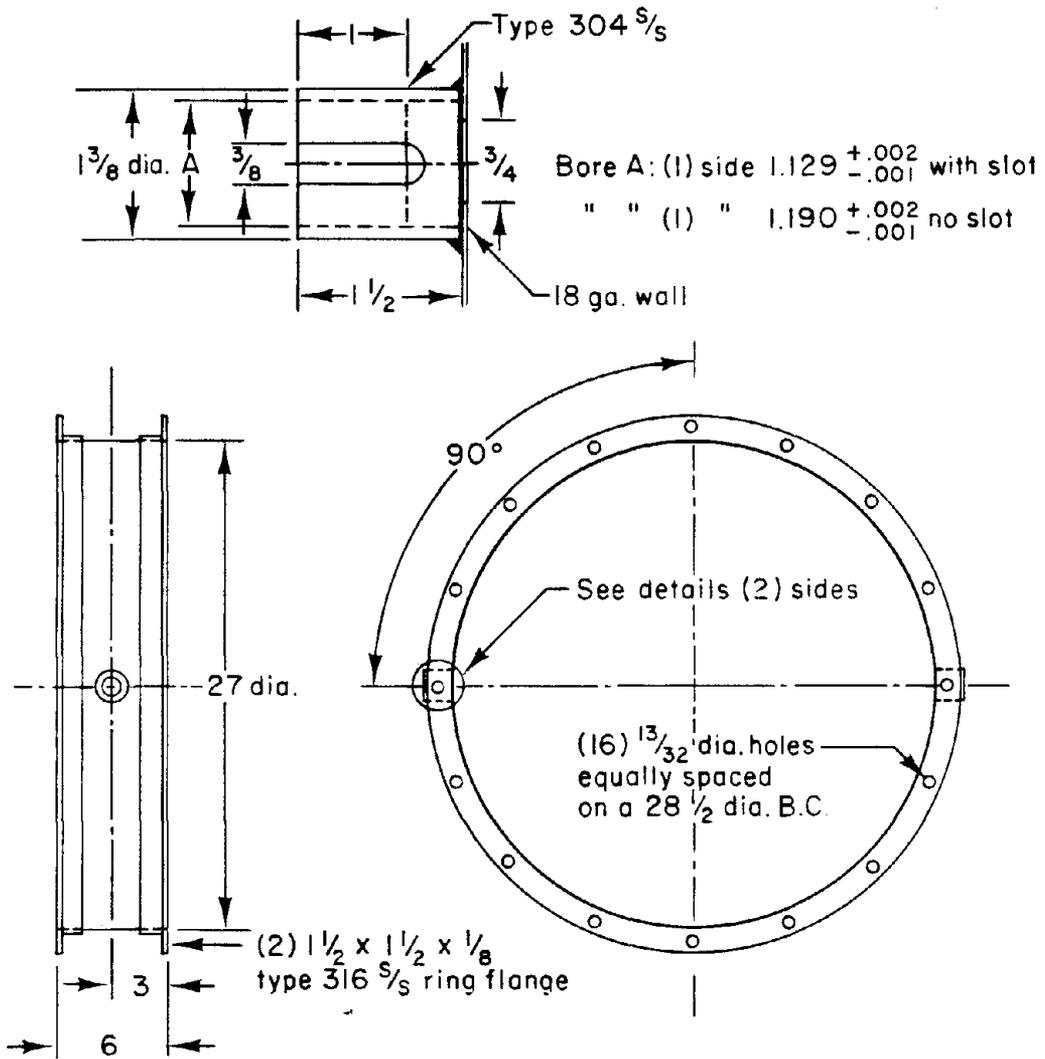




NOTE: all dimensions in inches

FIGURE A-3.- Straightening section and saddle hanger





NOTE : All dimensions in inches

FIGURE A-4.- Turbidimeter section

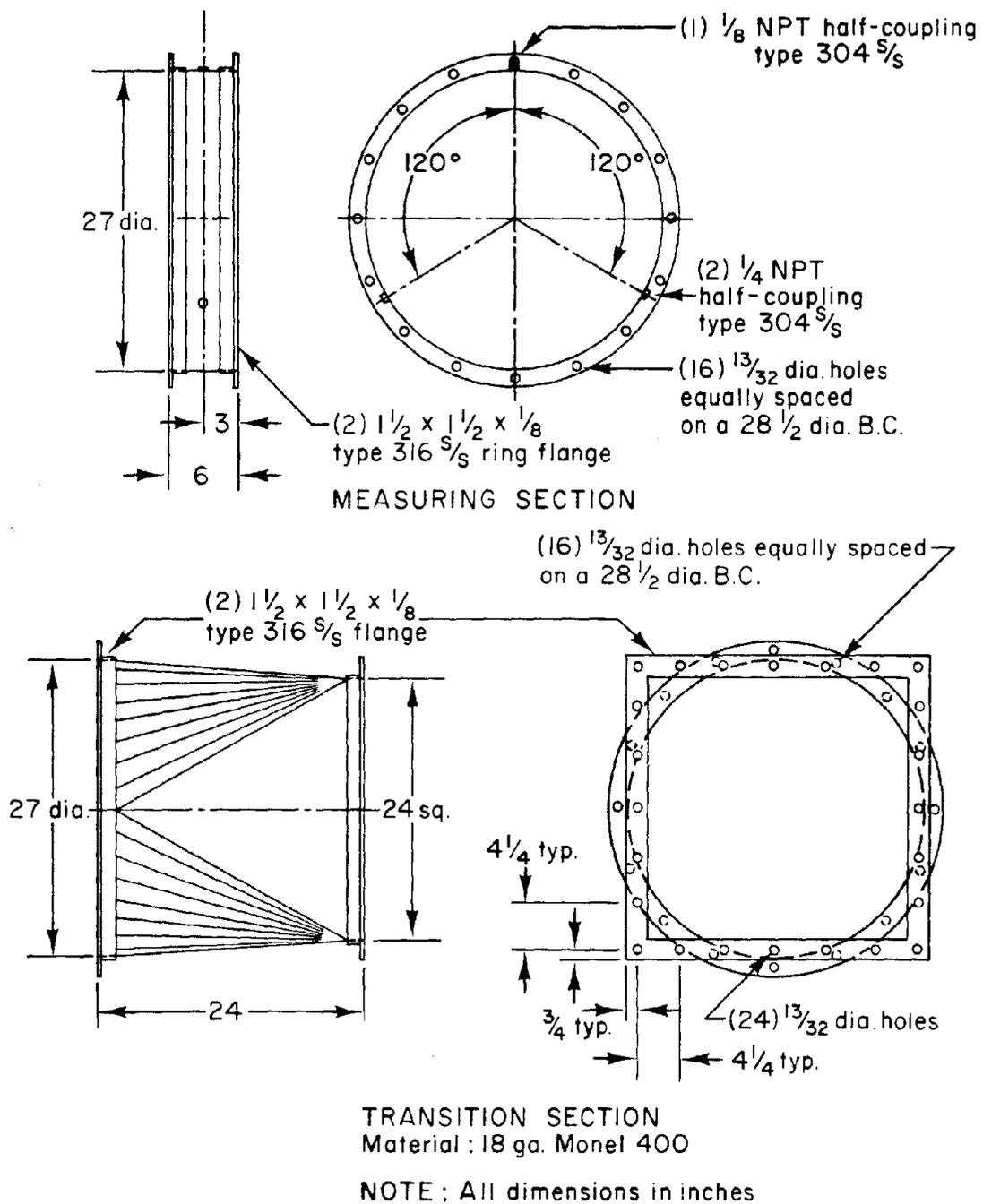
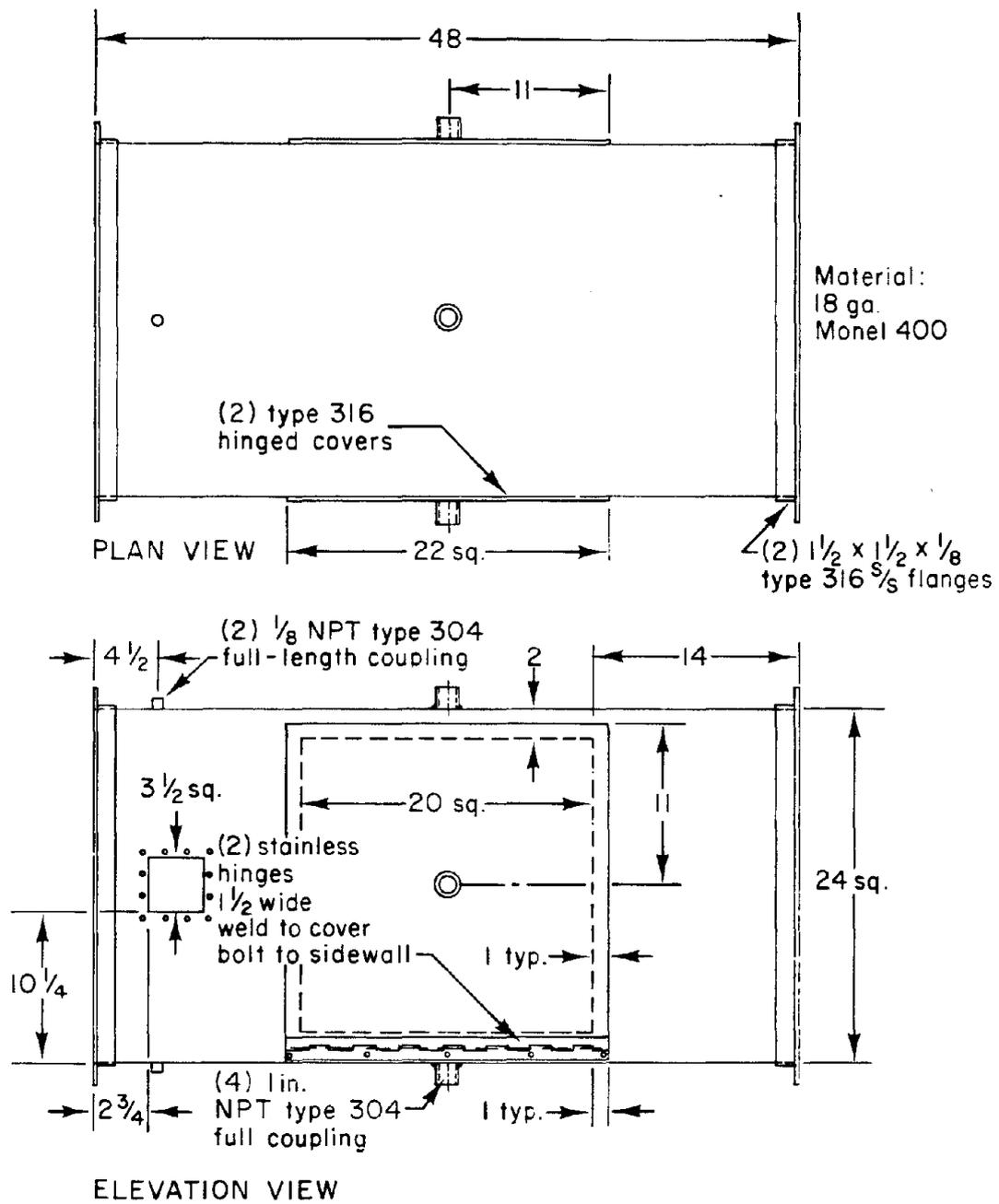


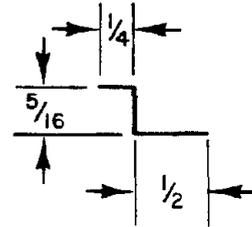
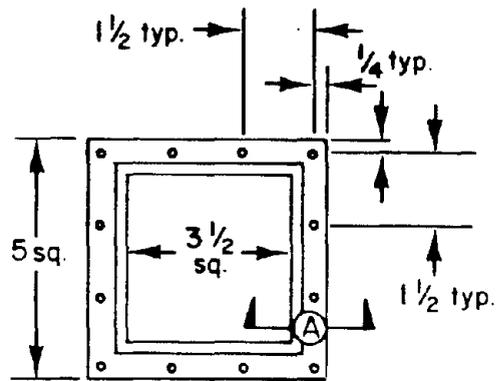
FIGURE A-5.- Measuring and transition sections





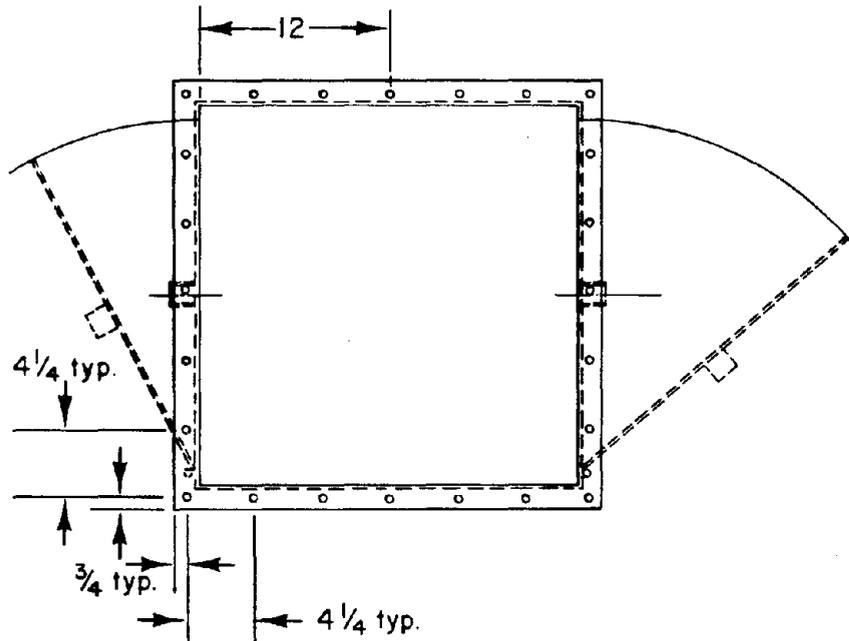
NOTE: All dimensions in inches

FIGURE A-6.- Test section - plan view - elevation view



WINDOW DETAIL

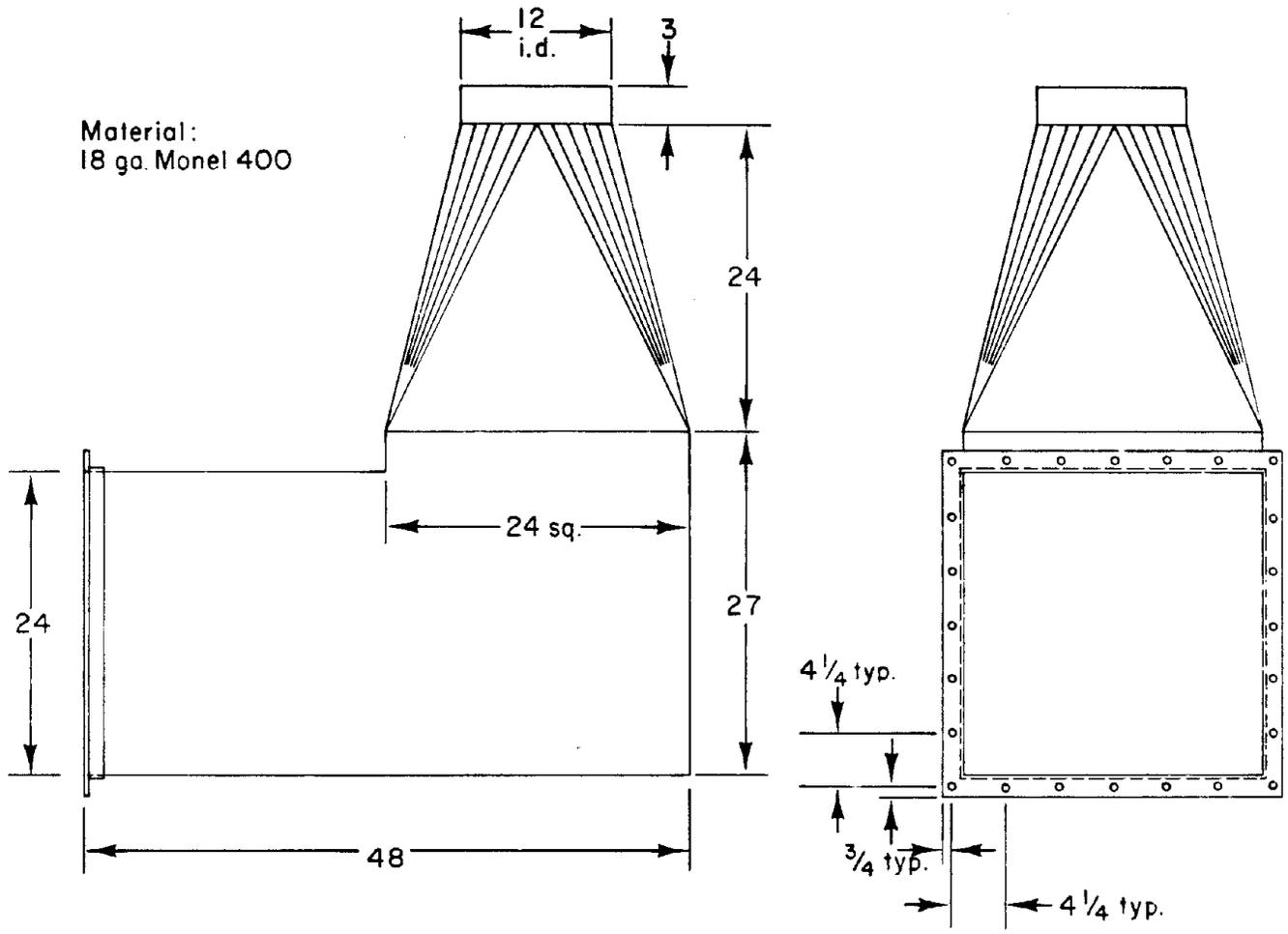
Ⓐ CROSS SECTION THRU FRAME
Material: 18 ga. Monel 400



END VIEW

NOTE
All dimensions in inches

FIGURE A-7.- Test section - window detail - end view



NOTE : All dimensions in inches

FIGURE A-8.- Transition ell



APPENDIX D

PHASE III REPORT

STANDARD TEST CRITERIA FOR EVALUATION OF UNDERGROUND FIRE DETECTION SYSTEMS

Prepared for

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

By

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Phase III Report

Contract No. H0113017

December 1983



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REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.
4. Title and Subtitle Standard Test Criteria For Evaluation of Underground Fire Detection Systems-Phase III		5. Report Date December 30, 1983	
7. Author(s) Jeffrey S. Newman		6.	
9. Performing Organization Name and Address Factory Mutual Research Corporation 1151 Boston-Providence Turnpike Norwood, Mass. 02062		8. Performing Organization Rept. No. J.I. OG2N4.RC	
12. Sponsoring Organization Name and Address U.S. Department of The Interior Bureau of Mines		10. Project/Task/Work Unit No.	
		11. Contract(C) or Grant(G) No. (C) H0113017 (G)	
		13. Type of Report & Period Covered Phase III Report 1983-November 19, 1983	
		14.	
15. Supplementary Notes			
16. Abstract (Limit: 200 words) This report presents the results of the third of a four-phase effort conducted for the Bureau of Mines to evaluate underground mine fire detection systems. The major accomplishments of Phase III are: 1) the construction, operation, and calibration of a fire test apparatus for evaluating mine fire detectors; 2) the quantification of several mine fire sources; and 3) the evaluation of several fire detector types including heat and CO gas detectors.			
17. Document Analysis a. Descriptors Fire Detectors Mine Fire Hazards Test Criteria b. Identifiers/Open-Ended Terms c. COSATI Field/Group			
18. Availability Statement Availability Unlimited		19. Security Class (This Report) Unclassified	21. No. of Pages 46
		20. Security Class (This Page) Unclassified	22. Price

FOREWORD

This report was prepared by Factory Mutual Research Corporation (FMRC), Factory Mutual System, Norwood, Massachusetts under USBM Contract No. H0113017. It was administered under the technical direction of the Pittsburgh Research Center with Dr. A.F. Cohen acting as Technical Project Officer. Mr. A.G. Young was the contract administrator for the Bureau of Mines. The report is a summary of the work recently completed as part of this contract during the period January 1, 1983 to November 19, 1983. This report was submitted by the author on December 30, 1983.

The author wishes to acknowledge gratefully the following persons who contributed to this project: Mr. W.R. Brown, Mr. D.S. Mann and Mr. J.R. Brown, for extensive contributions to the construction of the test apparatus; Mr. S.D. Ogden and Ms. J.A. Steciak for assistance in data acquisition and analysis, Dr. A.F. Cohen, Dr. G. Heskestad and Dr. A. Tewarson, for valuable contributions; and Mr. L.A. Post and Mrs. H.G. Hurley for their efforts in producing this report.

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INTRODUCTION

1.1 SUMMARY OF PHASE III

This report details the efforts of Phase III of a four-phase approach to establishing standard test criteria for the evaluation of underground mine fire detection systems. The objectives of Phase III were to: 1) construct and calibrate the fire test apparatus designed in Phase II for detector evaluation; 2) quantify potential fire sources; and 3) evaluate the response of selected fire detectors relative to the fire sources.

The test apparatus is a wind tunnel arrangement capable of directly evaluating detector response versus simulated mine fire environments for up to four detectors simultaneously with: 1) variable fire source intensity up to a maximum of ~100 kW; 2) a variety of materials in configurations up to 0.3 m x 0.3 m x 0.15 m high; and 3) ventilation air velocities up to 6.1 m/s (1200 ft/min).

Measured velocity and gas concentration profiles in the test apparatus confirmed that the flow entering the test section was well-mixed. Calibration tests, performed with premixed methane burners, showed that the overall accuracy of the test apparatus was $\pm 3\%$.

Fire characteristics of several fire sources, including Pittsburgh seam coal, Styrene-Butadiene (SBR) fire retardant treating conveyor belting, heptane and polystyrene, were quantified. These characteristics included: mass loss rates, critical heat fluxes, heat generation rates and various gas species generation rates. In particular, the combustion of coal, which is particularly difficult to characterize due to extensive surface char formation, was effectively quantified using a theoretical/analytical model which has not been previously verified experimentally.

Several heat detector types were evaluated using a "plunge" test to measure the response time index (RTI). RTI is nearly a constant for a given heat detector under various conditions of use and is given by the product of the time constant, τ , and the square root of the gas velocity, v ; i.e., $RTI = \tau v^{1/2}$. The values of RTI for the three "mine-permissible" sensors tested varied by more than a factor of 30, from a low (i.e., fast response) of $12 (m \cdot s)^{1/2}$ to a high (i.e., slow response) of $382 (m \cdot s)^{1/2}$.

Two types of CO gas detectors were evaluated using the fire test apparatus; one made by Energetics Science (Ecolyzer Model 5100) and the other made by Mine Safety Appliances (MSA/BUMINES prototype transducer). Both systems were shown to respond accurately and reliably to the mine fire sources tested. Their response times are well characterized by a time constant and a lag time.

Finally, additional testing is contemplated in Phase IV to further investigate both CO detector types as well as other sensor detection principles.

1.2 OBJECTIVE AND SCOPE

The objective of this project is to develop standardized test criteria and procedures which will assure that fire detectors selected for installation in mines will:

- 1) be reliable in operation;
- 2) be located in the most effective position; and
- 3) function routinely with minimal maintenance.

1.3 TECHNICAL APPROACH

The technical approach developed to meet the objective within the scope of this project consists of four distinct phases. This report addresses the results from the Phase III work effort. The following paragraphs outline the approach followed in Phases I, II and III accompanied by a brief discussion of the work elements expected to be accomplished in Phase IV.

Phase I

The Phase I effort (1) was primarily directed toward identification and acquisition of the data necessary to establish preliminary standard test criteria for mine fire detectors. This included: 1) review of pertinent literature; 2) gathering and analysis of FMRC's existing experimental data on fire environments and fire detector response characteristics; 3) identification of data gaps (if any); and 4) performance and analysis of additional fire tests (if required).

Phase II

A detailed design of a sensor evaluation test program and associated test apparatus was prepared under this work phase (2). The developed test program

is capable of evaluating detector spacing requirements referenced to Title 30 Code of Federal Regulations as influenced by fire and environmental parameters of an underground mine. Practical limits for evaluation were defined in this phase of the program. Detailed engineering drawings including suppliers were prepared for a fire test apparatus to be developed for detector evaluation purposes. In addition, the rationale for the design of the apparatus and component selection was provided in this work phase.

Phase III

The test apparatus designed by FMRC and approved by the Bureau under Phase II was constructed. The test apparatus was calibrated by using measured velocity and gas concentration profiles and well-defined fire sources (premixed methane burners and methanol pan fires). In addition, several other fire sources were evaluated: Pittsburgh seam coal, SBR (styrene-butadiene rubber) conveyor belt-ing, heptane, and polystyrene.

