NUREG/CR-1798
BNL-NUREG-51296
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ACCEPTANCE AND VERIFICATION FOR EARLY WARNING FIRE DETECTION SYSTEMS

(INTERIM GUIDE)

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May 1980

PREPARED FOR THE
U.S. NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555
UNDER INTERAGENCY AGREEMENT DE-AC02-76CH00016
NRC FIN NO. A-3335

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
and
National Technical Information Service
Springfield, Virginia 22161

ABSTRACT

This report has been written to provide an interim guide accounting for the basic factors that should be considered in formulating a fire detection system selection criteria and the verification of such a system.

The fire detection system selection criteria that is proposed here still requires a viable mix of good engineering judgement, the use of qualified investigators, and excellent reporting and administrative procedures; all of which should be coupled to the results of current research that has been discussed herein.

The fire detection analysis should address five major phases required in a fire detection analysis, viz, (1) establishing area detector requirements, (2) selection of specific detector types, (3) location and spacing of detectors, (4) installation tests and maintenance, and (5) administrative controls and reporting.

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1.0 INTRODUCTION

1.1 Background and Scope

The Nuclear Regulatory Commission (NRC) mandates the need for early detection and fire control in a nuclear power plant to limit damage to safety-related shutdown systems. Thus, fire detection, alarm, and extinguishment systems must be designed to the specific hazard to be protected in order to optimize both the operational effectiveness and economics of the system. However, the guidelines for the selection and installation of early warning fire detection systems to meet the general requirements found in General Design Criteria 3, "Fire Protection," of Appendix A to 10 CFR 50, "General Design Criteria for Nuclear Power Plants"(1) are currently based upon national standards and guides that present only the minimum requirements and are based upon specific fires typical of commercial or residential occupancies.

There are, however, a number of environmental factors and plant safety requirements, unique to nuclear facilities which preclude proper assessment and validation of the adequacy of these traditional detection