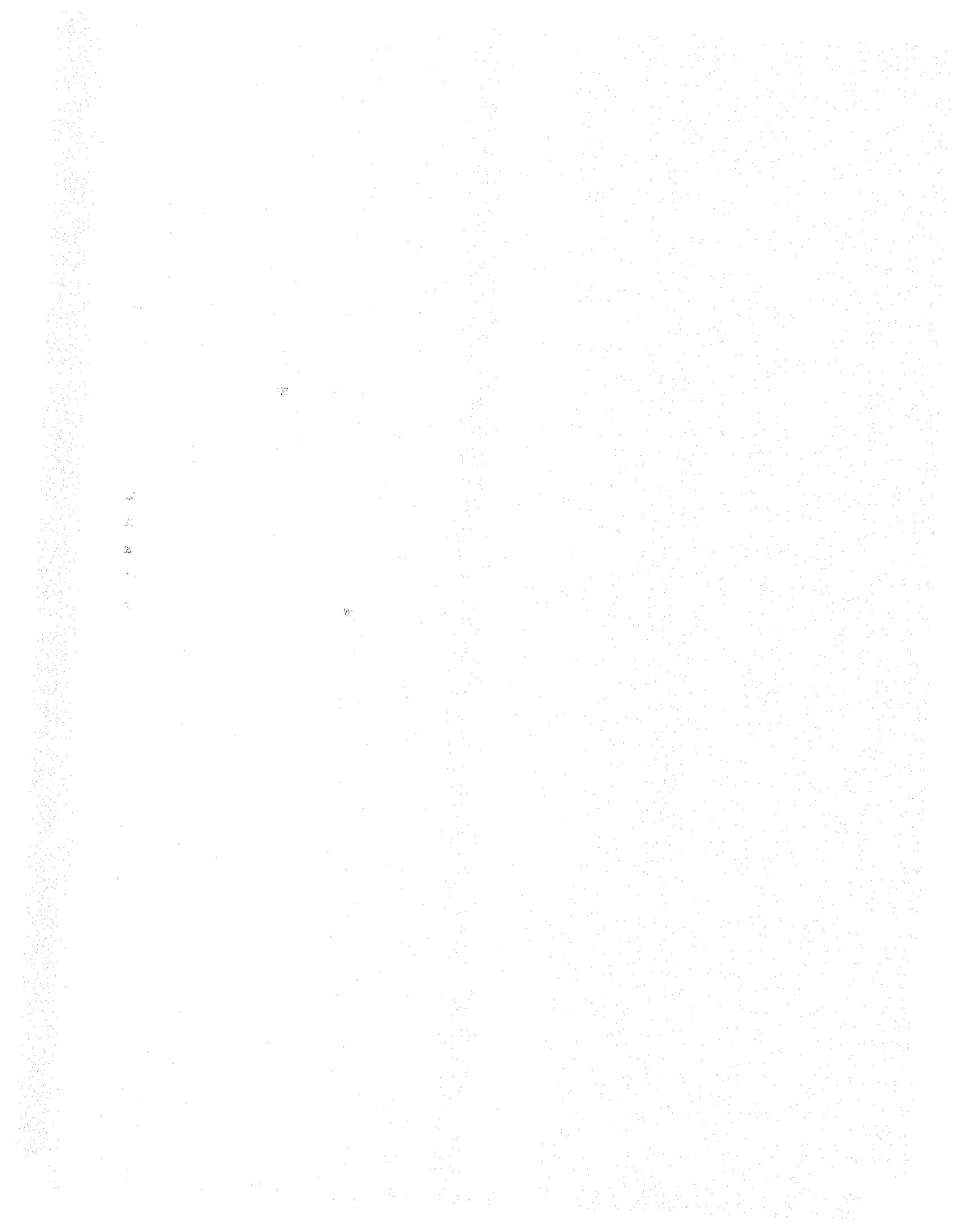
Five different models of fire detectors were evaluated. These consisted of three models of heat detectors and two carbon monoxide detection systems.

Phase IV

Within this phase fire and environmental performance specifications for the acceptance of mine fire detection sensors and sensing systems will be developed. The developed standards will specify optimum sensor spacing capability as related to Title 30 Code of Federal Regulations Paragraphs 75-1103-4, 75-1103-10 and will also specify the environmental conditions under which detectors used for mine applications must operate. This specification will include any special conditions and practices which should be followed by detector installers.

Also within this phase at least two additional types of fire detection systems will be evaluated based upon the Phase II results. This evaluation will be coupled with the development of a response theory for the various types of detectors.

Finally, such a broad work effort will probably indicate technology gaps in the field of detector behavior and installation. These areas will be evaluated for the need of future research work. The results of this evaluation will be presented in comment form providing the rationale for the identified research and a program plan indicating the magnitude of funding and manpower required to accomplish the proposed research efforts.



II

CONSTRUCTION, OPERATION AND CALIBRATION OF THE TEST APPARATUS

The test apparatus configuration is shown in Figures 1 and 2. Detailed design drawings are given in Reference 2. The apparatus consists of essentially two parts: 1) a fire source apparatus, and 2) a duct work fabricated from 18 B&S gage monel 400 metal for combustion product collection and distribution.

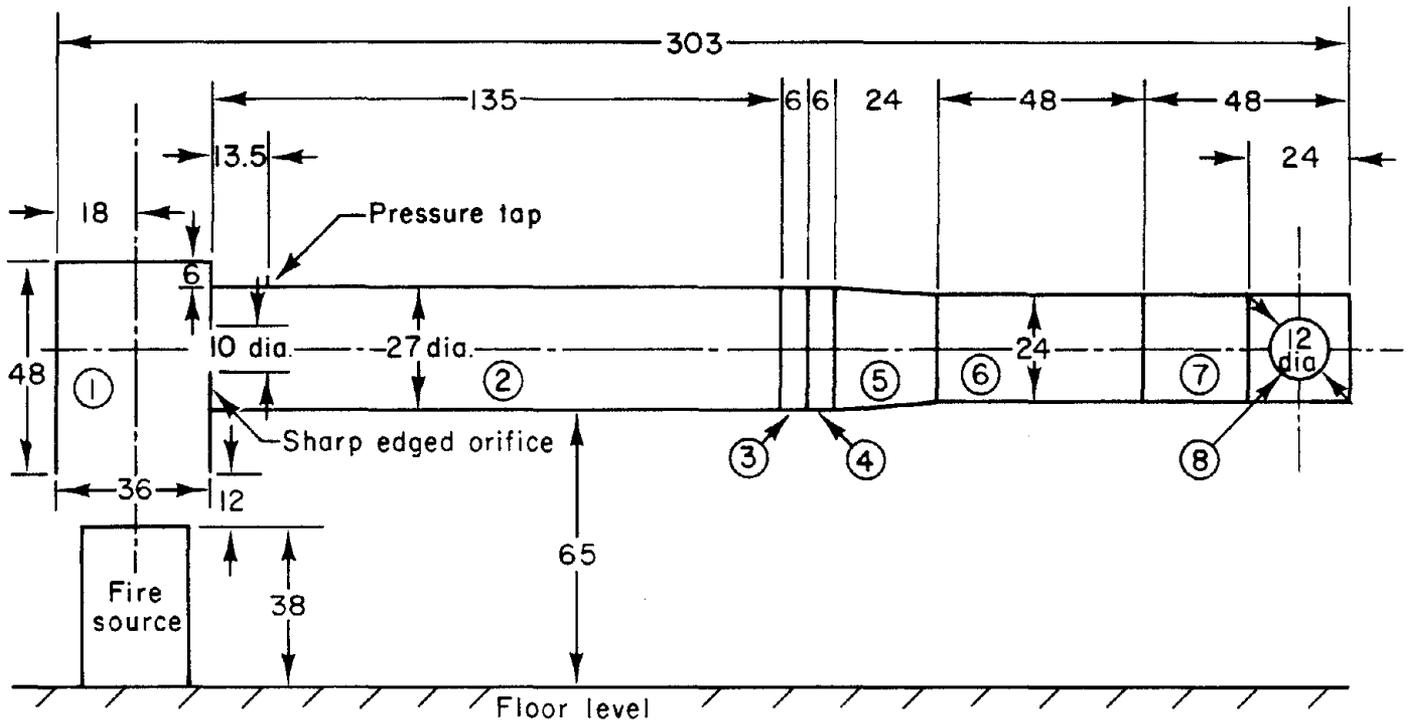
2.1 CONSTRUCTION

Construction of the test apparatus followed closely the original design drawings. However, two design changes have been made:

1) a sharp-edged, 10-in. dia, stainless-steel orifice plate was added to the front of the mixing section (see Figure 1) changing the orifice diameter from 17.5 in. to 10 in. This modification significantly improved the mixing in the duct; and 2) a 10-in. dia x 24-in. long quartz tube was added to the fire source apparatus (see Figure 2) between the radiant heaters and the fuel holder. This addition eliminated possible effects on the combustion of the fuel sample due to air jets produced from the large air-cooling requirements of the heaters.

2.2 OPERATION

In operation, all the combustion products (i.e., materials typical of a mine environment) generated by the fire source together with room air were drawn into the intake section (see Figures 1 and 3) by a downstream exhaust blower. After passing through the intake section, the total mass flow of combustion products and room air mixture, in proportion to the setting of the blast gate, flowed through the orifice plate positioned at the upstream end of the mixing section. Gas concentration data for determination of mass generation rates of CO, CO₂, H₂O, and total hydrocarbons, together with associated temperatures, were collected at the "measuring section," while the average gas velocity was determined by measuring the differential pressure across the upstream orifice plate. Measurements of gas as well as duct wall temperatures were also obtained. The "test section" was suitable for testing up to four fire detectors at one time. Test section view ports provided for visual observation, and separate ports for gas flow velocity and temperature probes were also included. After



NOTES :

All dimensions in inches

- | | |
|-------------------------------------|--|
| ① Intake section (square duct) | ⑤ Transition section (round to square) |
| ② Mixing section (round duct) | ⑥ Test section (square duct) |
| ③ Turbidimeter section (round duct) | ⑦ Transition ell (square to round) |
| ④ Measuring section (round duct) | ⑧ Blast gate (stock type 12 in.) |

FIGURE 1.- Test apparatus schematic (elevation view)

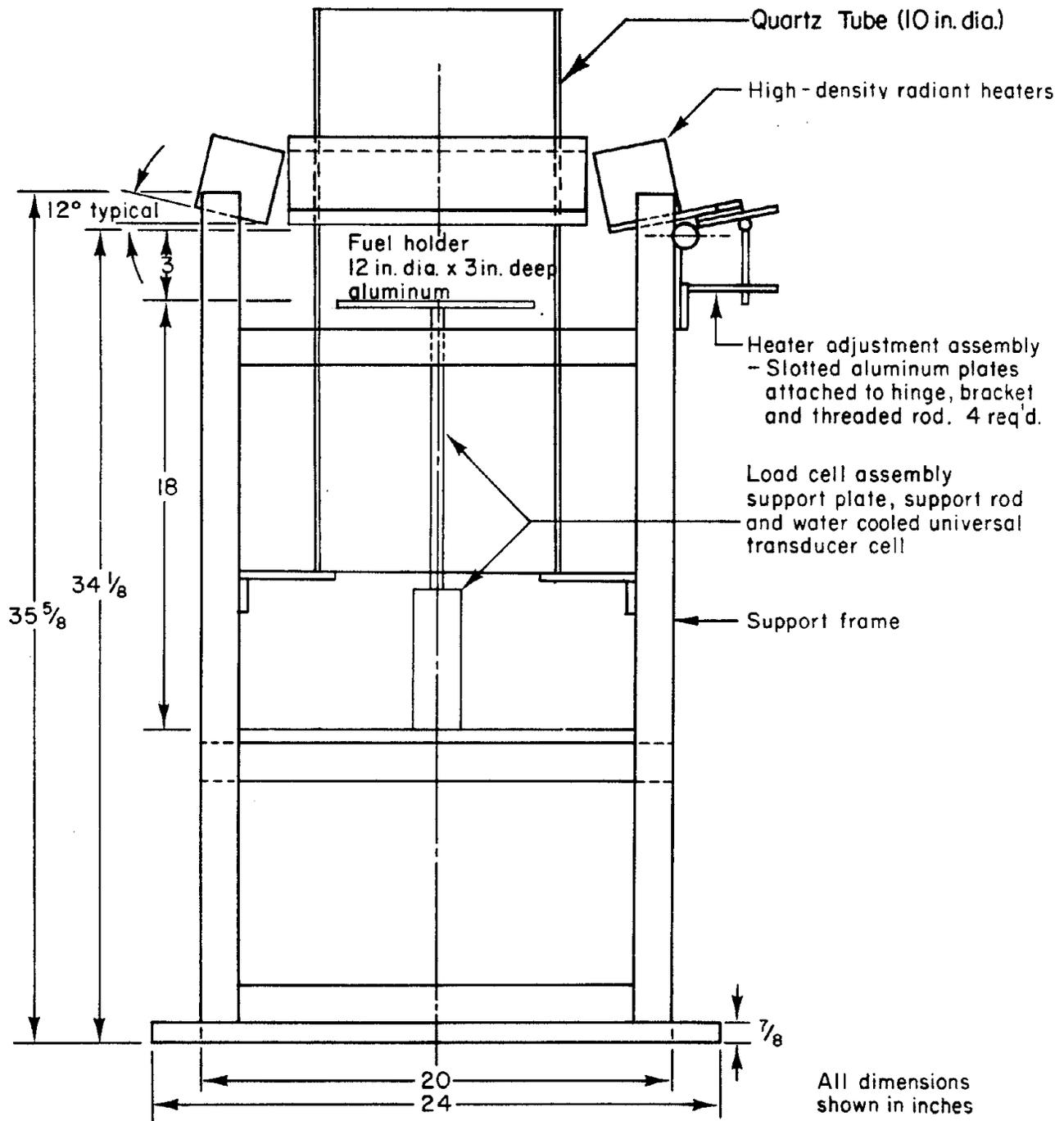
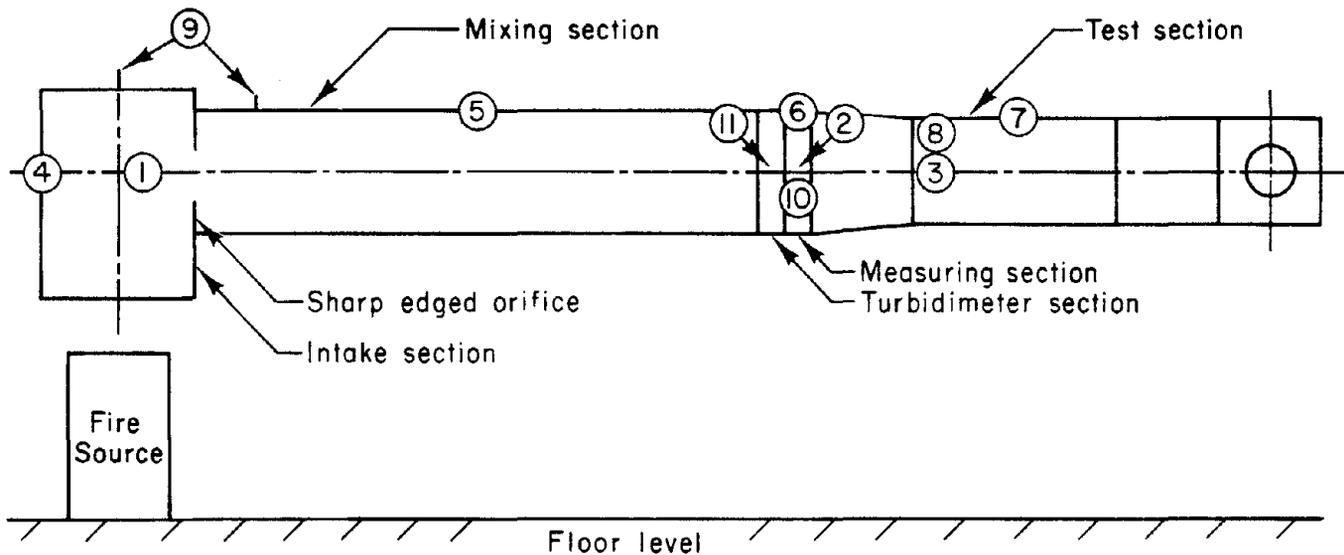
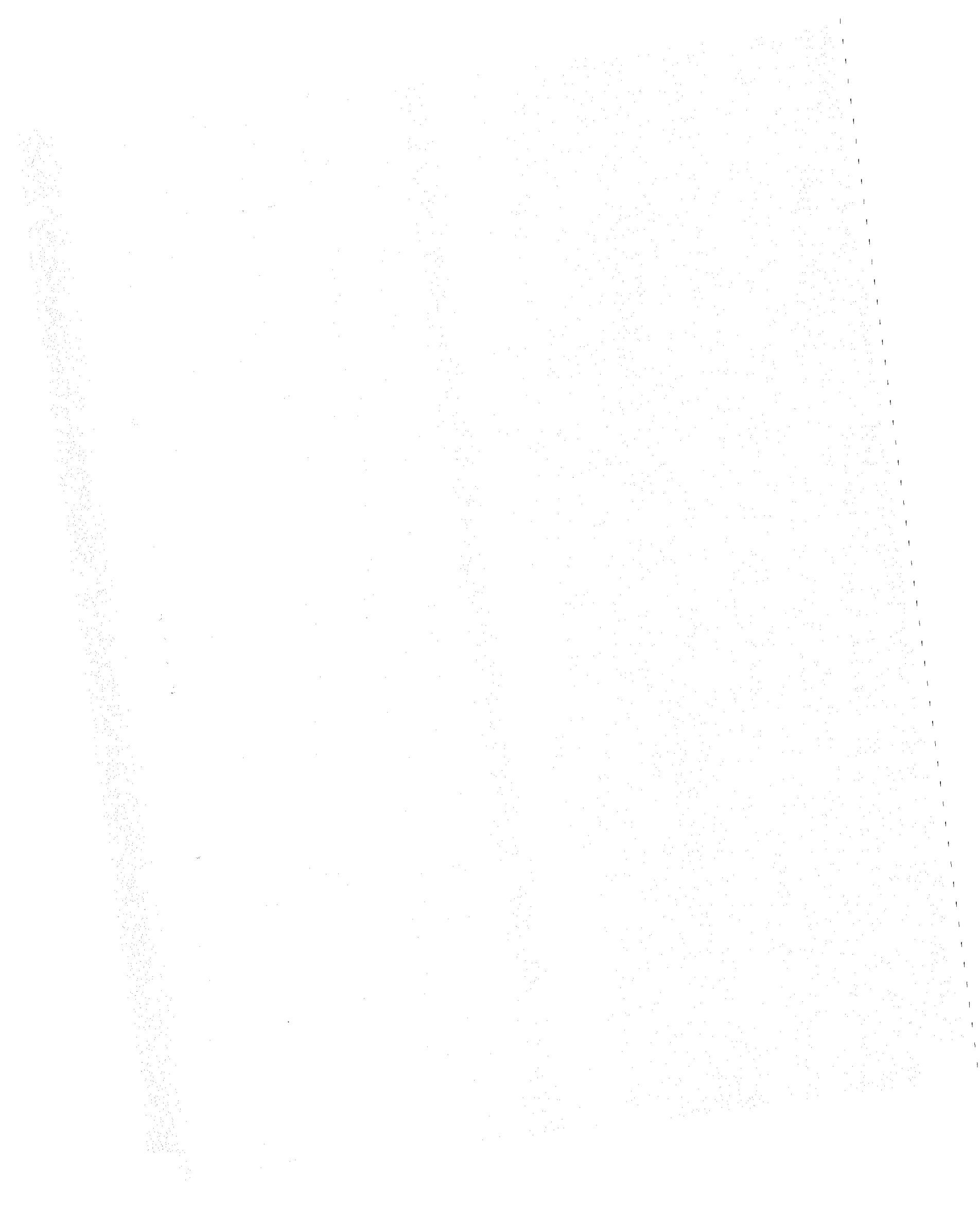


FIGURE 2.- Fire source apparatus



<u>LOCATION</u>	<u>INSTRUMENTATION DESCRIPTION</u>
① - ③	Gas temperatures
④ - ⑦	Wall temperatures
⑧	Pitot - static probe
⑨	Differential pressure transducer
⑩	Gas sampling probe
⑪	Smoke turbidimeter

FIGURE 3.- Duct instrumentation



passing through the test section, the gas flowed through the transition ell and was exhausted through the blast gate and outlet duct to the exhaust blower.

The fire source apparatus was capable of generating products of combustion from a variety of fuels typical of those found in an underground mine environment, e.g., coal, conveyor belting, flammable liquids, etc. In addition, the amount of combustion products generated by a specific fuel was adjustable by: 1) varying the surface area of the fuel up to a maximum of 0.3 m x 0.3 m (12 in. x 12 in.) or typically 0.2 m x 0.2 m (8 in. x 8 in.) with the quartz tube in place; and 2) varying the external heat flux applied to the fuel surface up to a maximum of approximately 85 kW/m².

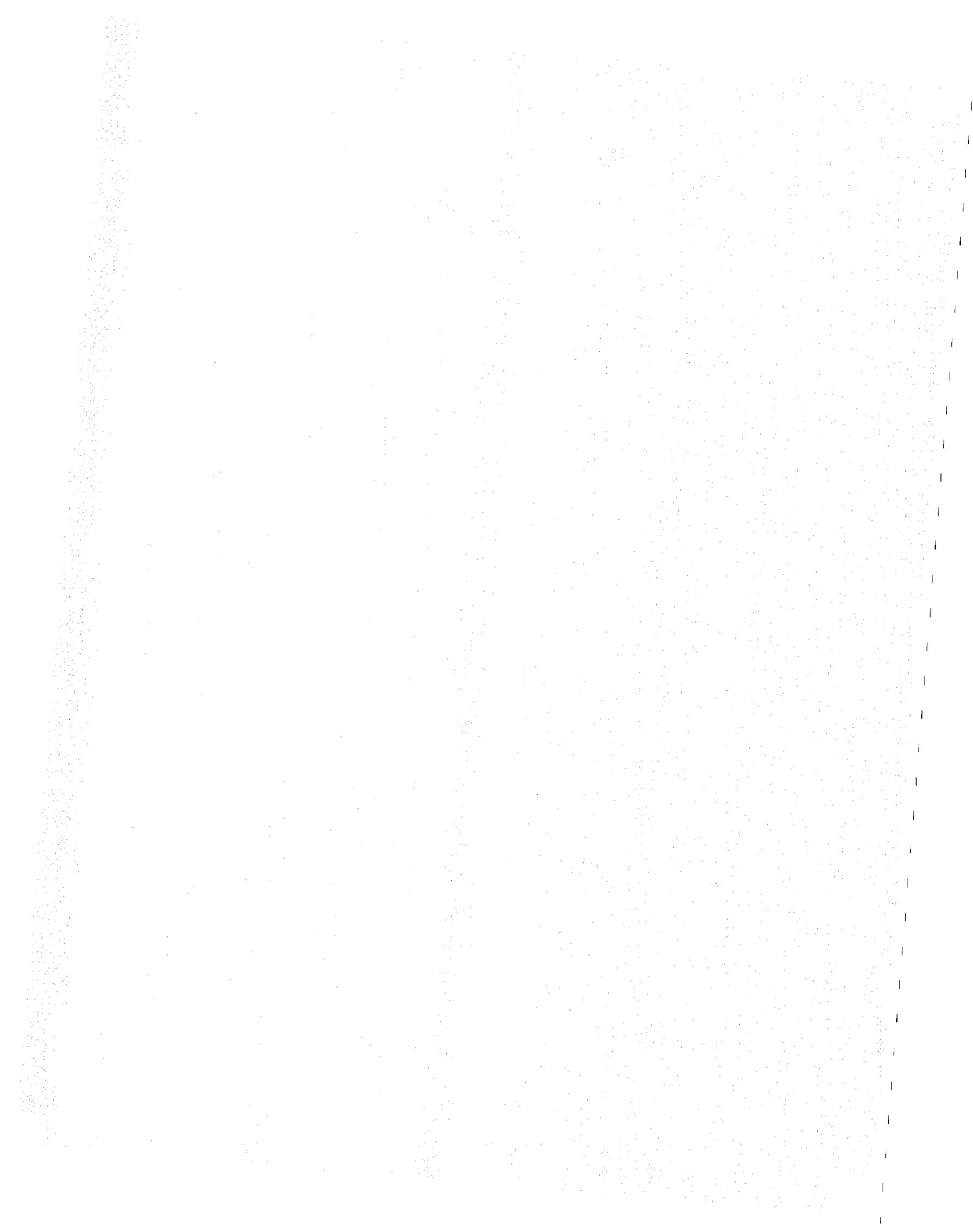
The test apparatus had an operating range to include gas temperatures up to at least 100°C (212°F) and gas velocities to about 6.1 m/s (1200 ft/min). The 0.6 m x 0.6 m x 1.2 m long (2 ft x 2 ft x 4 ft) test section was capable of conveniently testing up to four mine fire detectors at a time.

2.3 CALIBRATION

Calibration of the test apparatus was performed in the following areas: 1) gas velocity profiles, 2) gas concentration profiles, 3) heat release rates, and 4) heat fluxes to the fuel surface.

Measurements of gas velocity were made (using a pitot-static probe) across the square test section of the apparatus over the velocity range from 0.5 m/s to 4.5 m/s. The resulting velocity profiles, normalized with the centerline velocity (v_o) are shown in Figure 4. These measured profiles are seen to be very flat with variations within ±5% of the centerline velocity except in the boundary layers on the walls. The average velocity over the cross section (found by integrating the area under the curves in Figure 4) is within 2% of the centerline velocity, typically 1%. At gas velocities greater than 4.5 m/s the profiles are not as uniform, although the test apparatus can be used to test fire detectors at velocities up to about 6.0 m/s.

Measurements of gas concentration were made for CO₂ across the round measuring section of the apparatus over the velocity range from 0.5 m/s to 4.5 m/s. The resulting radial profiles for 4.5 m/s, normalized with the centerline CO₂ gas concentration (CO_{2o}) are shown in Figure 5. Although three radial traverses



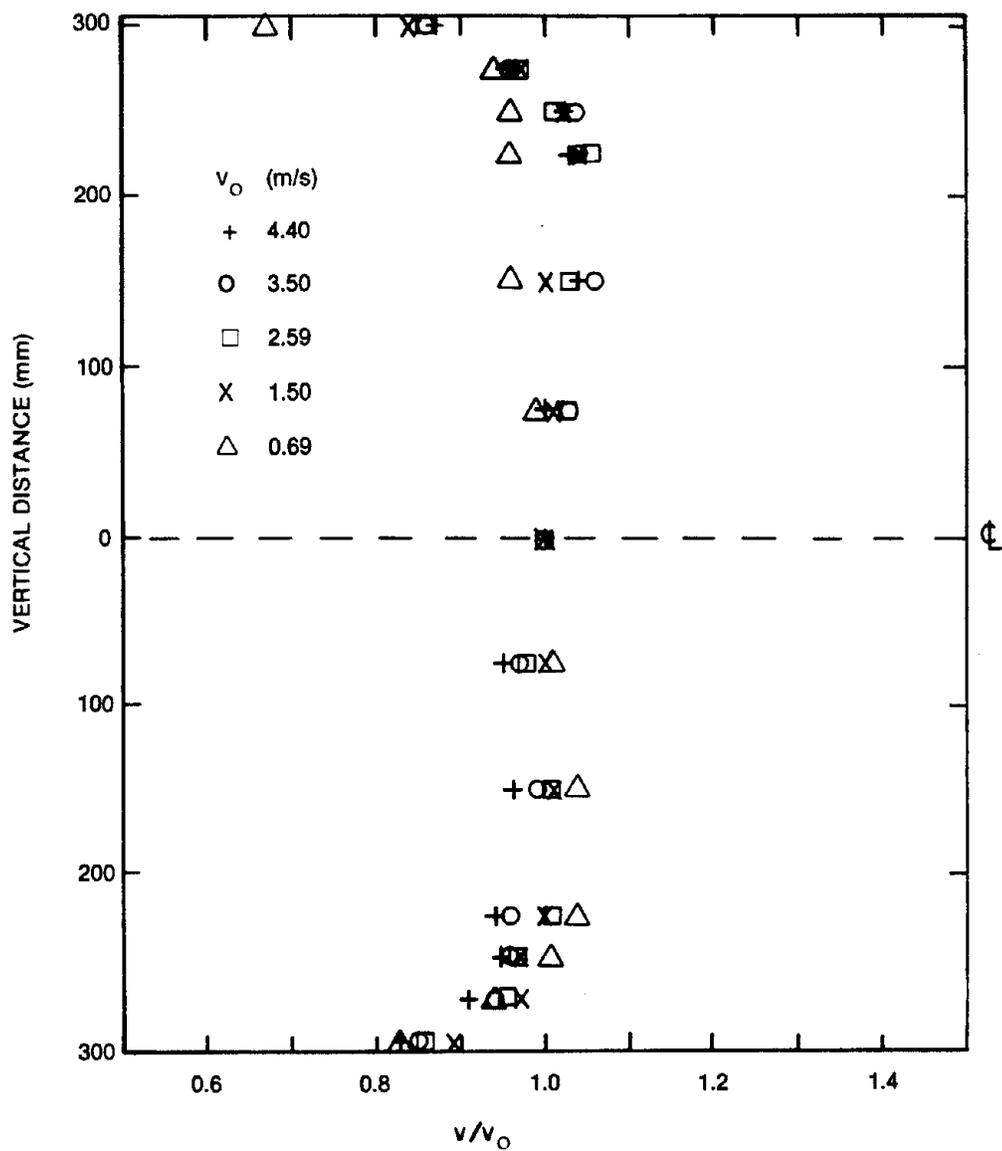
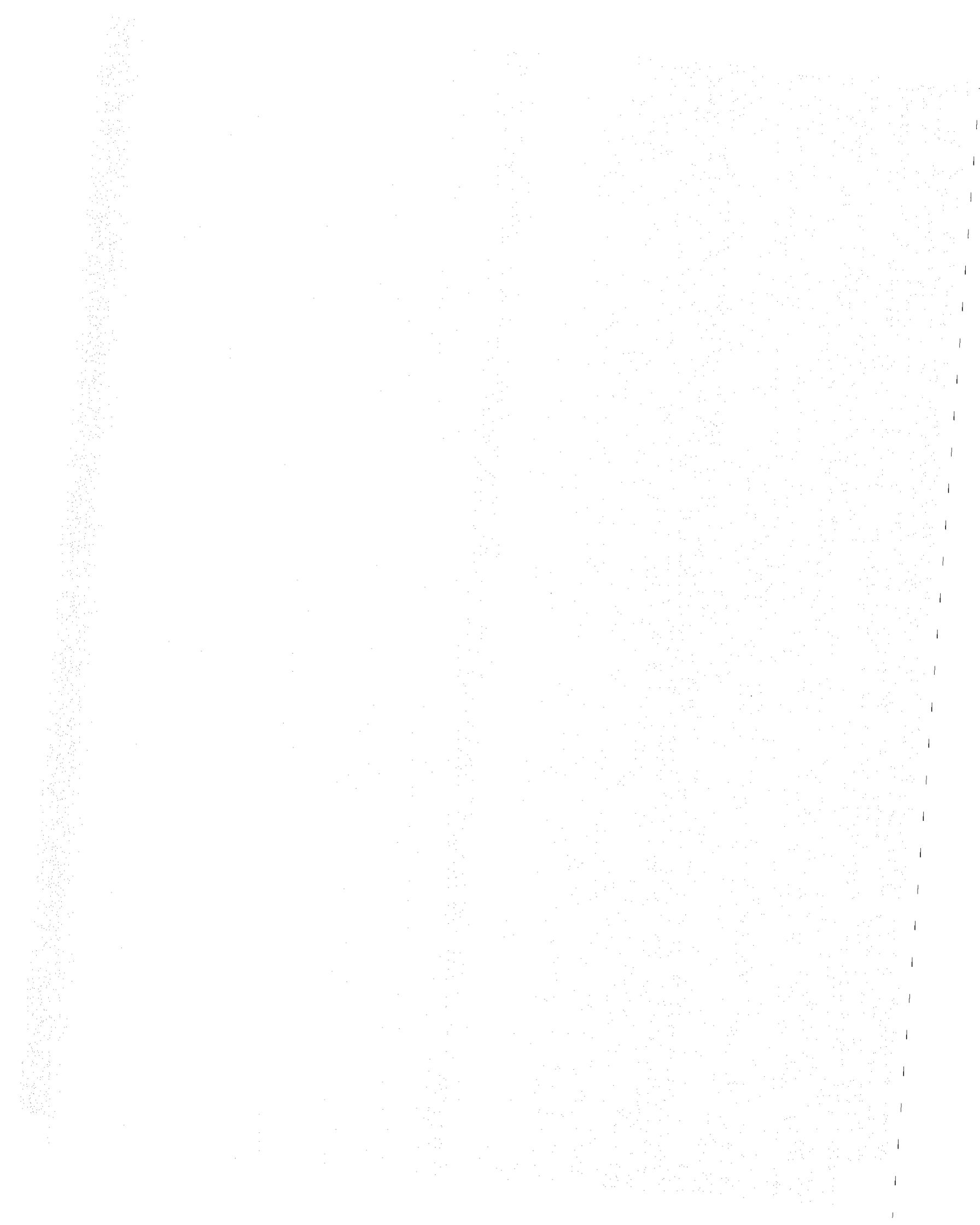


FIGURE 4.- Gas velocity profiles



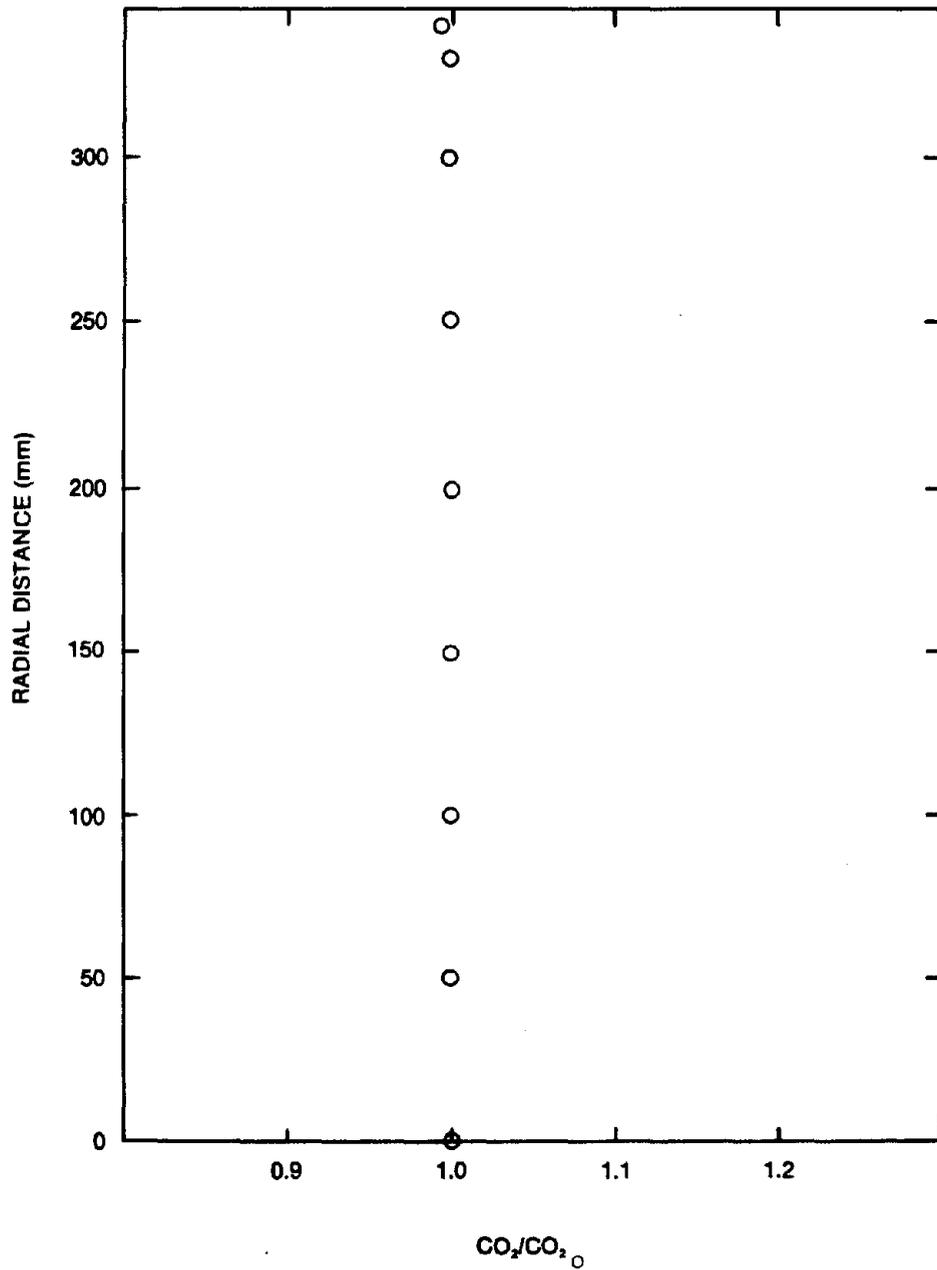
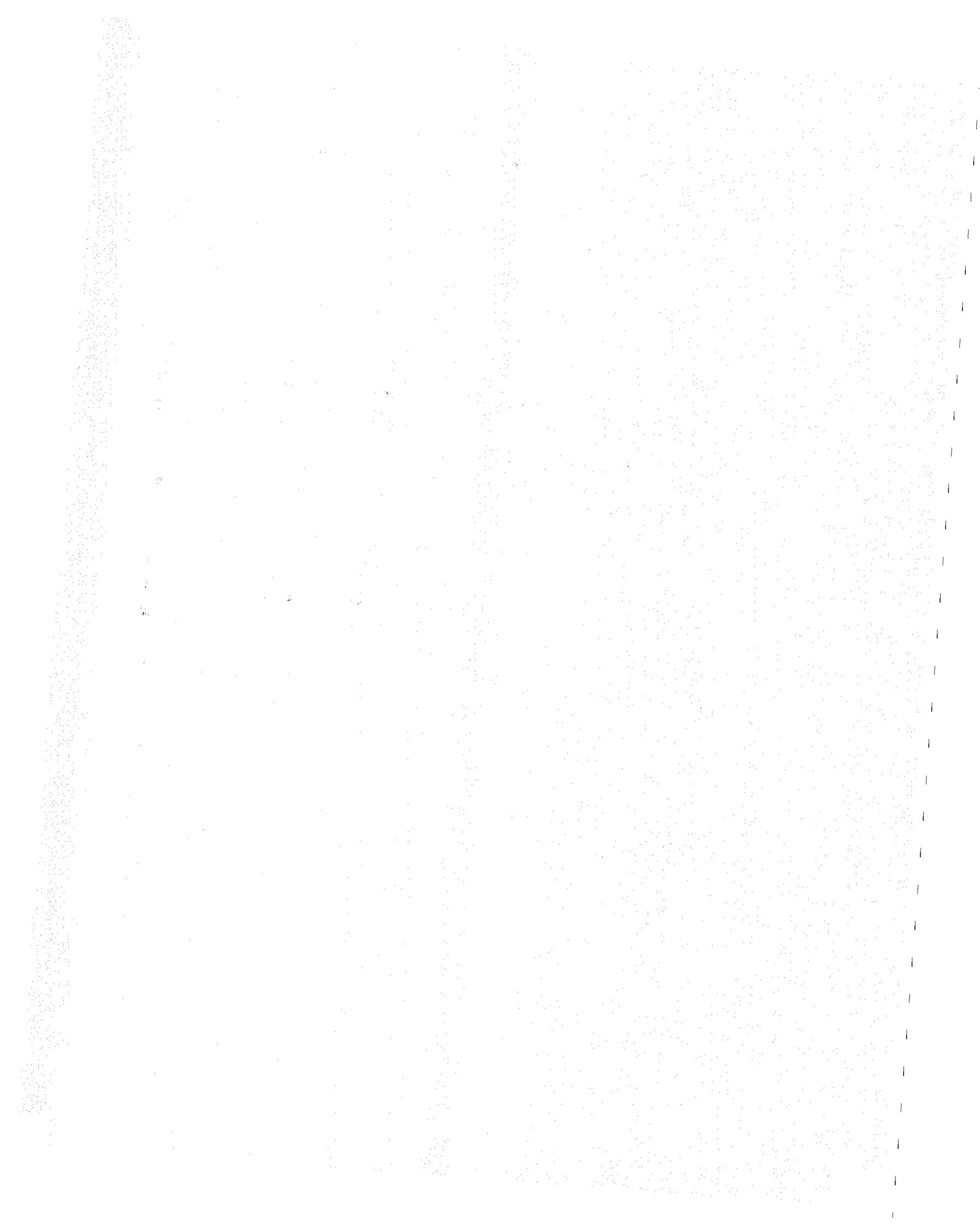


FIGURE 5.- Gas concentration profiles for CO₂

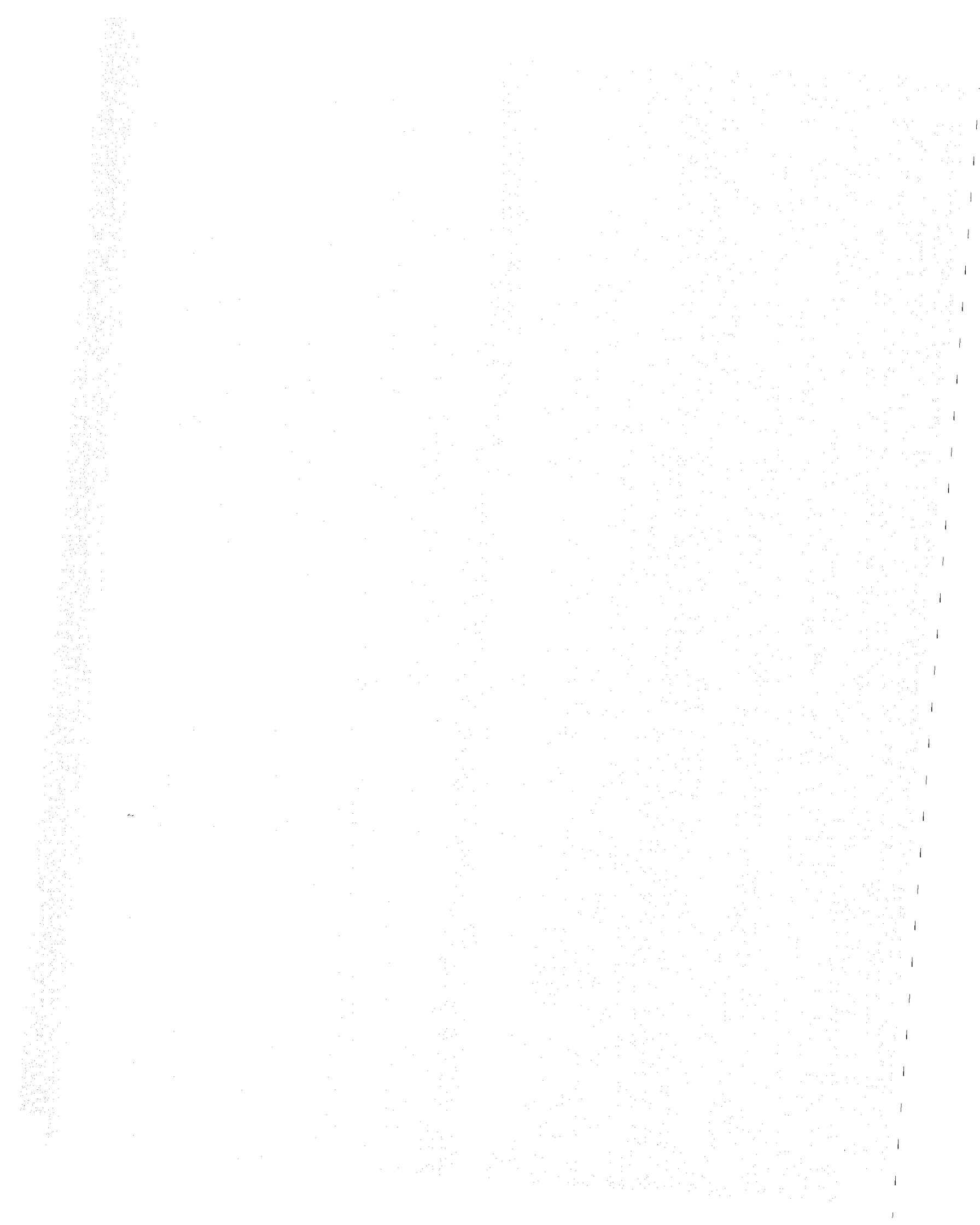


spaced 120° were made, the profiles are so flat that the measurements fall on top of each other, indicating that the flow is very well-mixed.

To determine that the test instrumentation was operating properly, as well as to verify the gas velocity and concentration calibrations, tests were conducted with premixed methane-air burners. Figure 6 plots the heat input (computed from the methane gas flow rate and heating value) versus the measured heat output as determined by temperature ("convective heat release rate") and gas concentration measurements ("actual heat release rate") (3). The premixed burners should give nearly ideal (i.e., 100%) combustion of the methane with little radiation, as shown by the closeness between actual and convective heat release rates. In addition, tests conducted with methanol pan fires yielded equally good results for actual heat release rates.

The excellent agreement between the calculated and measured heat release rates verifies the proper operation of the apparatus and instrumentation for both actual and convective heat release rates. In addition, the accurate measurement of other quantities such as generation rates of CO, THC (total hydrocarbons), H₂O, etc. was practically assured, which was confirmed by additional tests made to determine the minimum resolution of the instruments. On the basis of these tests, the overall accuracy (including resolution) of the apparatus is approximately ±3%.

The final calibrations performed consisted of measuring the magnitude and uniformity of heat flux provided by the radiant heaters. Figure 7 gives the heat flux at the sample surface in kW/m² versus voltage applied to the heaters. Over the voltage operating range of 100-480 volts AC, the flux can be varied between approximately 5-85 kW/m². The flux is uniform to ±10% over the entire sample surface (0.25 m x 0.25 m (10 in. x 10 in.)) horizontally as well as vertically for heights ±0.05 m (±2 in.). The range in available heat fluxes is more than sufficient to generate combustion products from mine materials such that potential mine fire environments can be adequately simulated.



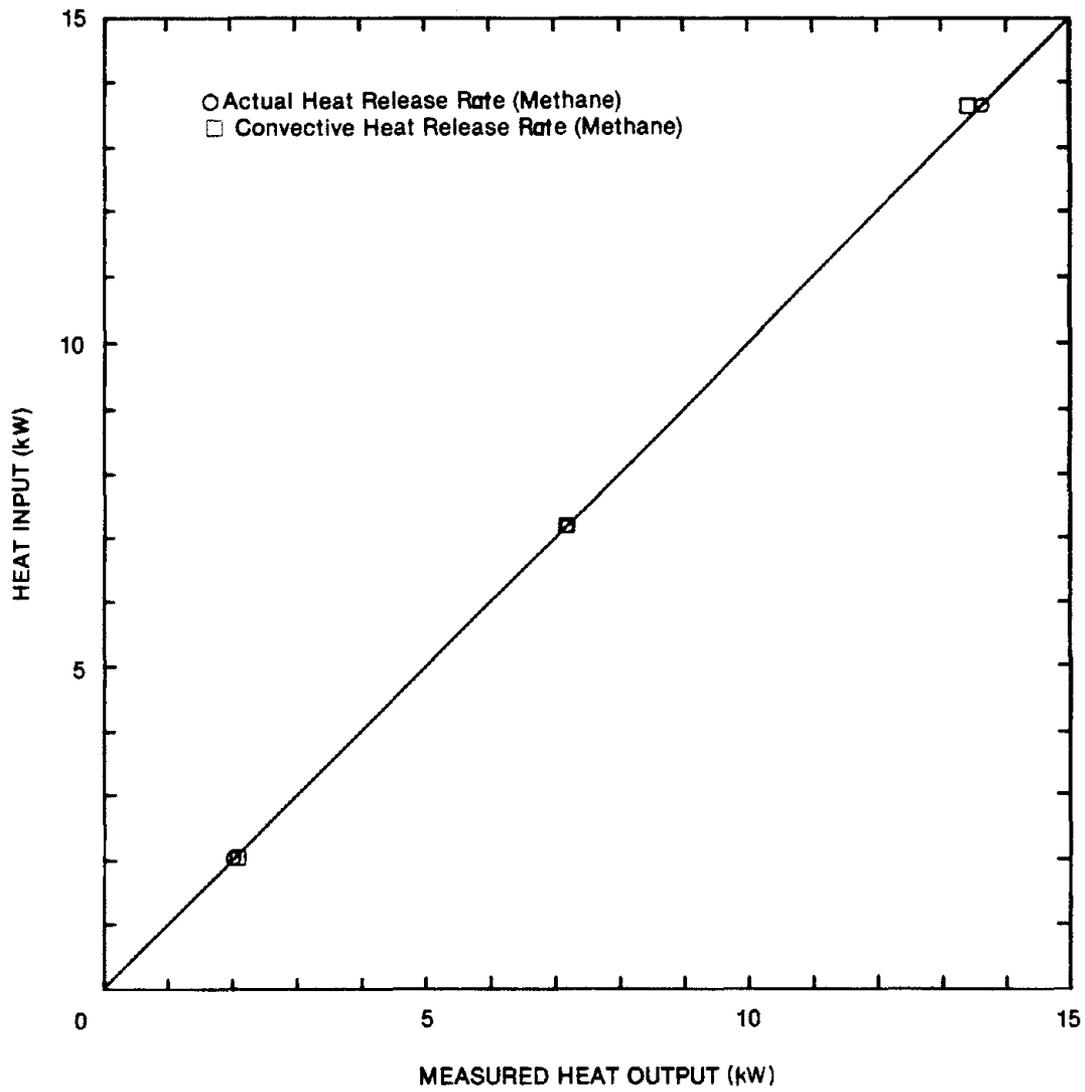
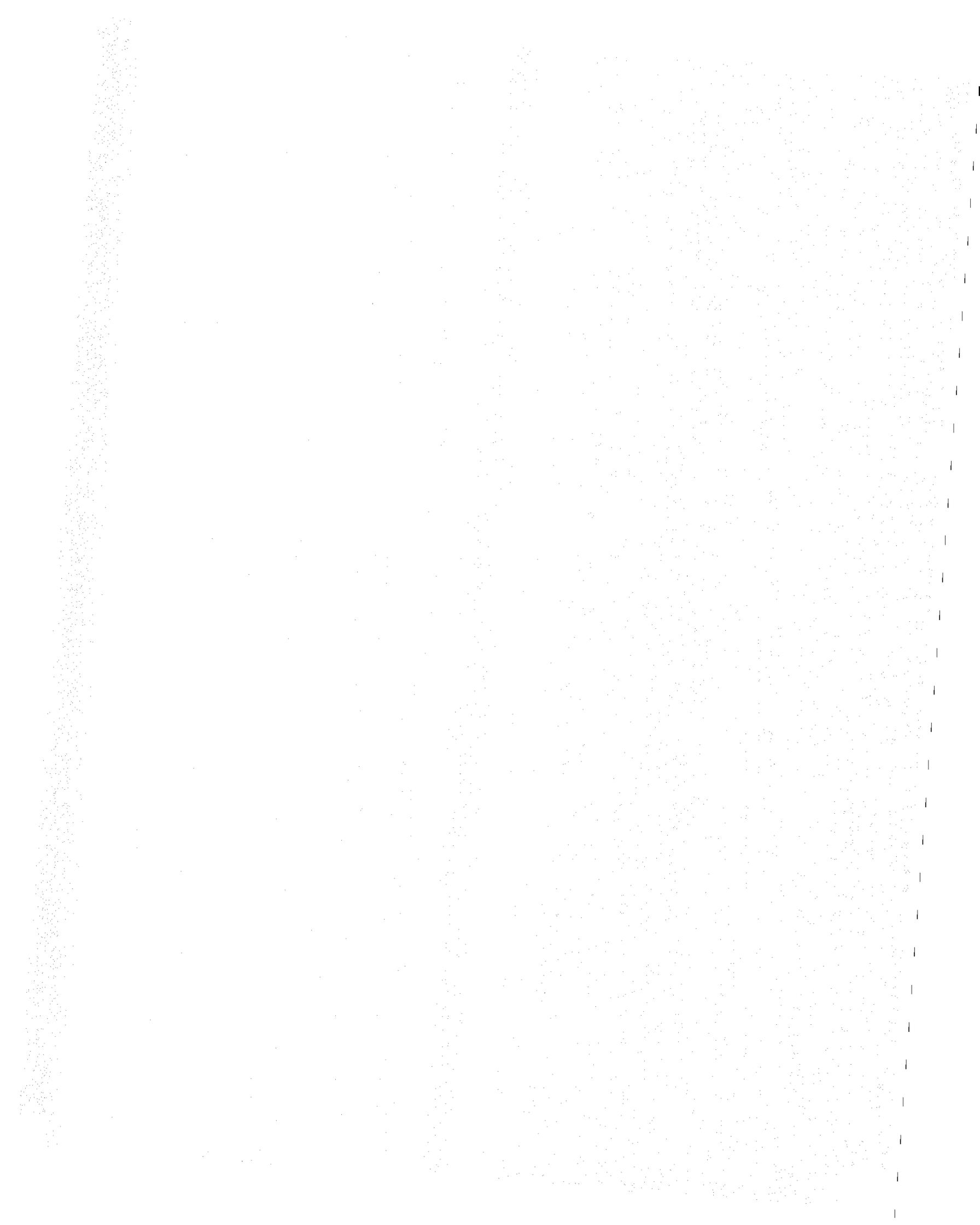


FIGURE 6.- Heat input versus measured heat output for methane



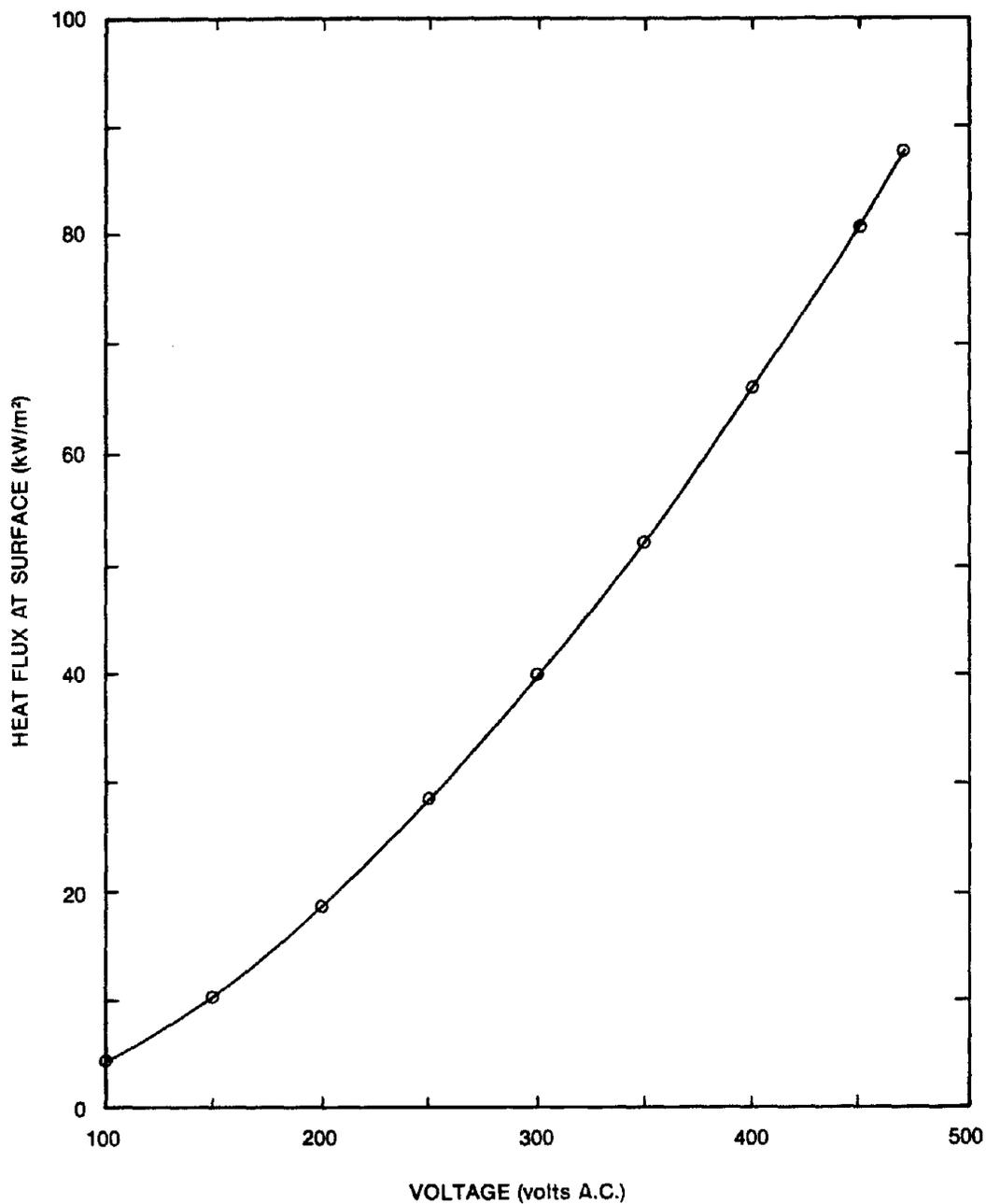
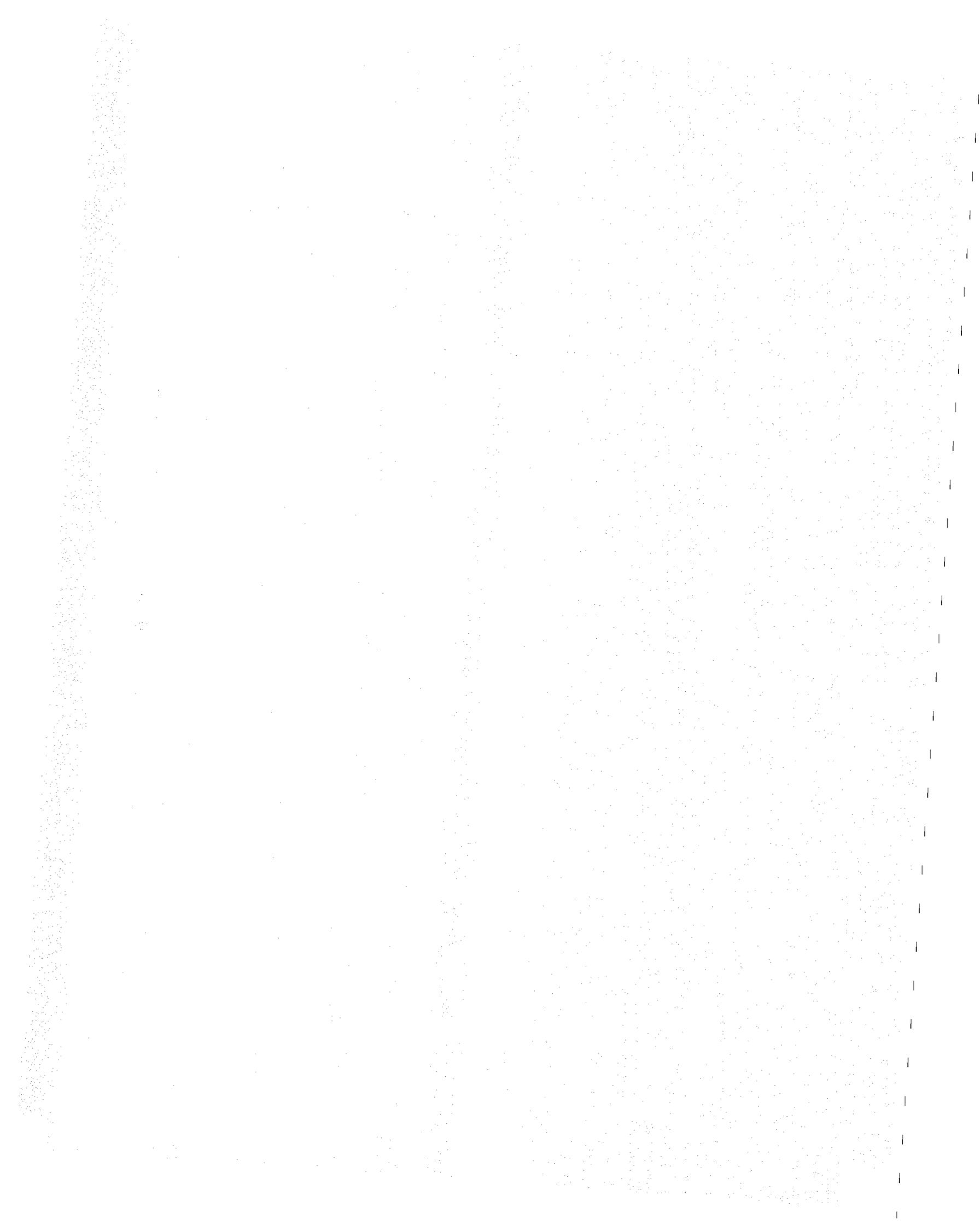


FIGURE 7.- Heat flux at sample surface versus applied voltage to the radiant heaters



III
FIRE SOURCE EVALUATION

A number of research efforts (3-6) have resulted in the characterization of the combustion properties for a variety of materials which could be present within an underground mine. The following properties are considered important in the assessment of the influence of any specific material on the post-ignition environment in a mine: 1) the mass loss rate per unit surface area, \dot{m}'' ; 2) the actual heat of combustion of the material, H_A (determined by the ratio of the actual heat release rate per unit surface area, \dot{Q}_A'' to \dot{m}''); and 3) the fractional yield of the combustion product species i , Y_i (defined as the mass ratio of species, i , to the total mass of all combustion products). These properties combined with the mine geometry and the ventilation conditions determine the mine fire environment. Previous efforts have quantified the influence of the fire source characteristics on the mine fire environment (2,7,8).

Phase III efforts have focused on: 1) supplementing previous data for combustion properties for mine materials, particularly for coal; and 2) defining "standard" fire sources for detection purposes.

Before quantifying, \dot{m}'' , H_A and Y_i for any material, it is important to determine ignition criteria for the material, particularly \dot{q}_{cr}'' , defined as the critical flux for piloted ignition.

Figure 8 plots the inverse of the energy required for piloted ignition ($1/E_{ig}$) versus the applied external flux (\dot{q}_e'') for Pittsburgh seam coal and styrene-butadiene (SBR) fire retardant conveyor belting. E_{ig} is the time to ignition (t_{ig}) multiplied by \dot{q}_e'' . This type of plot is particularly useful to quantify \dot{q}_{cr}'' and is determined by the intercept of each curve, with the y-axis. For Pittsburgh seam coal, $\dot{q}_{cr}'' \approx 19 \text{ kW/m}^2$ while for SBR fire retardant belting, $\dot{q}_{cr}'' \approx 21 \text{ kW/m}^2$. It should be noted, however, that the heat flux for sustained combustion is $\approx 30 \text{ kW/m}^2$ for the coal, while for the belting sustained combustion was obtained at 21 kW/m^2 (\dot{q}_{cr}''). The latter case is typical for most materials. The difference between ignition and sustained combustion for the coal is most likely due to the formation of a heavy char layer on the coal surface which significantly changes the combustion characteristics.

Figure 9 presents the mass loss rate, \dot{m}'' , as a function of \dot{q}_e'' for Pittsburgh seam coal. Four plots are given, the temporal maximum mass loss

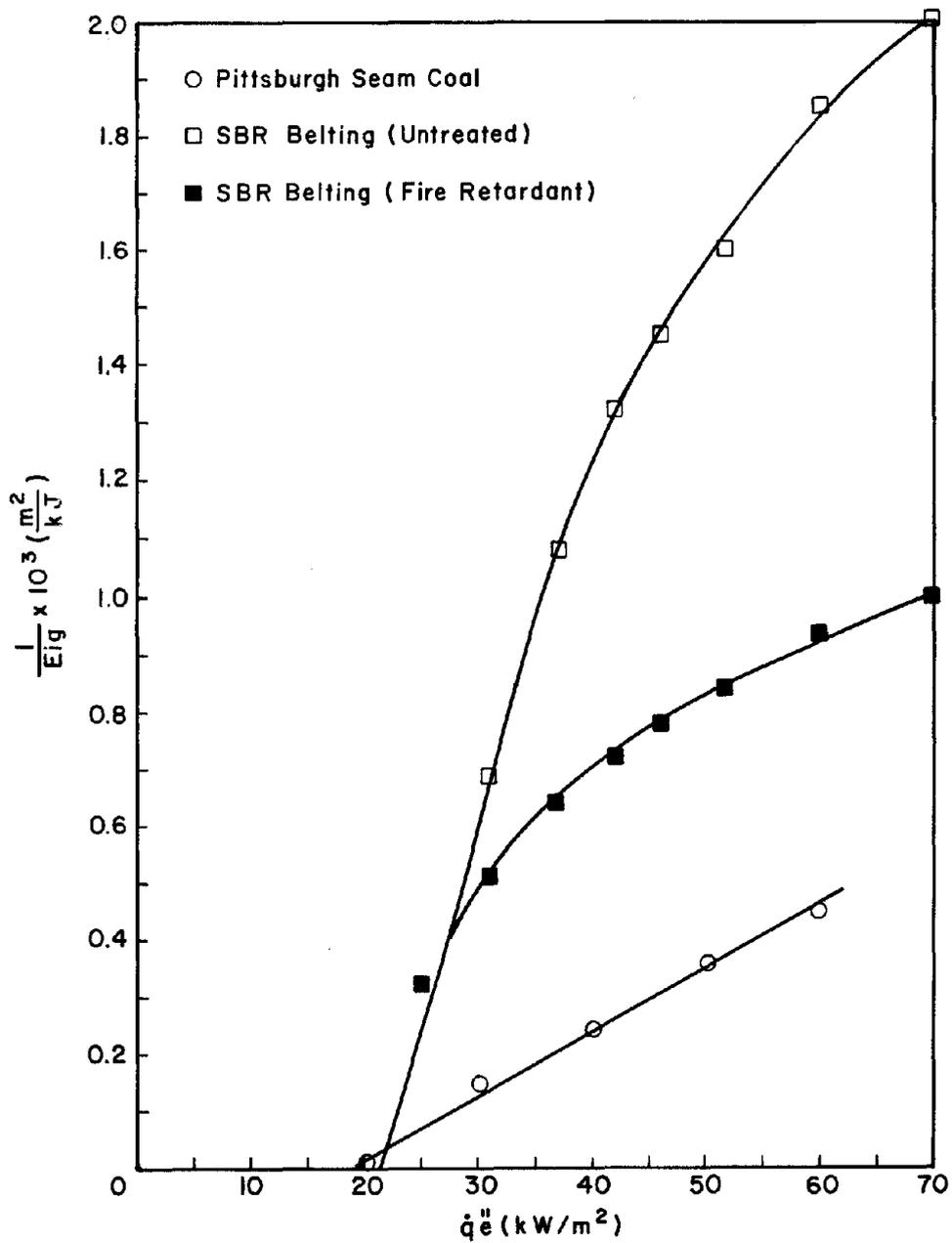
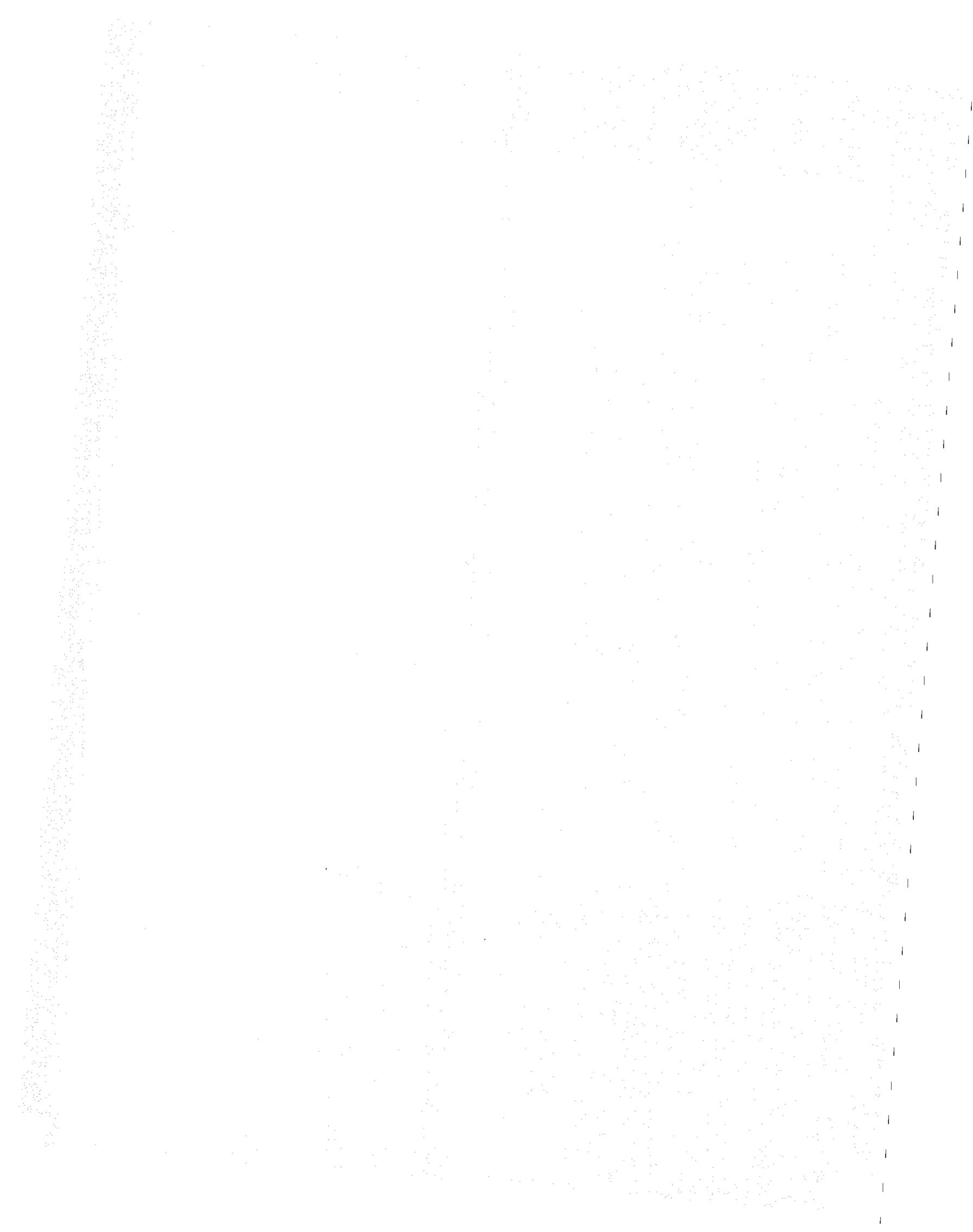


FIGURE 8.- Relationship between ignition energy and external heat flux

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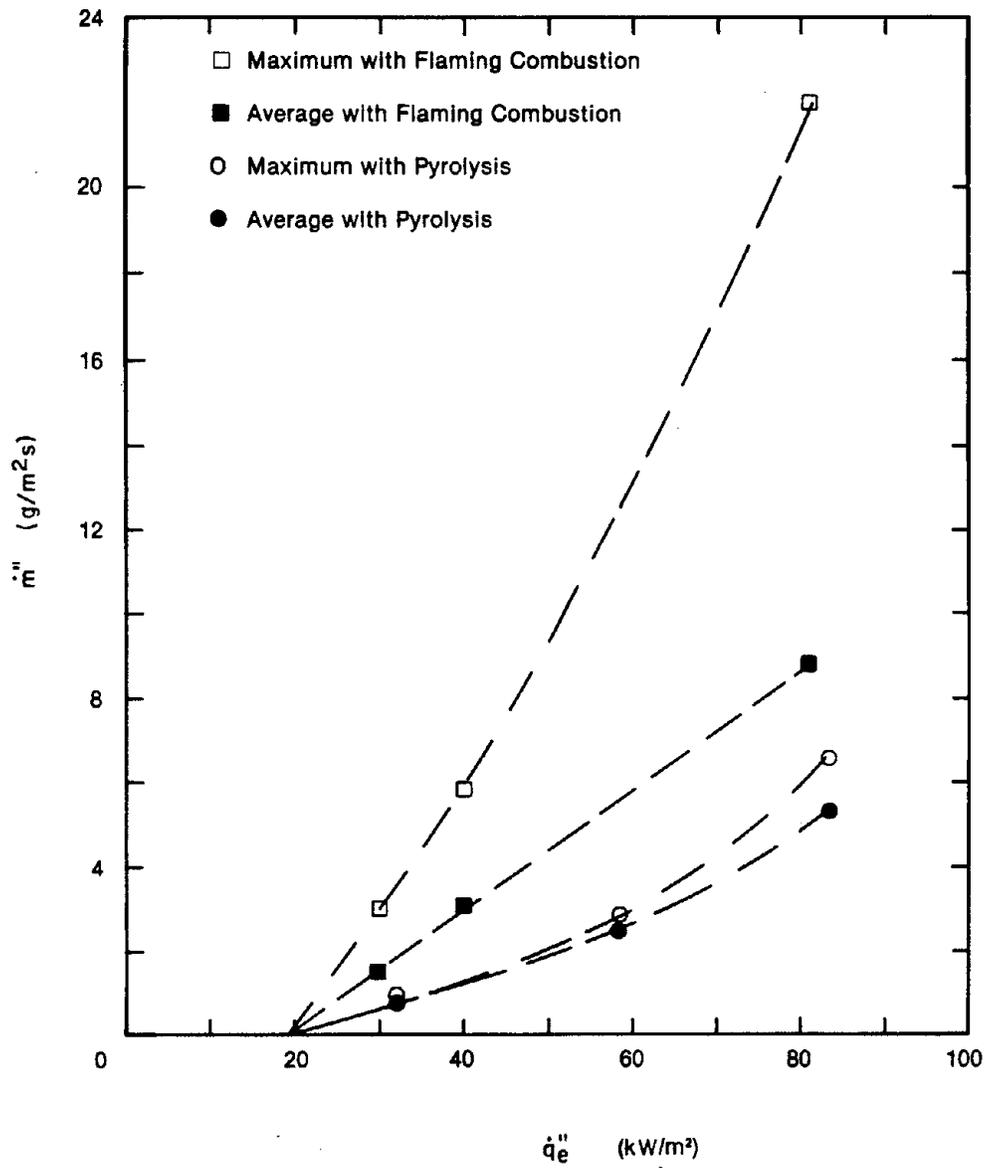
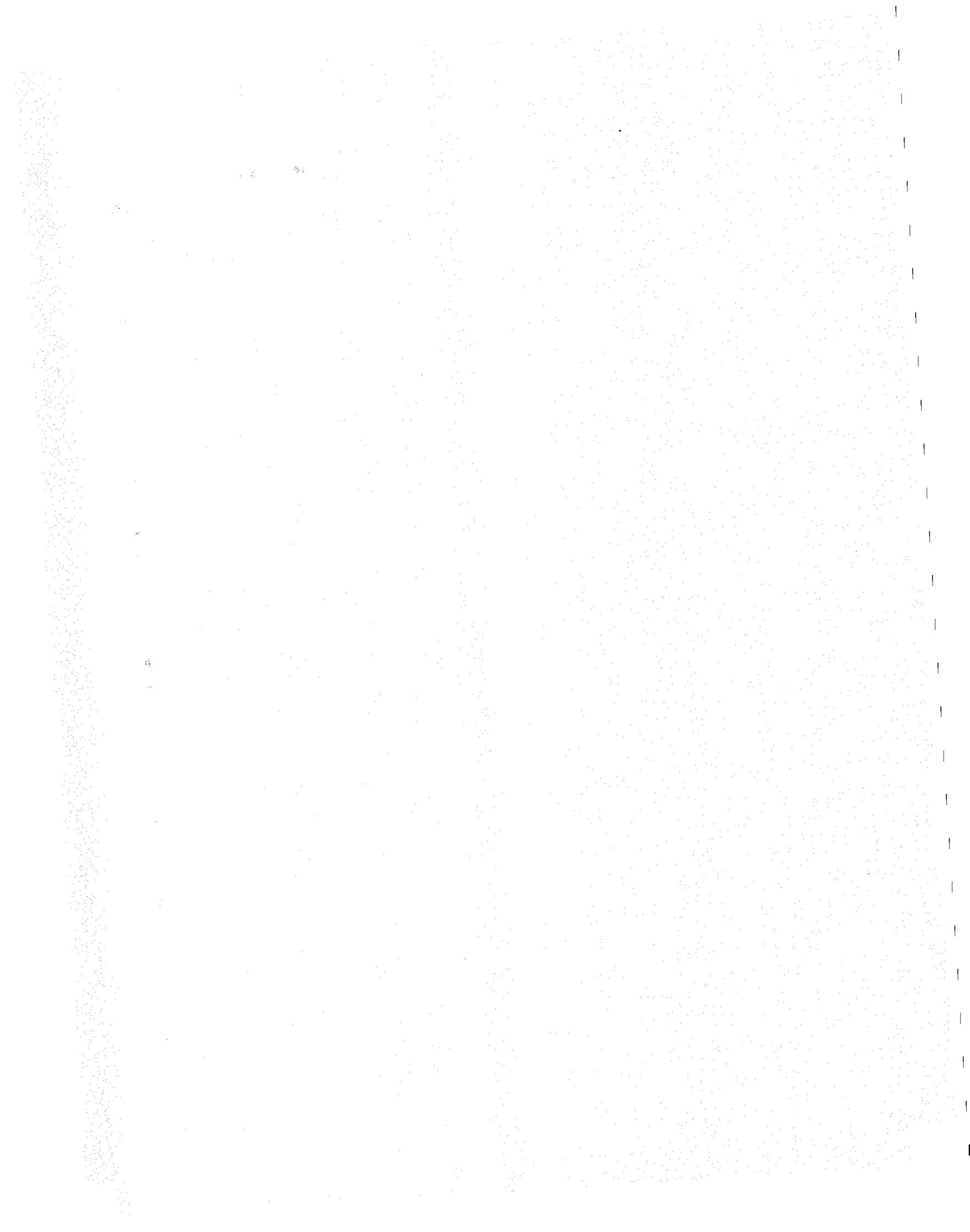


FIGURE 9.- Mass loss rate versus external heat flux for Pittsburgh seam coal



rate with either flaming combustion or pyrolysis (9) and the average mass loss rate over 5 min for either flaming combustion or pyrolysis (9). It is significant that: 1) all the plots have the same intercept ($\sim 19 \text{ kW/m}^2$); 2) the maximum and average pyrolysis are very similar; and 3) flaming combustion produces a maximum mass loss rate that is much larger when compared to the 5-min average. Again, this difference is most likely associated with the rapid development of a significant char layer.

In order to account for the effects of char layer growth on the coal mass loss rates (and associated combustion characteristics), the following analytical formulation was used:

$$\dot{m}'' (t - t_p)^{1/2} = k (\dot{q}_e'' - \dot{q}_{cr}'')^{1/4} \quad (1)$$

where t = time (s), t_p = time to peak mass loss rate (s) and k = constant. Equation (1) has been modified from an analytical expression given in Reference 10 to account for t_p and \dot{q}_{cr}'' . Table 1 examines the validity of eq (1) with $\dot{q}_{cr}'' = 19 \text{ kW/m}^2$. The k values thus obtained are quite uniform for $\dot{q}_e'' \geq 40 \text{ kW/m}^2$ and for either pyrolysis or flaming combustion. The analytical expression appears to break down near $\dot{q}_e'' = 30 \text{ kW/m}^2$, probably due to the closeness of the critical flux to the external flux. In fact, the flux for sustained ignition for coal, as noted previously, is 30 kW/m^2 .

In general, the mass loss rate of most materials, unlike coal, can be simply quantified by assuming $\dot{m}''/\dot{q}_e'' \approx \text{constant}$, which is valid as long as \dot{q}_e'' is large compared to \dot{q}_{cr}'' and the flame heat flux (for flaming combustion). Typically, this is the case for $\dot{q}_e'' \geq 40 \text{ kW/m}^2$, and therefore, most of the fire source evaluations were performed at a minimum of 40 kW/m^2 .

Four materials were selected for extensive evaluation of combustion characteristics using the test apparatus - Pittsburgh seam coal, SBR belting, polystyrene, and heptane. Pittsburgh seam coal and SBR belting were chosen as typical potential fire sources in the underground coal mine environment and therefore important to quantify for fire detection evaluation. Polystyrene and heptane were selected as well-defined and reproducible hydrocarbon fuels which can be used to generically represent a variety of materials, e.g., electrical cabling, belting, lubricating fluids, diesel, and other liquid fuels.

TABLE 1. - Coal mass loss rate summary

\dot{q}_e'' (kW/m ²)	max \dot{m}'' (g/m ² ·s)	t_p (s)	$\dot{m}'' \sqrt{(t - t_p)}$	k
83.7	6.7 (p)	53	72	25
80.5	22 (c)	74	73	26
58.6	3.0 (p)	236	58	23
40.0	5.8 (c)	32	45	21
31.8	0.9 (p)	129	14	7
30.0	2.3 (c)	477	7	4

p = pyrolysis

c = flaming combustion

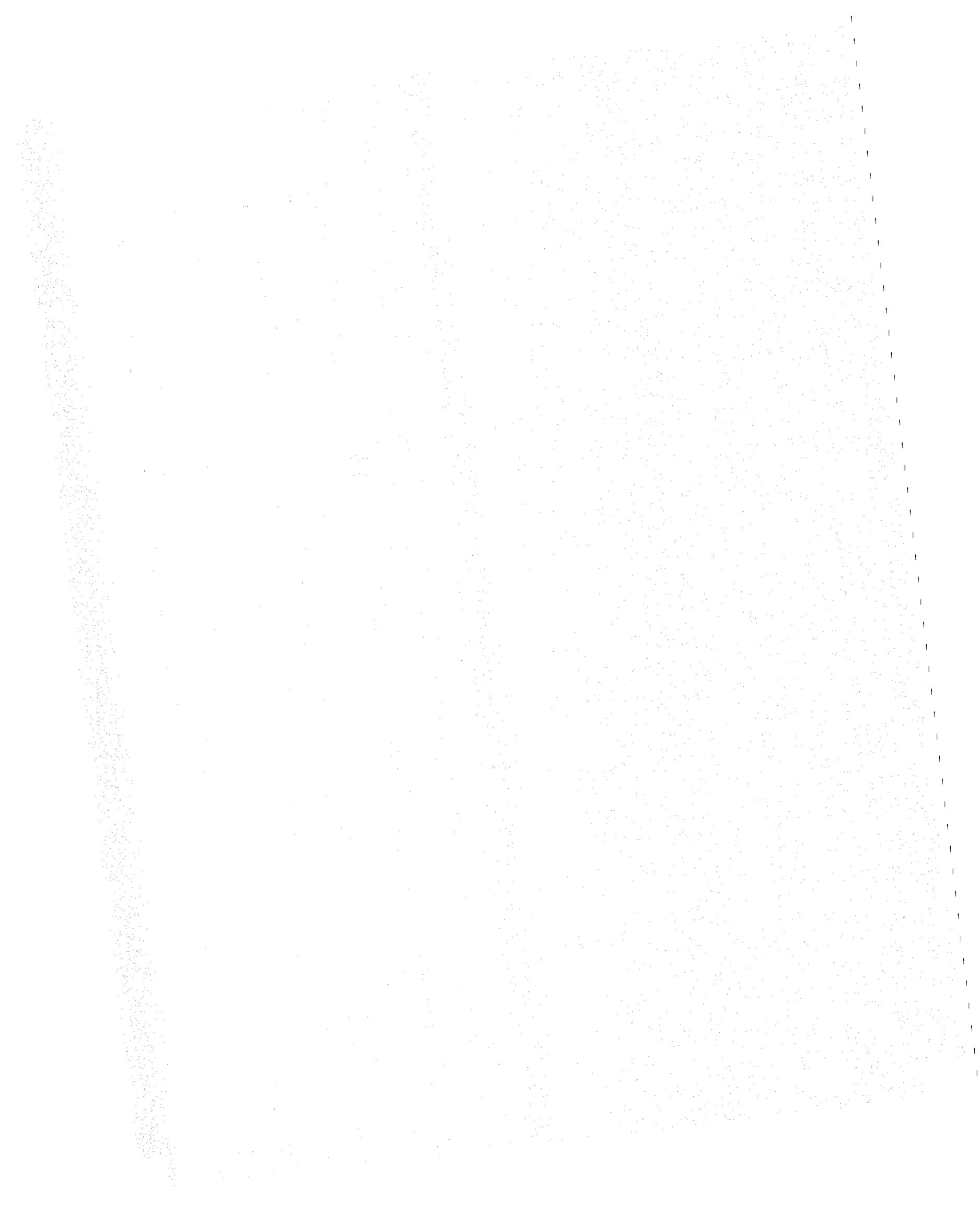


Table 2 gives a summary of the following combustion characteristics for Pittsburgh seam coal, SBR belting, polystyrene at $\dot{q}_e'' = 40 \text{ kW/m}^2$, and heptane with no external flux: 1) fractional yields, Y_i , where $i = \text{CO}_2, \text{H}_2\text{O}, \text{CO}$ and THC (total hydrocarbons); 2) H_A ; 3) χ_A , actual combustion efficiency (defined as the ratio of H_A to the theoretical heat of combustion); 4) \dot{m}'' at steady state; and 5) $\dot{m}''/\dot{q}_e''^*$.

The data for polystyrene and heptane combustion characteristics are in good agreement with previously reported results (5,6), which further verifies the accuracy of the test apparatus. The data for SBR belting are also in good agreement with limited data from the literature (3). Although no data are available for comparison with the Pittsburgh seam coal flaming combustion results, the pyrolysis mass loss rates (9) discussed previously have been shown to be consistent with current combustion data and equally well-characterized by the analytical expression given by eq (1).

In conclusion, needed data for fire source quantification have been accurately obtained. These data will be used for: 1) fire detector evaluation as described in Section IV; and 2) fire detector spacing guidelines as a function of the fire source (and corresponding fire environment) which will be reported later in Phase IV.

* $Y_i, H_A,$ and χ_A are insensitive to \dot{q}'' for overventilated conditions.

TABLE 2. - Fire source quantification

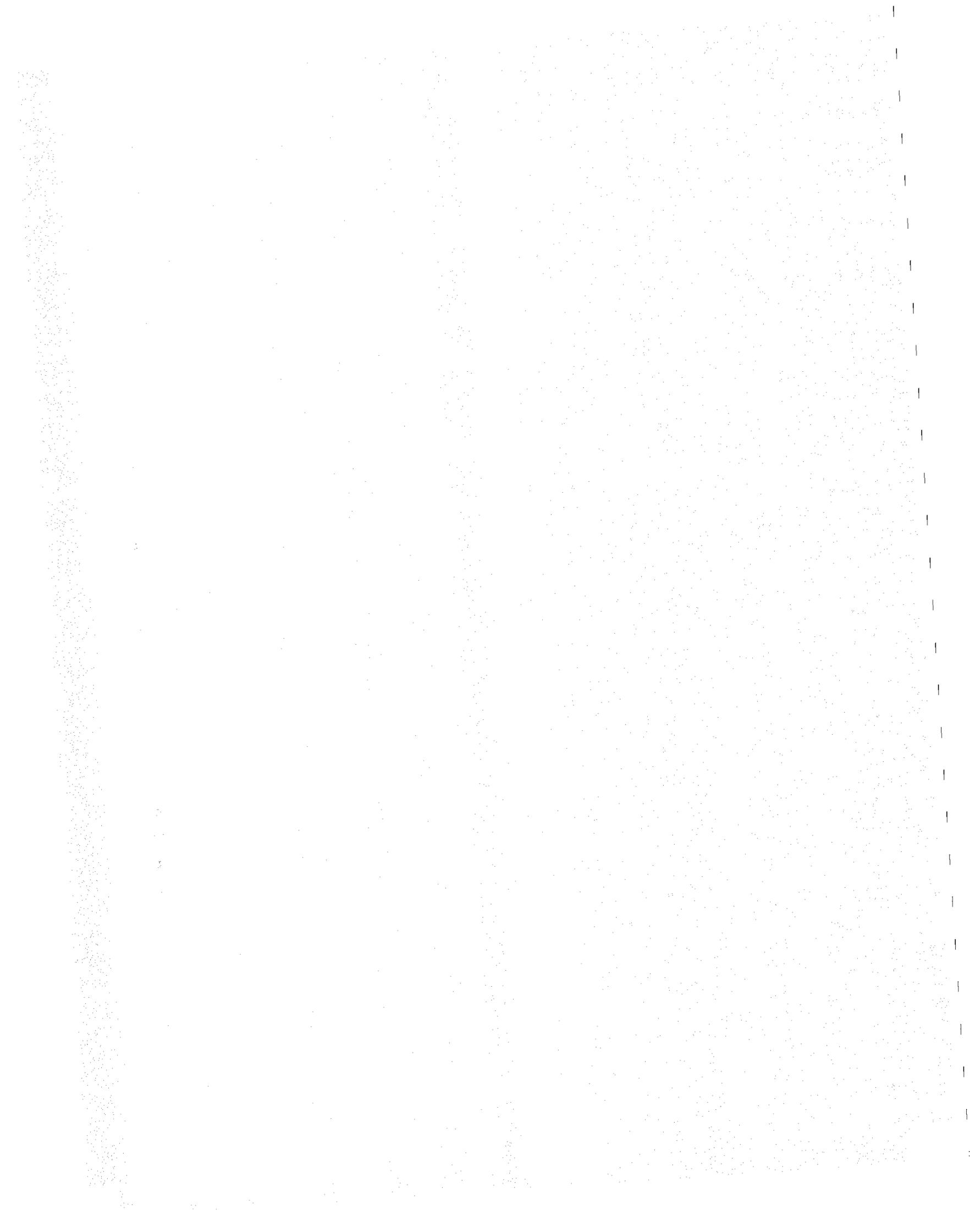
Fuel	Y_{CO_2} (g/g)	Y_{H_2O} (g/g)	Y_{CO} (g/g)	Y_{THC} (g/g)	H_A (kJ/g)	X_A^a	\dot{m}'' (g/m ² ·s)	\dot{m}''/\dot{q}_e'' (g/kJ)
Coal ^b	0.96	NA	0.030	0.0001	9.5	0.28	NA	NA
SBR Belting ^b	1.28	0.76	0.059	0.0070	16.9	0.49(0.49)	17	0.43
Polystyrene ^b	1.88	0.83	0.097	0.0224	24.5	0.62(0.65)	38(38) ^c	0.95
Heptane	2.84	1.30	0.008	0.0005	41.0	0.93(0.90)	32(66) ^c	NA

^a based on CO and CO₂ or H₂O (in parentheses) showing that either C or H balances give similar results

^b measured at $\dot{q}_e'' = 40 \text{ kW/m}^2$

^c asymptotic limit

NA - not applicable



IV

FIRE DETECTOR EVALUATION

The response characteristics of fire detectors may be initially described by the detector type. Generally, fire detectors may be classified as either: 1) heat detectors, which include the fixed temperature type and the rate-of-rise type; or 2) product(s) of combustion type, which includes ionization detectors, photo-electric detectors and gas detectors. For each detector type, the response characteristics of the detector may be measured by a combination of the following factors:

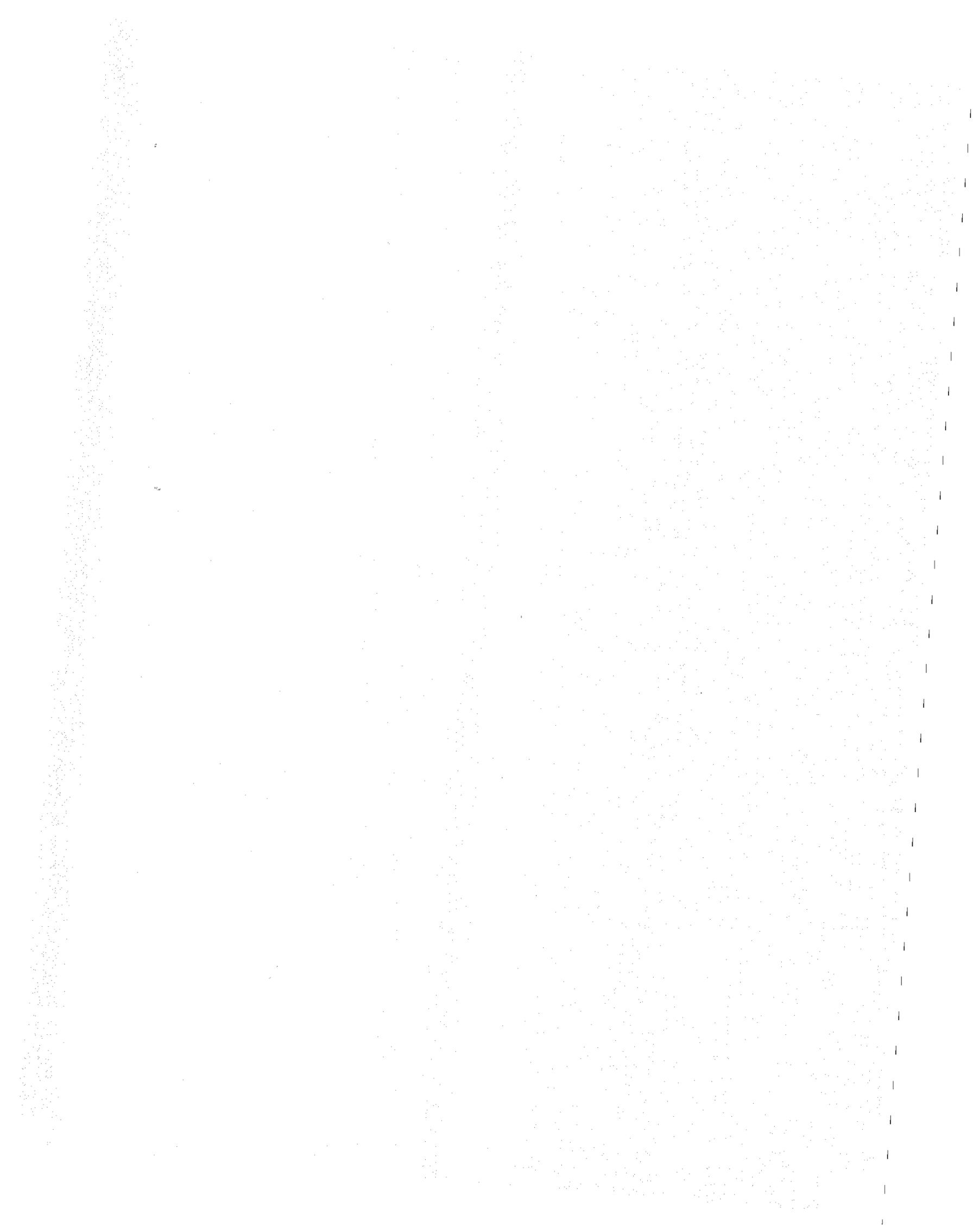
- 1) response (alarm) time;
- 2) temperature, rate of temperature rise, velocity, obscuration, gas concentration, etc. of local environment; and
- 3) repeatability (precision), reliability, etc.

Selected heat detectors were evaluated using a "plunge-test" tunnel which is conventionally used for sprinkler approval (11). Selected product of combustion type detectors were evaluated using the test apparatus (described in Section II) under laboratory ambient conditions with the source fires described in Section III to simulate mine fire environments.

4.1 HEAT DETECTOR EVALUATION

The "plunge" test method (11) consists of suddenly immersing an object, such as a heat detector (or sprinkler), in a gas flow of constant temperature and velocity. This method allows the accurate and reproducible measurement of heat detector sensitivity and provides test results that are directly relatable to the expected performance of the heat detector in the field. The test apparatus, as shown in Figure 10, is a closed-circuit, hot-air tunnel, heated electrically, and incorporates an insulated test section with a test velocity of approximately 2.5 m/s. Other details are given in Reference 11.

Previous work (11) has shown that the only variables of importance in the response of a sensing element of a sprinkler (or heat detector) are the actuation temperature ("temperature rating") and the time constant, τ . In addition, the time constant has been shown to depend on the square root of the gas velocity. Therefore, if the time constant is known at a reference velocity, v_0 , the time



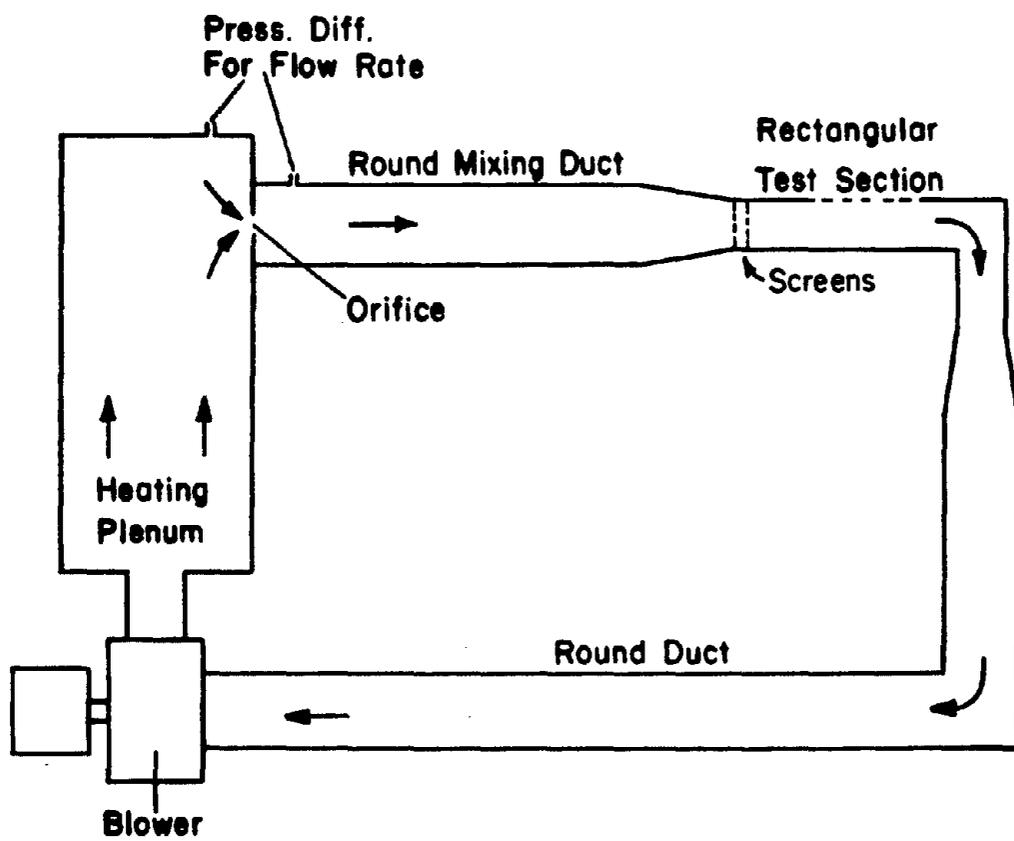


FIGURE 10.- Schematic design of plunger-test tunnel

constant at any other velocity, v , can be calculated from:

$$\tau = \tau_0 (v_0/v)^{1/2} \quad (2)$$

where τ (s) corresponds to v (m/s) and τ_0 (s) corresponds to v_0 (m/s). For convenience, the product $\tau v^{1/2}$ is used as a measure of sensitivity and is termed the "Response Time Index" or RTI. Therefore,

$$\text{RTI} = \tau v^{1/2} \quad (3)$$

Values of the RTI for three types of heat detectors used in "mine-permissible" systems are given in Table 3. As shown, these values vary over a wide range between 12 and 382 (m·s)^{1/2}. To put these numbers in perspective, the range of RTI values for UL-listed heat sensors is approximately 40-120 (m·s)^{1/2}. Further, Factory Mutual approved sprinklers range in RTI from approximately 100-400 (m·s)^{1/2}. These numbers should also be compared to the "ideal" heat sensor referenced in Title 30 CFR 75.1103 for spacing specifications. A close approximation to an ideal heat sensor would be a fine wire thermocouple. For example, a 0.25 mm (0.01 in.) dia thermocouple has an RTI of approximately 1 (m·s)^{1/2}. Thus, at a velocity of 1 m/s, the time constants for the fine wire thermocouple, Thermotech, MSA and Pyott-Boone heat sensors would be 1, 12, 59, and 382 s, respectively.

4.2 PRODUCT OF COMBUSTION DETECTOR EVALUATION

The following two types of carbon monoxide gas detection systems/sensors were evaluated using the test apparatus (previously shown in Figures 1 and 2): 1) an Energetics Science Ecolyzer Model 5100 System with 5001-DGFR-50/500 Remote Sensing Heads; and 2) an MSA prototype CO transducer under joint development by the Bureau of Mines and Mine Safety Appliances Co. (MSA).

4.2.1 Ecolyzer CO Detection System

The Ecolyzer System was ordered with three sensing heads, each of which was calibrated according to the manufacturer's instruction manual prior to testing. A series of "cold flow" tests was initially performed to investigate the response

TABLE 3. - Heat detector response

Manufacturer	RTI(m·s) ^{1/2}	Actuation Temp. (°C)
Thermotech ^{a,b}	12±2	52.8 (127°F)
MSA ^b	59±3	57.2 (135°F)
Pyott-Boone	382±56	55.0 (131°F)

^a sensor used in system manufactured by Notifier of Western Pennsylvania

^b Factory Mutual System Approved

and accuracy of the sensors to a step input of a known CO source at a given ambient velocity. The CO source was a gas jet from a compressed gas bottle of known CO content (balance nitrogen) introduced at the bottom of the intake section shown in Figure 1. The velocity was fixed in the test section, as previously described, before each test. Figure 11 illustrates the responses of the reference gas analyzer* (designated by ref. in the figure) and the three Ecolyzer sensors (grouped together in Figure 11) versus time. Several points should be noted from Figure 11: 1) the Ecolyzer responses are well-behaved and grouped very closely together; 2) the time responses appear to be first order with a time lag, which will be discussed later; and 3) the final response values appear to correspond accurately to the reference gas concentration. Figure 12 gives the time response for the Ecolyzer at 3.5 m/s. Although only one sensor response is plotted for clarity, the same observations at 3.5 m/s were noted as at 0.5 m/s.

Assuming that each Ecolyzer sensor behaves as a first order system coupled with a time lag, then the time response of the sensor can be given as:

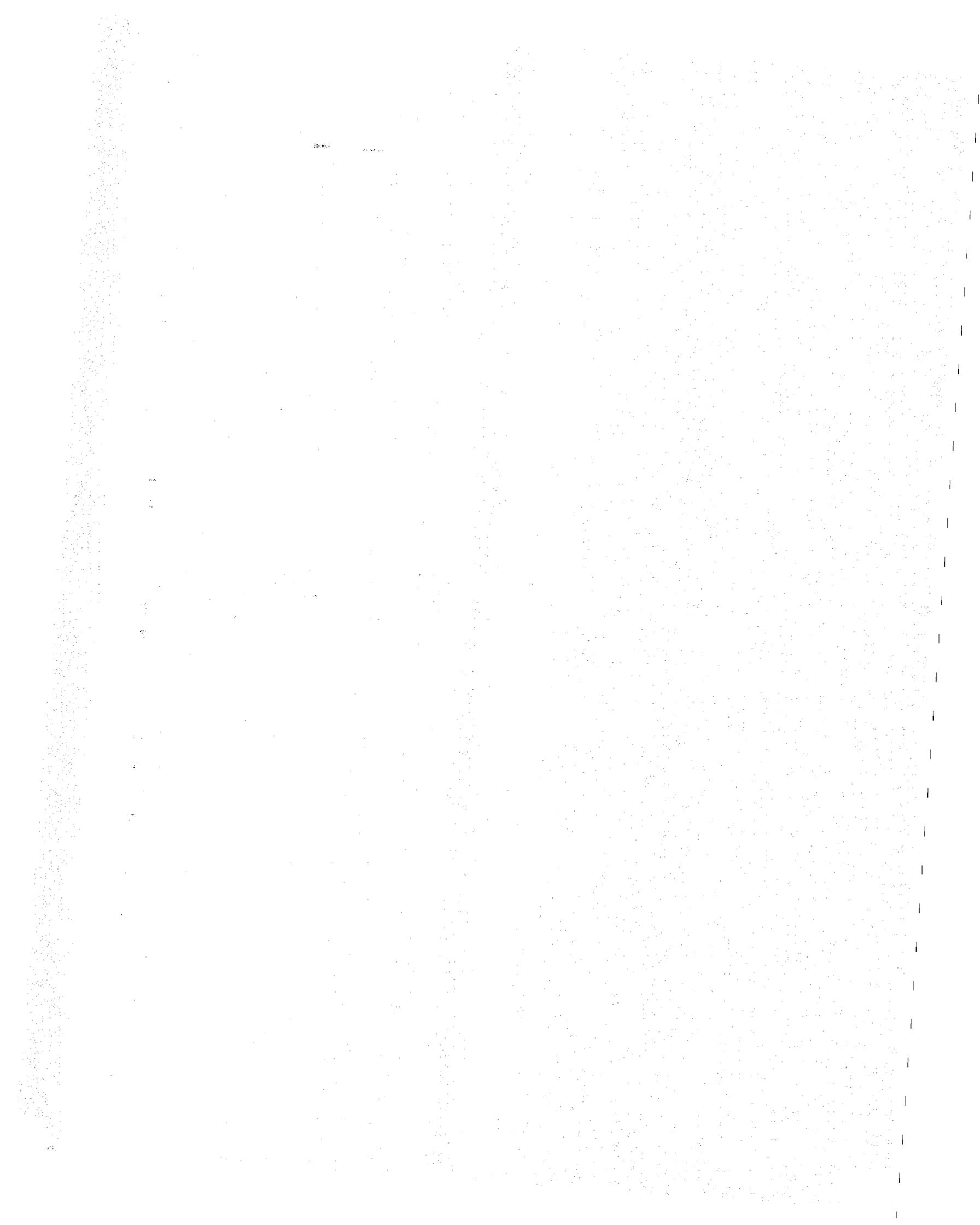
$$\frac{dC_s}{dt} = \frac{1}{\tau} [C_o (t-t_\ell) - C_s(t)] \quad (4)$$

where t is the time in s; C_s is the instantaneous CO gas concentration in ppm as measured by the sensor at time t ; C_o is the reference CO gas concentration in ppm at time $t-t_\ell$; τ is the sensor time constant in s; and t_ℓ is the lag time in seconds. In addition, it appears that t_ℓ is associated with a delay in mass transport through the diffusion filter, while τ can be thought of as the time constant for the sensor cell.

If it is assumed that the CO gas concentration is introduced as a step input, then the fractional response, C_s/C_o , of the sensor can be expressed as:

$$C_s/C_o = 1 - e^{-(t-t_\ell)/\tau} \quad (5)$$

* The reference analyzer has a small time constant (approximately 0.5 s) such that it closely follows the actual CO gas concentration.



where t is the time in s relative to the time when the sensor was first exposed to the step input. While it can be noted in Figures 11 and 12 that the cold CO source is not an ideal step input (i.e., there is some "smearing" in the initial step as shown by the reference analyzer response), eq (5) was initially assumed for ease of analysis. The values of τ and t_{ℓ} were first obtained by best fit of eq (5) to the actual response curves, then cross-checked with eq (4). The following average values were obtained for the Ecolyzer sensors; averaged over three sensors and all velocities investigated:

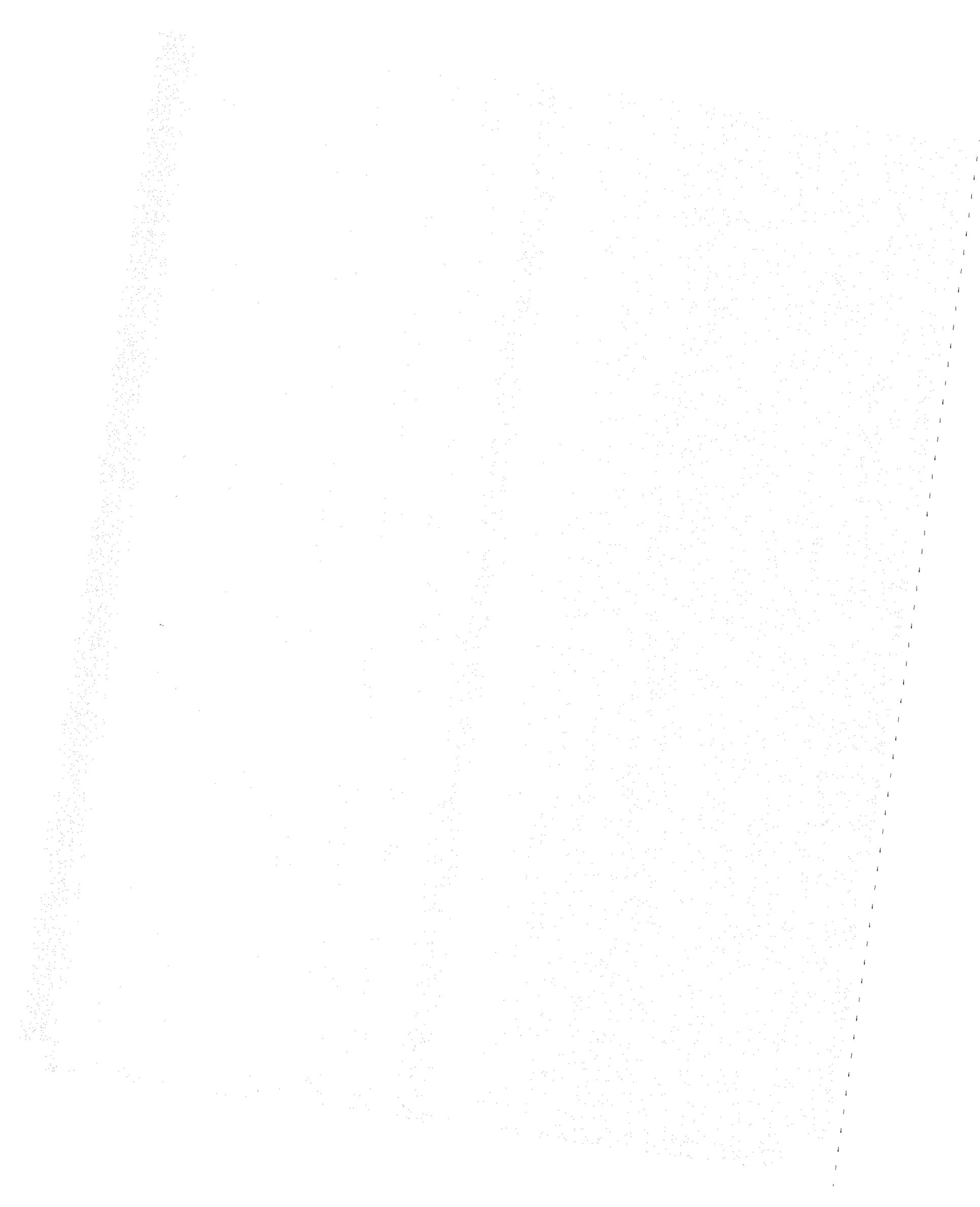
$$\tau = 23 \pm 2 \text{ s}$$

$$t_{\ell} = 16 \pm 2 \text{ s.}$$

Figures 13-15 illustrate the Ecolyzer responses to several fire sources described in Section III: SBR belting, Pittsburgh seam coal, and heptane. Figure 16 plots measured-versus-predicted CO concentrations for the Ecolyzer sensors. The points plotted are composite data for three sensors with the symbol size representative of the variation in the data. Predicted values were obtained using $\tau = 23 \text{ s.}$ and $t_{\ell} = 16 \text{ s}$ and solving eq (4) for $C_g(t)$. For the cold CO source tests, three points were checked corresponding to approximately 20, 60, and 80% of the sensors' final response. For the fire sources, CO concentrations were determined at times when dC_g/dt could be accurately assessed. The agreement is very good and confirms that the Ecolyzer response can be accurately determined for any specified CO source using eq (4) with average values of τ and t_{ℓ} .

4.2.2 MSA CO Sensors

Three MSA CO sensors were tested in a fashion similar to the Ecolyzer sensors, i.e., calibration followed by testing with cold CO point sources and with various fire sources at variable gas velocities. Figure 17 plots the responses of the three MSA sensors to a step input of cold CO at an ambient gas velocity of 0.5 m/s. The responses appear to be comparable to those previously observed for the Ecolyzer sensors. One exception is a somewhat larger variation in response between the different sensors. This was attributed to the calibration procedure supplied with the sensors. Therefore, the sensors were subsequently recalibrated using improved procedures and variations between sensors were nearly identical to those previously found for the Ecolyzer. For comparison, the MSA sensor response at 3.5 m/s is shown in Figure 18. (Again, only one sensor response is plotted for clarity.)



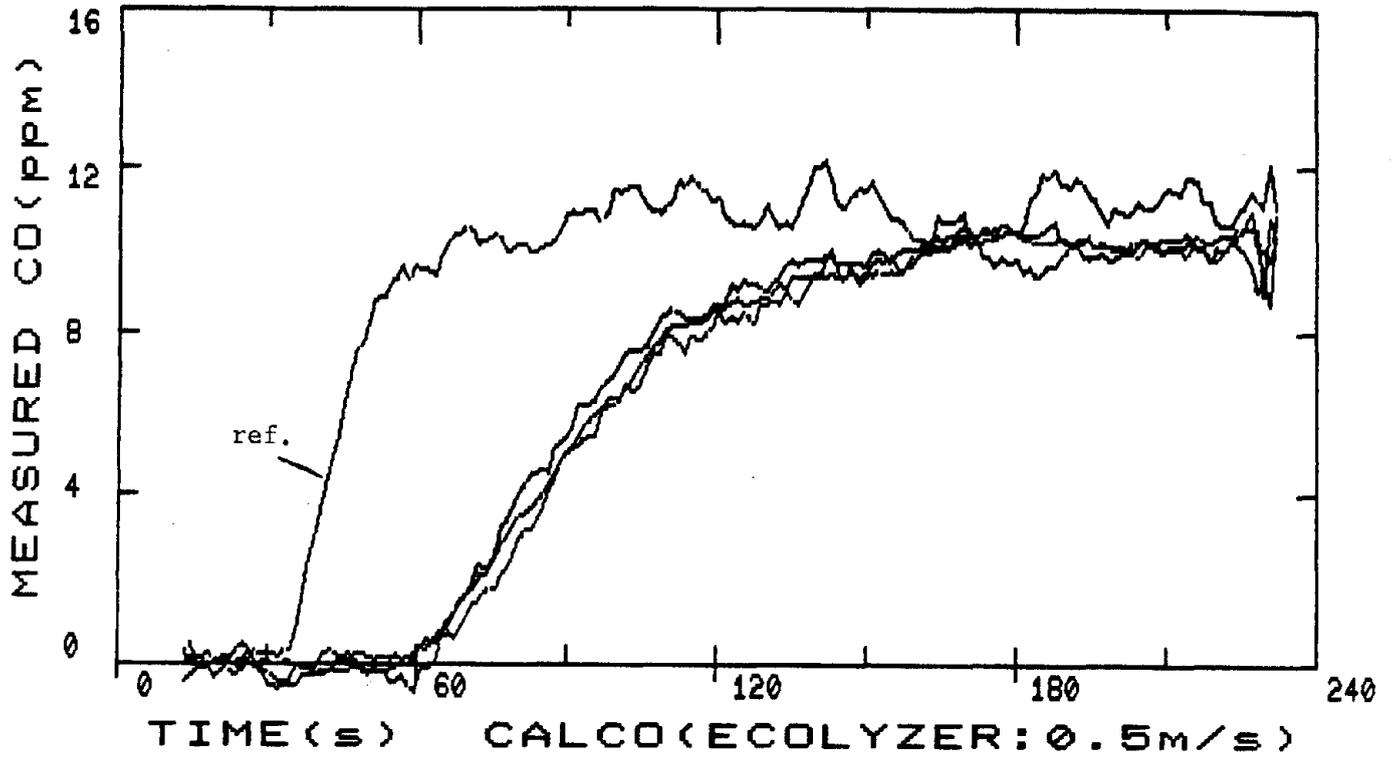


FIGURE 11.- Ecolyzer response at 0.5 m/s with cold CO source

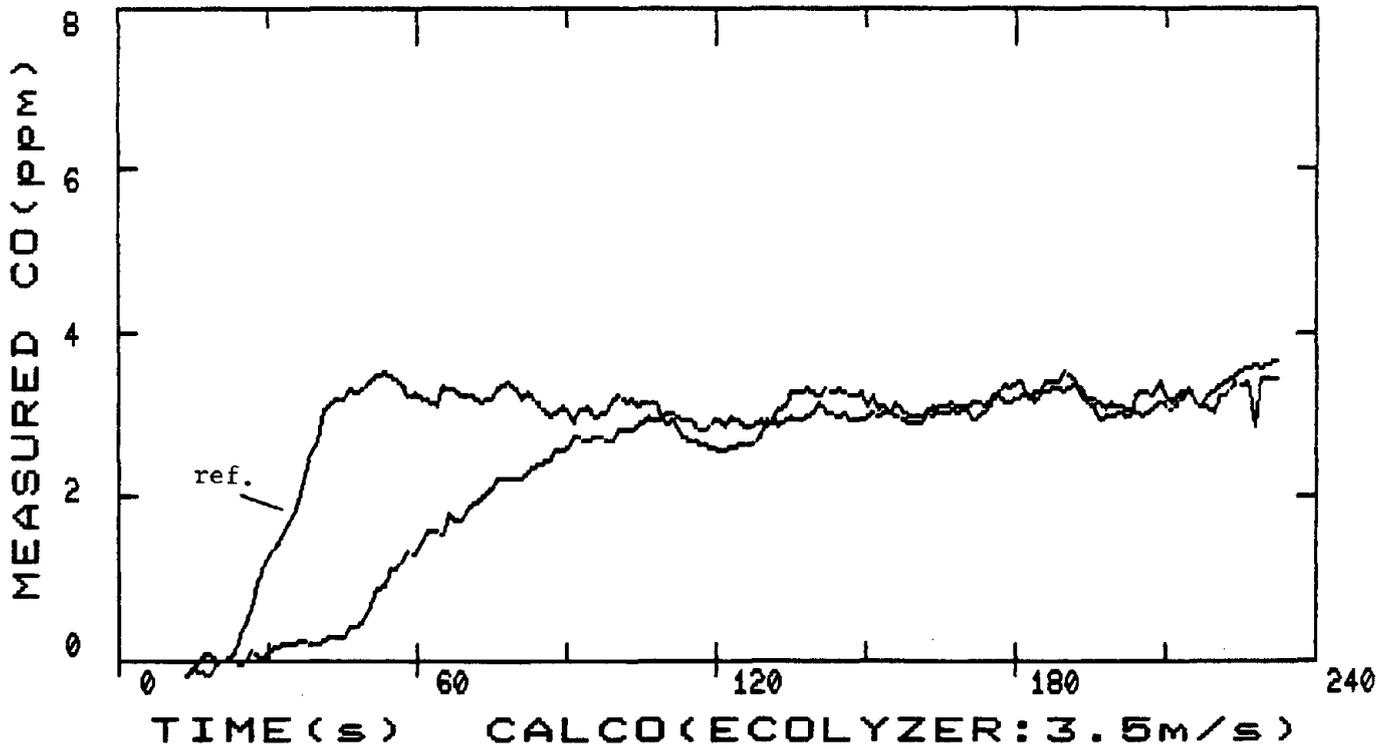


FIGURE 12.- Ecolyzer response at 3.5 m/s with cold CO source

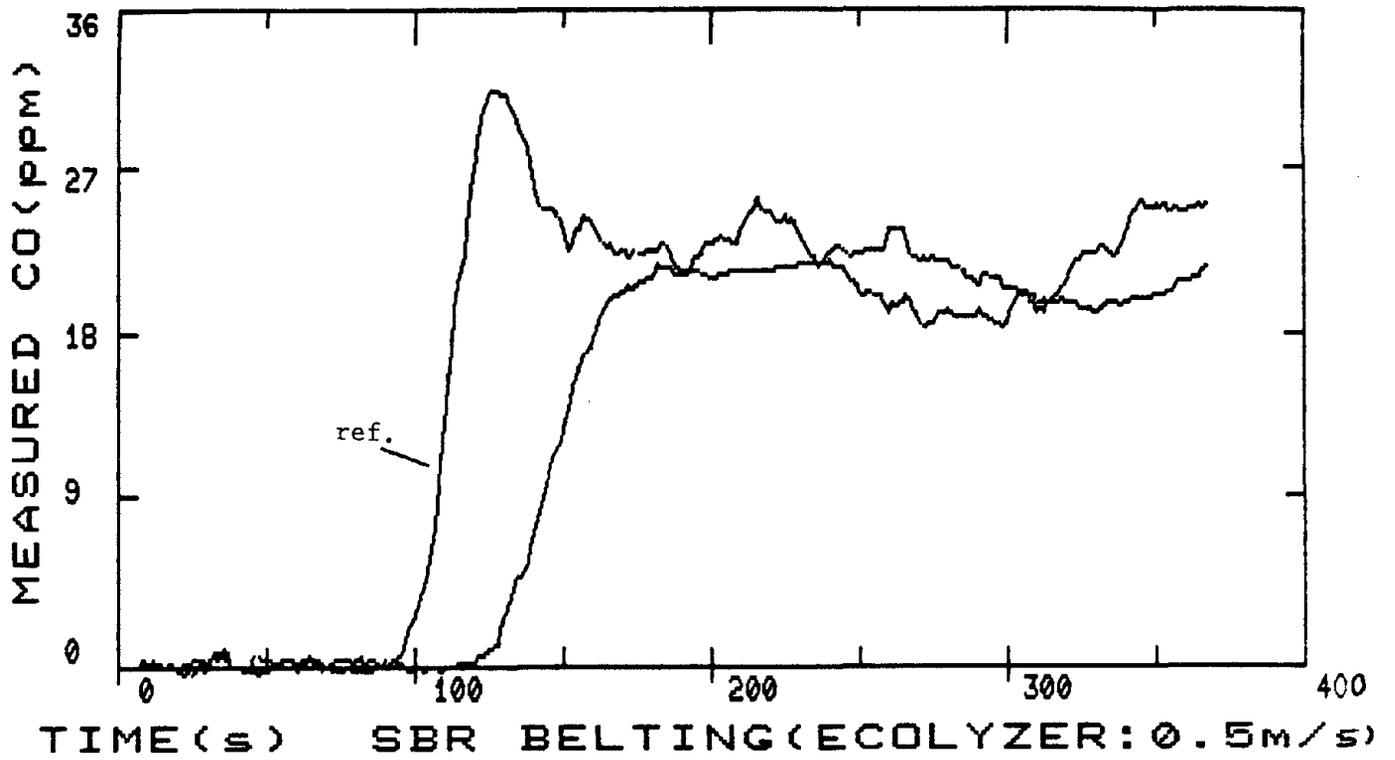


FIGURE 13.- Ecolyzer response at 0.5 m/s for SBR belting

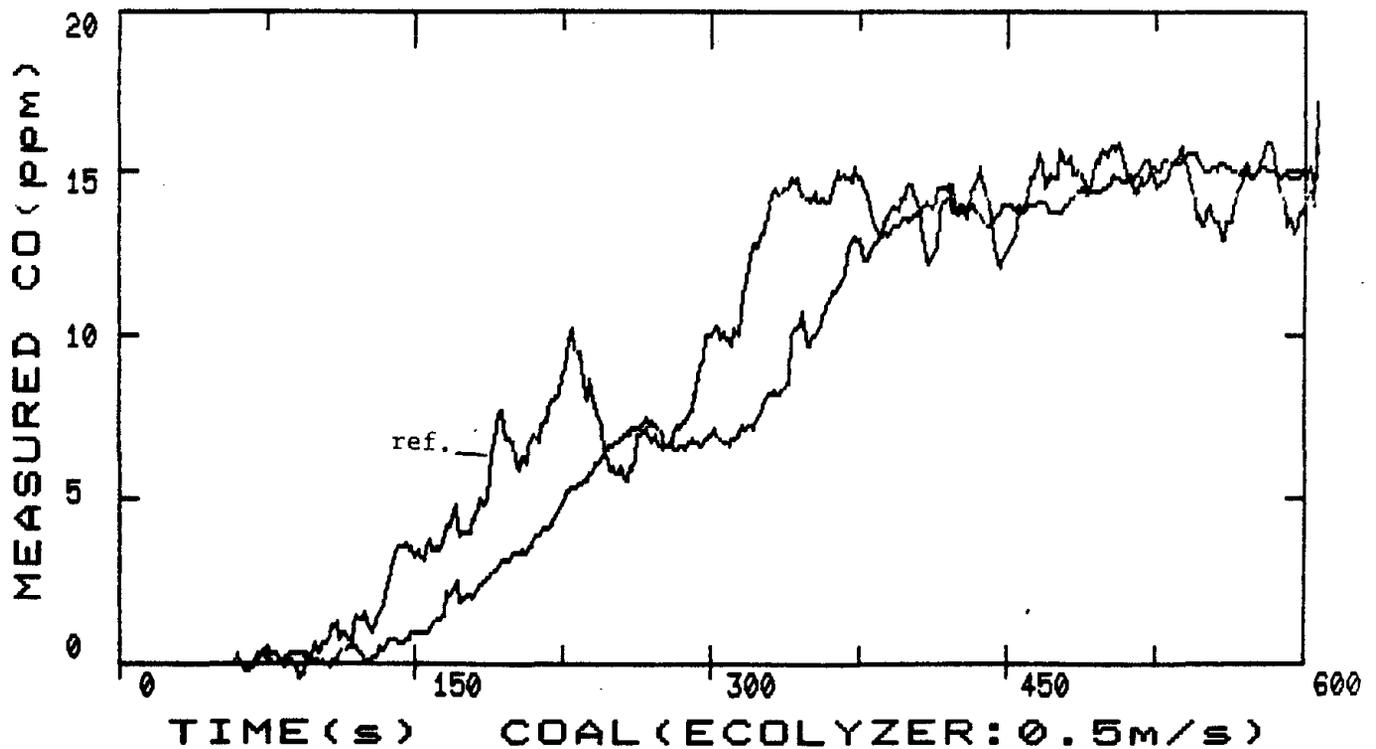


FIGURE 14.- Ecolyzer response at 0.5 m/s for Pittsburgh seam coal

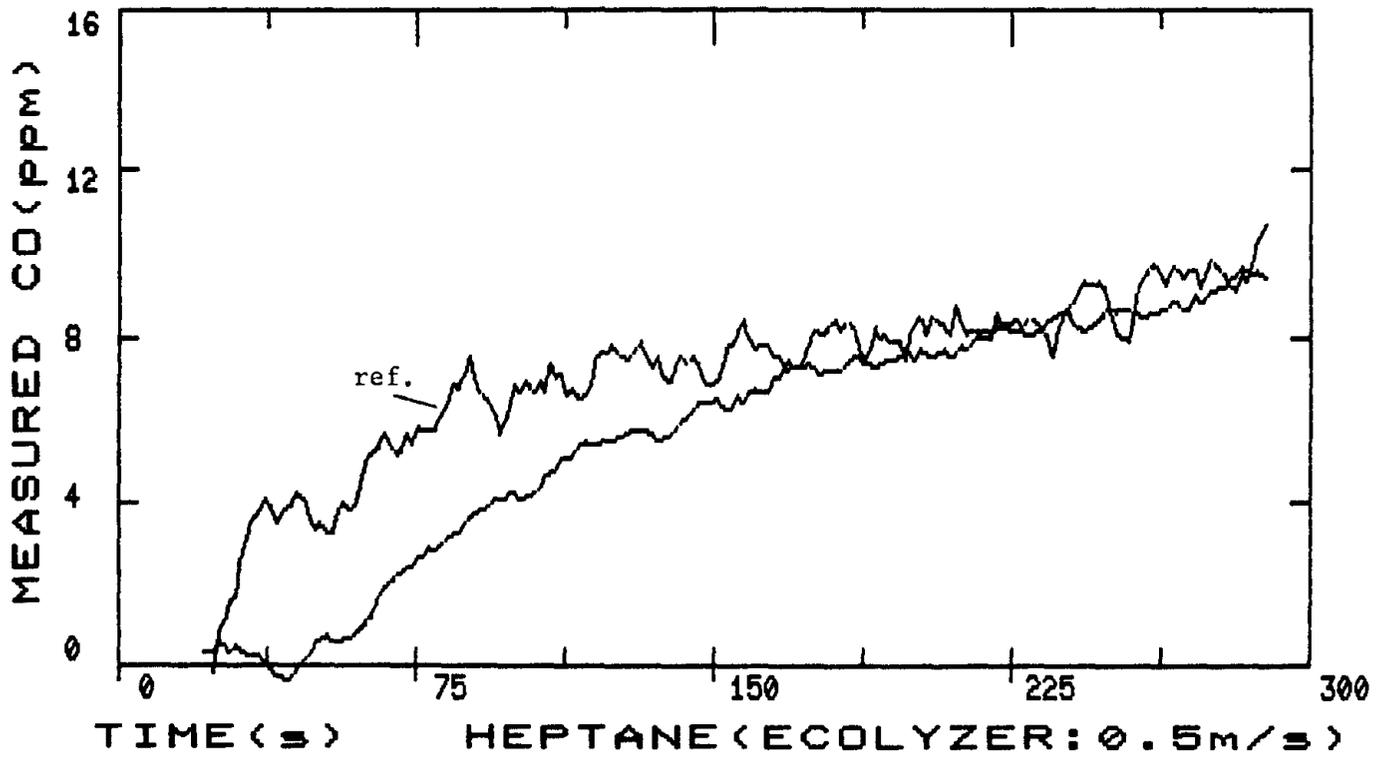


FIGURE 15.- Ecolyzer response at 0.5 m/s for heptane

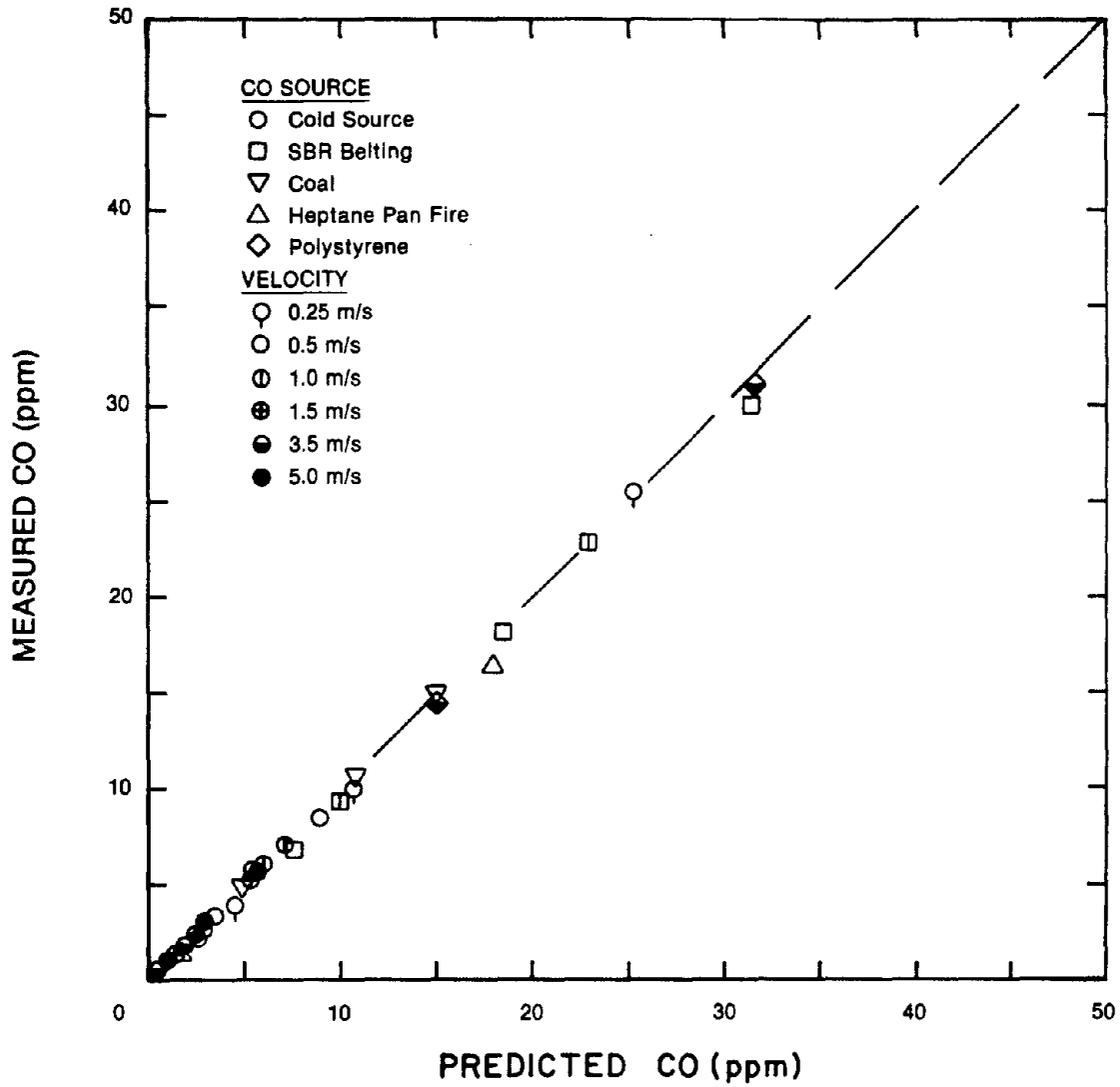
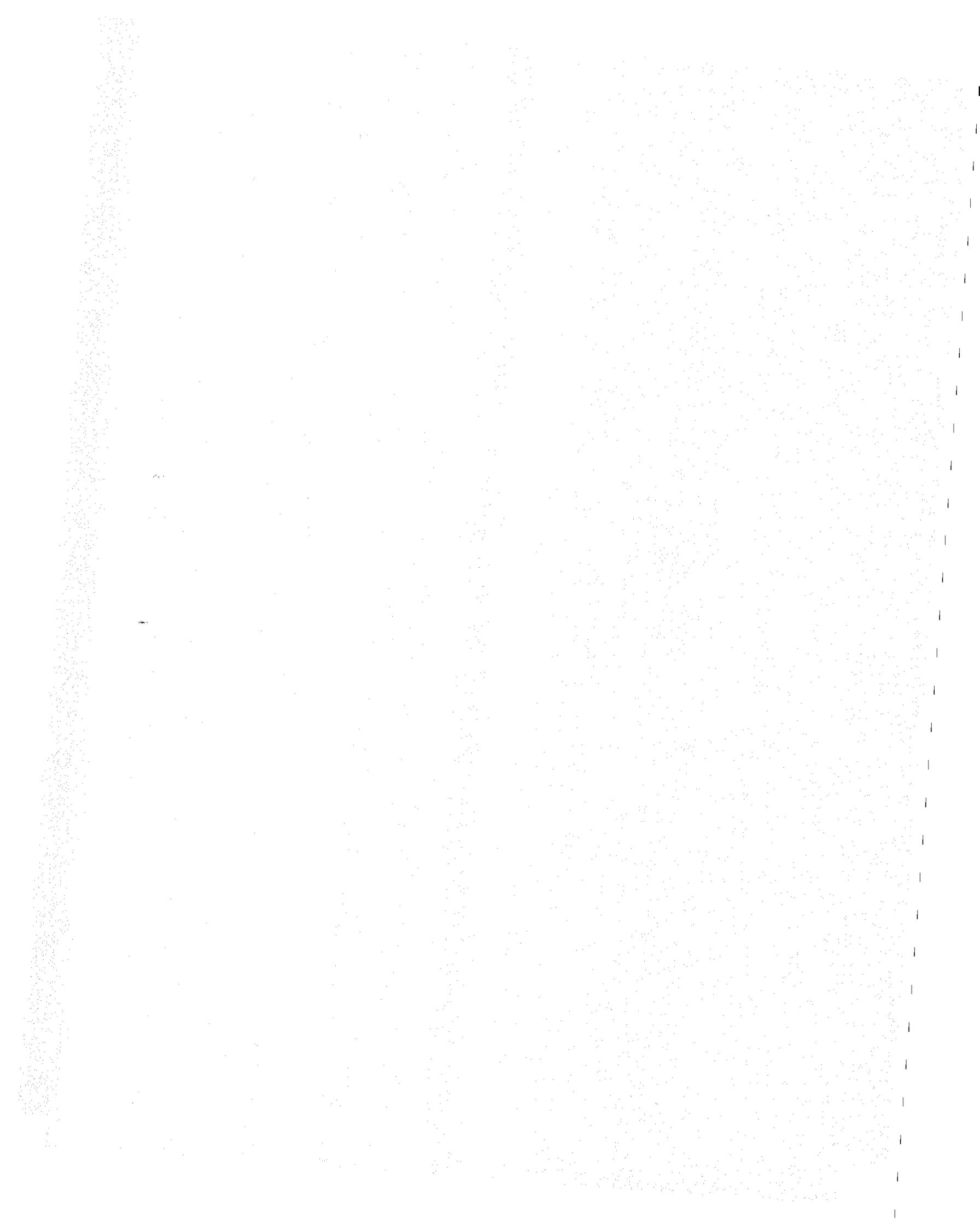


FIGURE 16.- Measured versus predicted CO concentration for Ecolyzer sensors



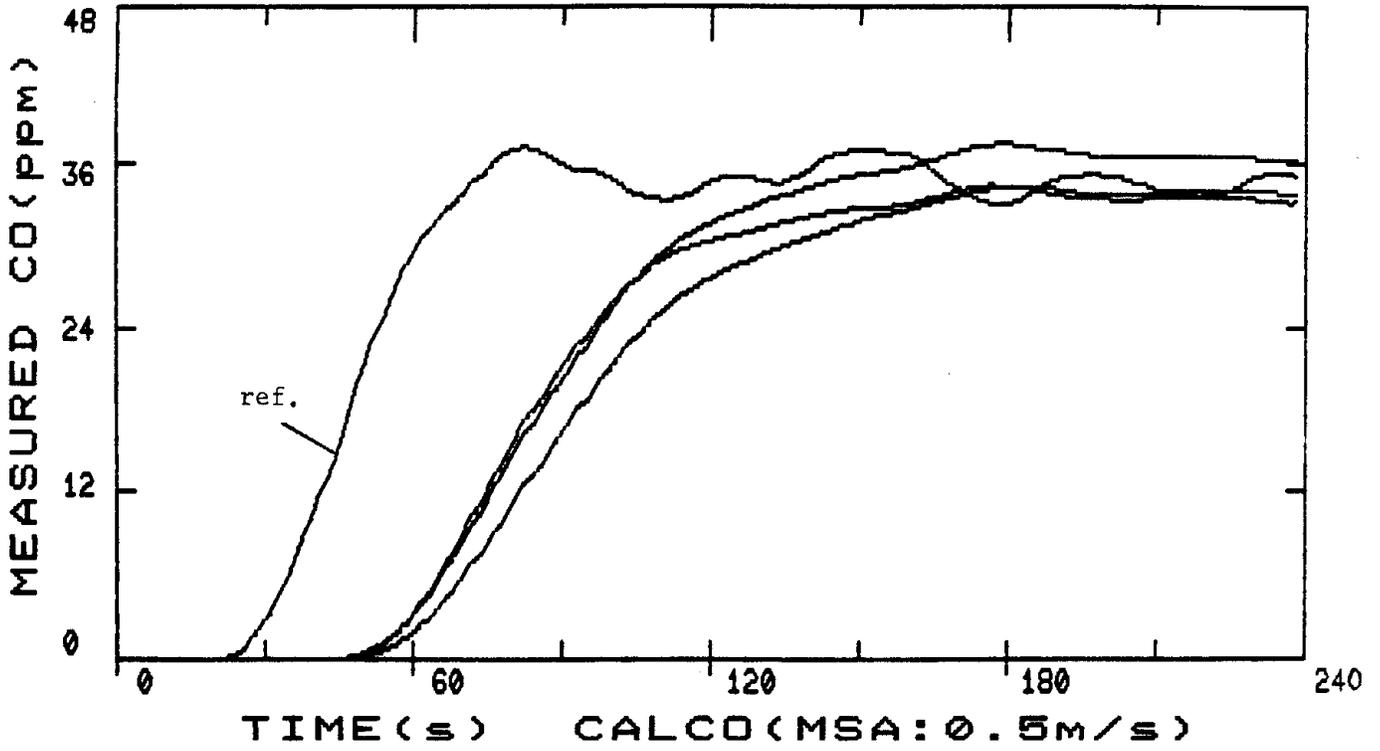


FIGURE 17.- MSA response at 0.5 m/s with cold CO source

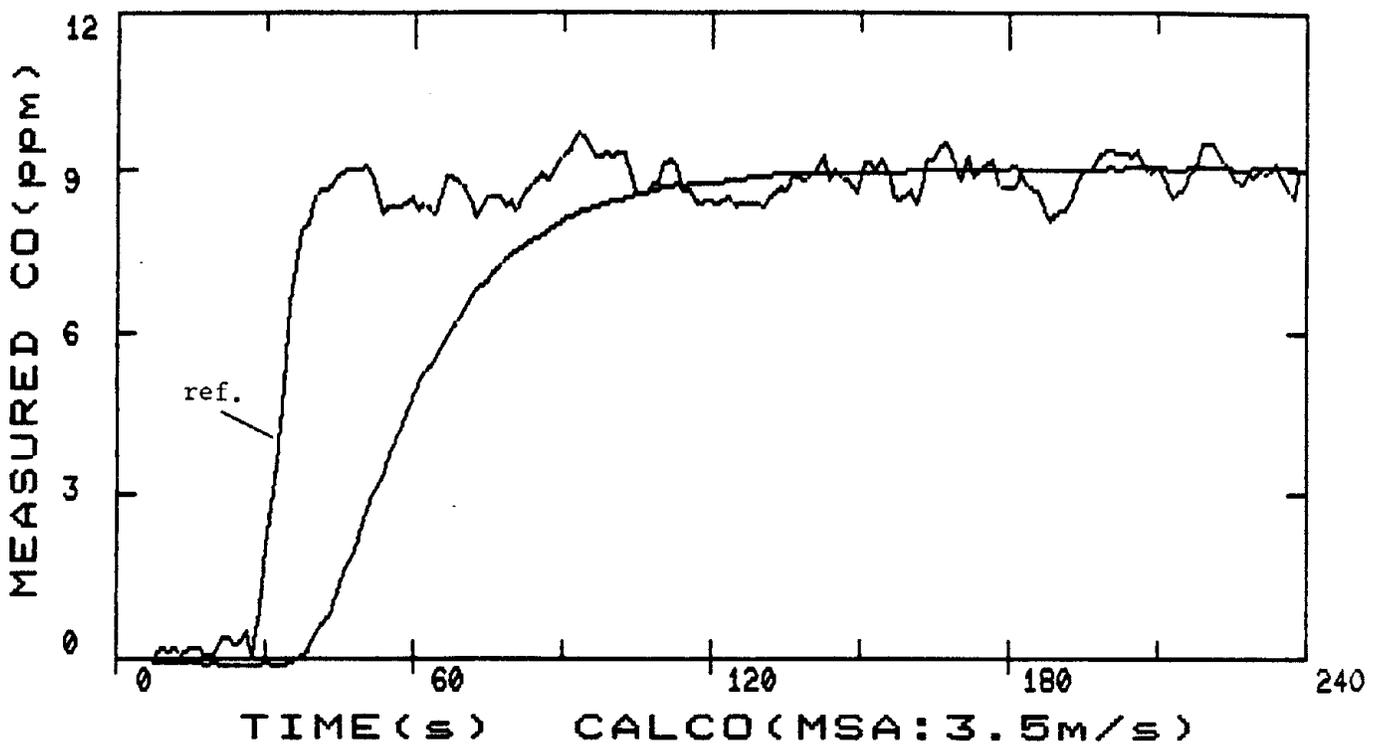


FIGURE 18.- MSA response at 3.5 m/s with cold CO source

The following average values of τ and t_{ℓ} were obtained for the MSA sensors using the method previously described:

$$\tau = 29 \pm 2 \text{ s}$$

$$t_{\ell} = 14 \pm 2 \text{ s.}$$

Again, τ and t_{ℓ} were found to be essentially velocity independent. Figure 19, similar to Figure 16, plots measured-versus-predicted CO concentrations for the MSA sensors. The points, as before, are composite data for the three sensors and were obtained by the same method used for the Ecolyzer sensors. The very good agreement for both the cold CO sources and various fire sources at various velocities as noted in the figure again justifies the use of average values of τ and t_{ℓ} with eq (4).

4.2.3 Ecolyzer Versus MSA Sensor Comparison

In general, no significant differences were found in the performance including response time, accuracy and reliability of the two sensor types tested. Figures 20 and 21, for example, illustrate the responses of the Ecolyzer and MSA sensors to SBR belting and heptane at 0.5 m/s. The responses are very close, such that the variations between the two sensor types are within the individual variations observed for the three sensors tested of each type (consequently, labels delineating the two different sensors have been left off intentionally).

The following is a composite list of observations about the two sensor types:

Ecolyzer Sensors

- 1) Although some difficulty occurred initially with the sensor cells leaking no problems were observed with replacement cells.
- 2) The response times increased due to some clogging of the sensor filters after extensive fire testing with exposure to very sooty fire sources. While this was remedied by cleaning of the filters, in practice the filters should be simply changed periodically.
- 3) The documentation describing the system and its components is good.
- 4) The sensors were observed to respond accurately at ambient temperatures up to 60°C for the duration of the fire tests.
- 5) The sensors are conveniently and accurately calibrated.
- 6) Sensor drift at laboratory ambients is approximately ± 1 ppm/month.

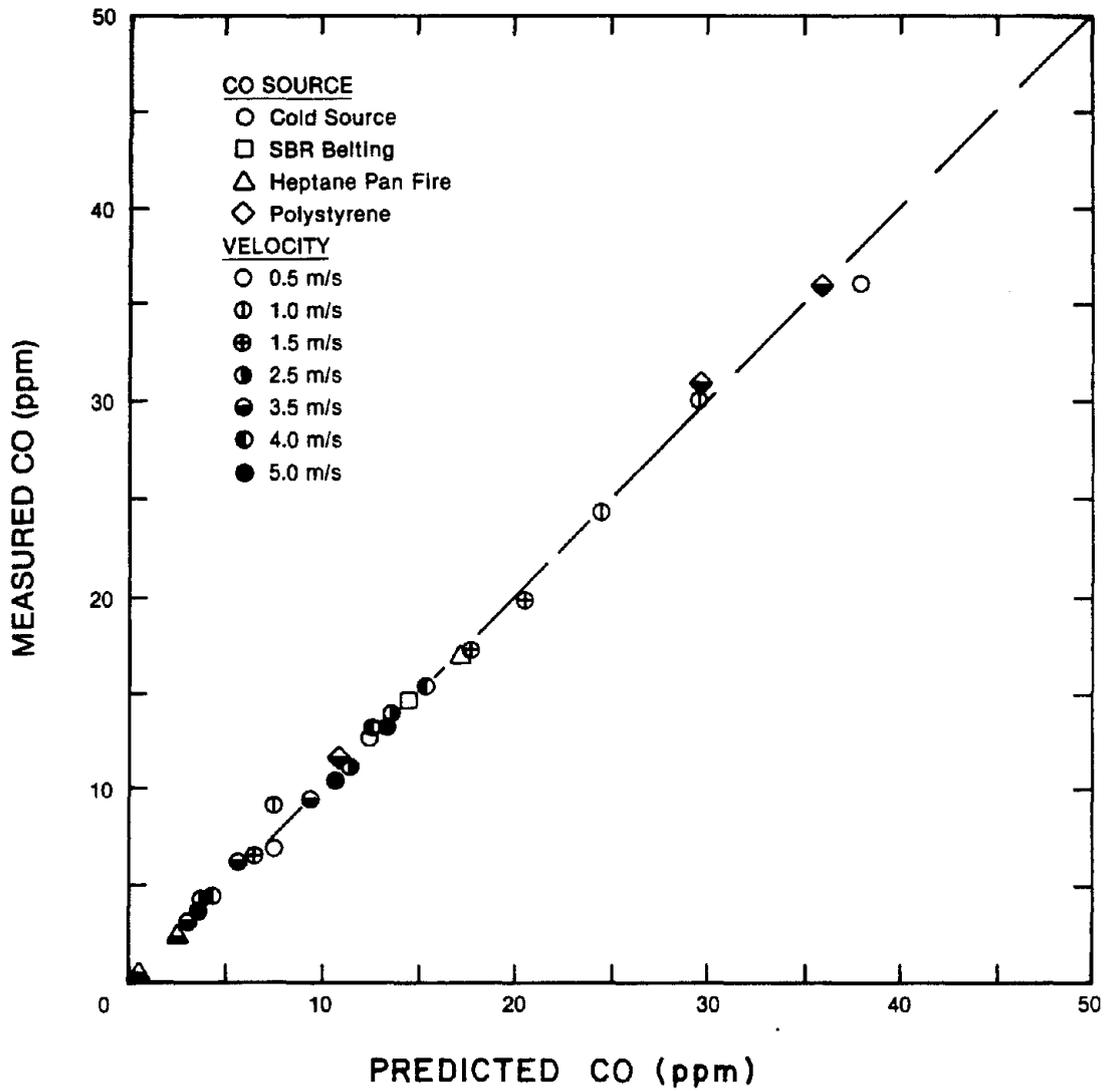
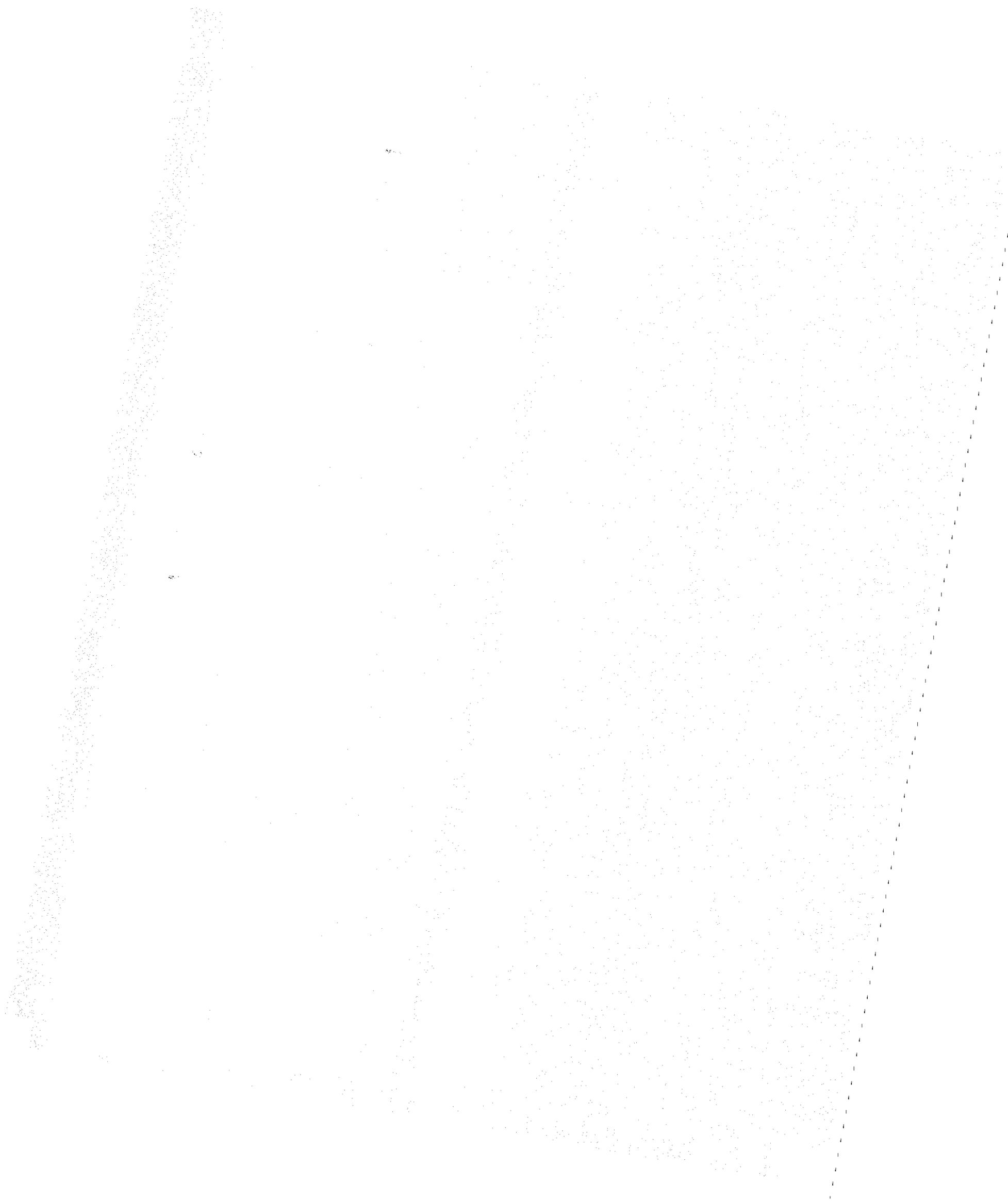


FIGURE 19.- Measured versus predicted CO concentration for MSA sensors



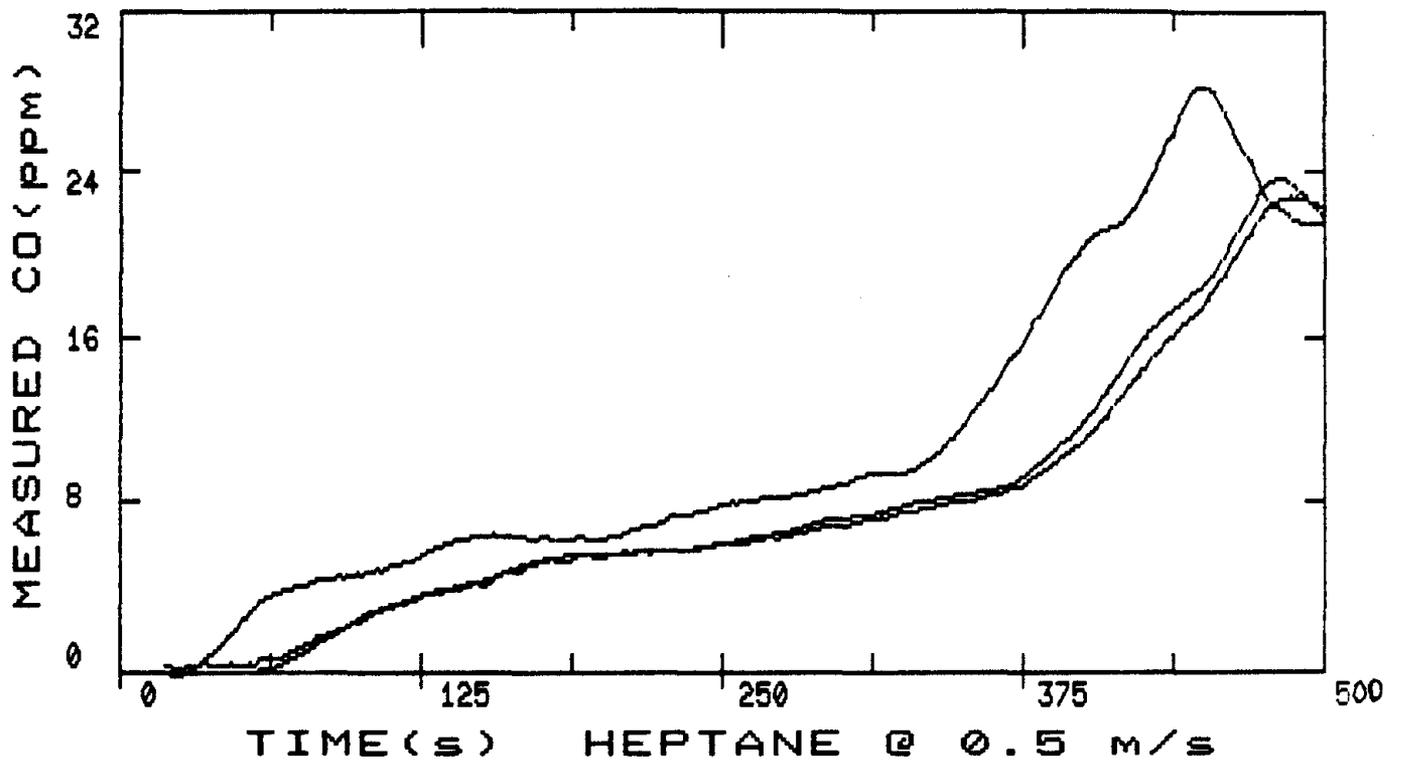


FIGURE 20.- Ecolyzer and MSA response at 0.5 m/s for heptane

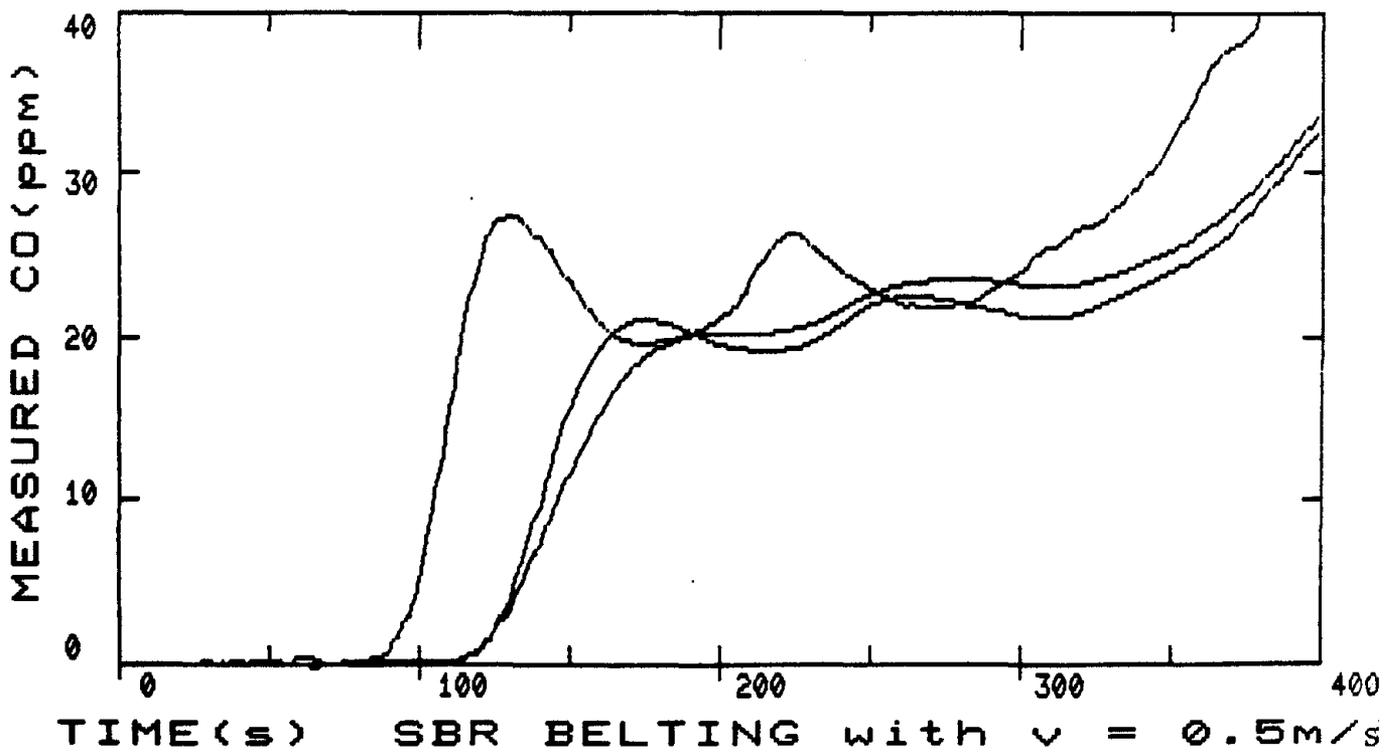


FIGURE 21.- Ecolyzer and MSA response at 0.5 m/s for SBR belting

7) The sensors can be calibrated at one range, i.e., 500 ppm and accurately switched to a second range, i.e., 50 ppm without recalibration.

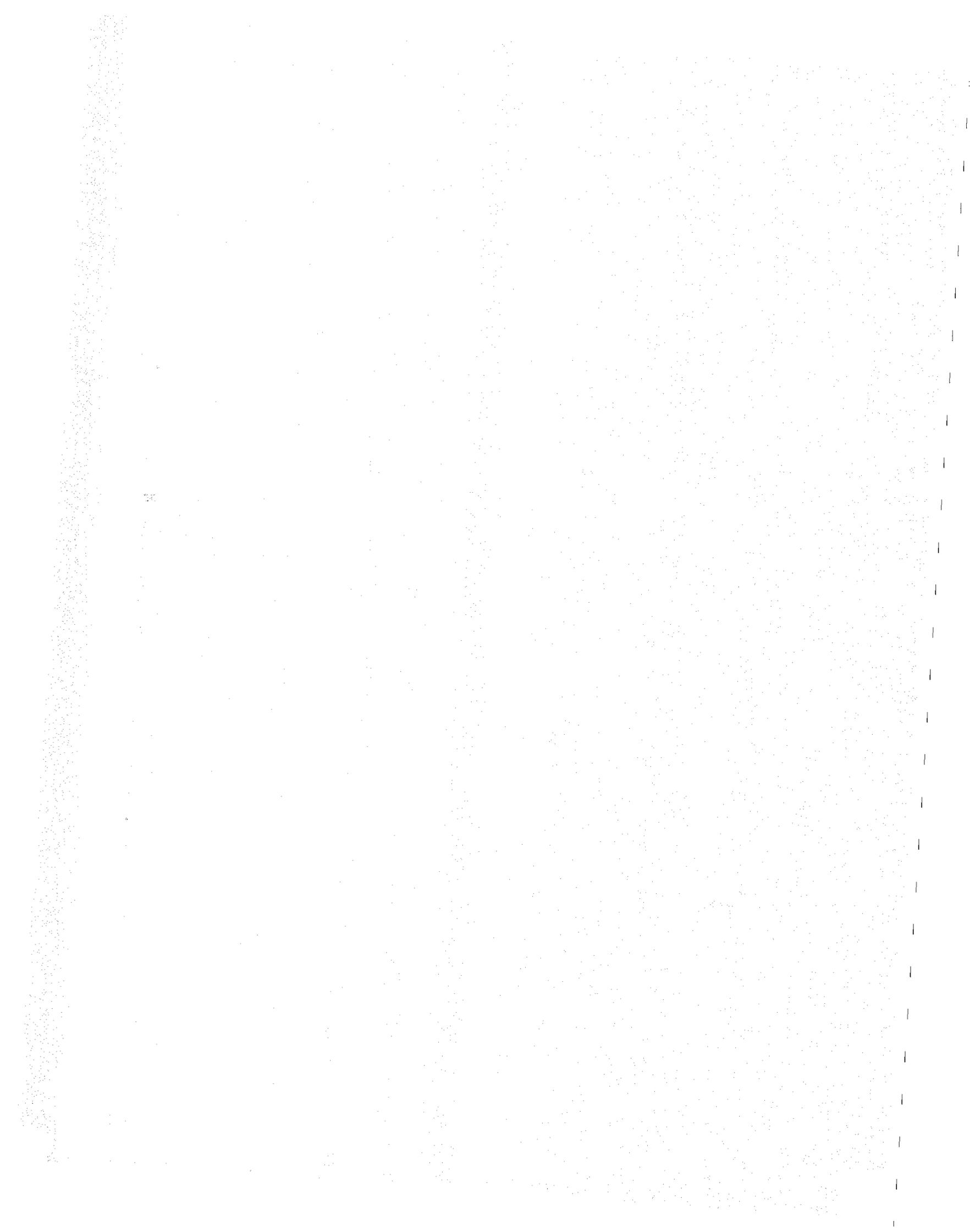
8) The sensors remained in calibration throughout the course of testing (approximately three months).

MSA Sensors

1) The calibration procedure including method of input gas introduction is incomplete.

2) The documentation for this prototype system still needs to be developed.

3) Sensor drift at laboratory ambients is approximately ± 1 ppm/month.



FUTURE WORK

In addition to the Phase IV work efforts described in Section 1.3, further testing is being considered for the previously investigated Ecolyzer and MSA CO detectors. Other sensor detection principles will also be evaluated.

5.1 ADDITIONAL TESTING FOR CO DETECTORS

The applicability and advisability of additional testing, similar to that described in the Instrument Society of America's tentative standard ds 12.13, Part 1, "Performance Requirements - Combustible Gas Detectors" (April 1982) and the Factory Mutual Research Approval Standard "Combustible Gas Detectors" (September 1982), is being investigated for possible inclusion in Phase IV work efforts. This type of testing, when applied to CO detectors, could be useful for the assessment of detector response, reliability and suitability for a particular mine fire environment application. Although the suitability of both the Ecolyzer and MSA sensors as mine fire detectors has been demonstrated, additional testing, for example, in the following areas may be desirable:

- 1) temperature/humidity variation,
- 2) gas humidity variation, and
- 3) electromagnetic interference.

5.2 EVALUATION OF OTHER SENSOR DETECTION PRINCIPLES

In order to extend the developed testing procedures to other sensor detection principles, arrangements are being made to purchase and test two additional fire detector types: 1) three Becon Mark IV ionization detectors, and 2) one Spanair CO₂ gas analyzer. These detectors have been specifically developed for mining applications.

VI
CONCLUSIONS

On the basis of the test results and analysis of the Phase III work efforts, several conclusions were made relating to the development of standardized test criteria and procedures for mine fire detectors:

1. The test apparatus performs as designed and is capable of accurately evaluating potential mine fire sources as well as simulating a wide range of mine fire environments.
2. Several fire sources, including Pittsburgh seam coal, SBR fire retardant conveyor belting, heptane, and polystyrene, have been characterized relative to mass loss rates, critical heat fluxes, and generation rates of heat and gas species.
3. The mass loss rate of coal has been shown to follow an analytical formulation based upon the external and critical heat fluxes.
4. Heat detectors can be characterized using the concept of "RTI," response time index, which is a well defined function of the detector time constant and the gas velocity.
5. The values of RTI for mine-permissible heat detection systems vary by more than a factor of 30, between 12 and $382 \text{ (m}\cdot\text{s)}^{1/2}$.
6. CO diffusion gas detectors can be characterized by a time constant and a lag time.
7. Both CO sensor types evaluated, one made by Energetics Science and the other by Mine Safety Appliances, accurately and reliably respond to mine fire sources.
8. Additional testing including other sensor detection principles should be considered in Phase IV work efforts.

NOMENCLATURE

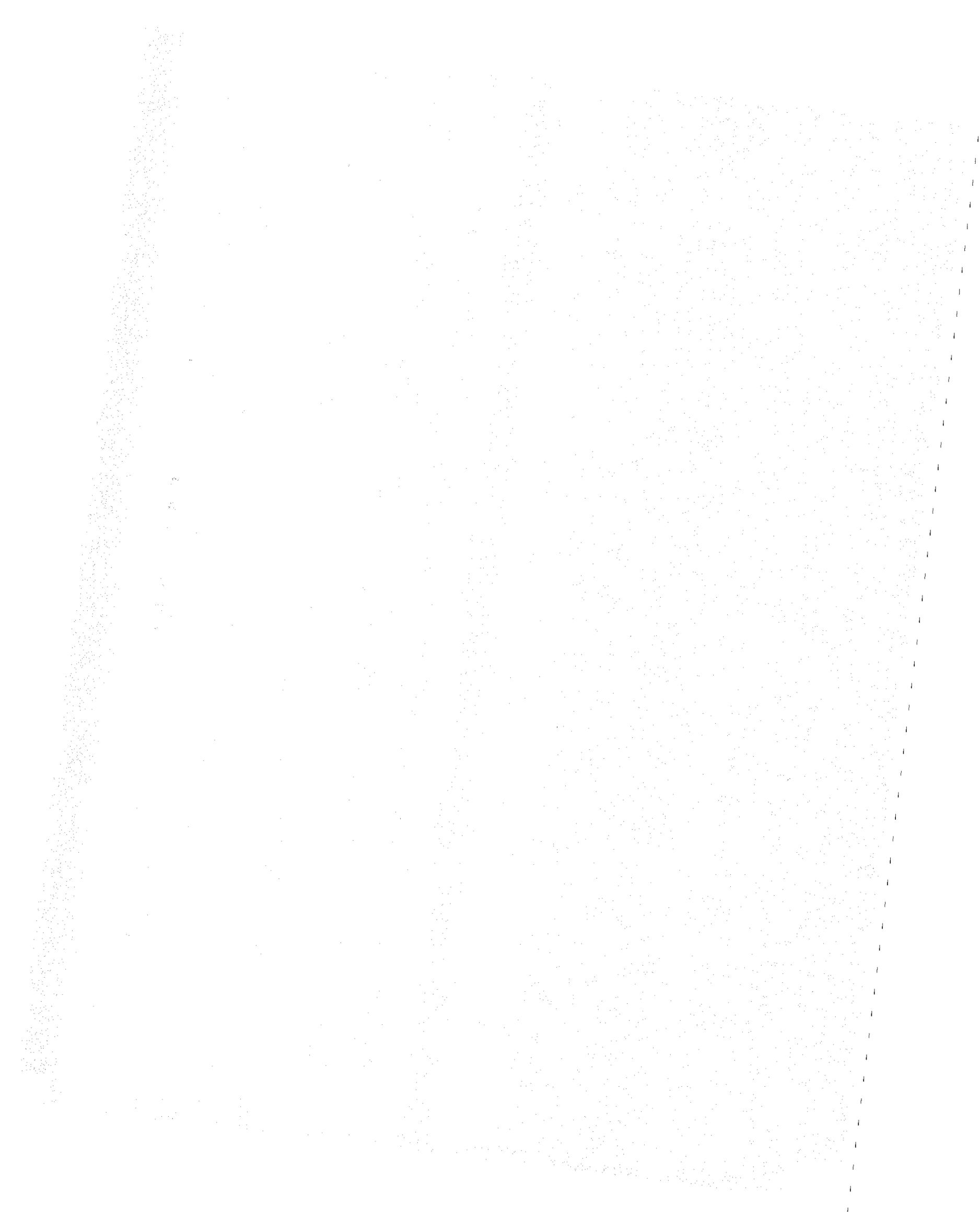
c	gas concentration (ppm)
E	energy (kJ/m^2)
H	heat of combustion (kJ/g)
k	constant in eq (1)
\dot{m}''	mass loss rate ($\text{g/m}^2 \cdot \text{s}$)
\dot{q}''	heat flux (kW/m^2)
\dot{Q}''	heat release rate (kW/m^2)
RTI	response time index ($\text{m} \cdot \text{s}$) ^{1/2}
t	time (s)
v	gas velocity (m/s)
Y	mass yield of combustion product (g/g)

Greek

τ	time constant (s)
χ	fraction

Subscripts

A	actual
CO	carbon monoxide
CO ₂	carbon dioxide
cr	critical
e	external
H ₂ O	water
i	individual products (CO ₂ , H ₂ O, CO, THC)
ig	ignition
l	lag
o	reference or centerline
p	peak
s	sensor
THC	total hydrocarbons



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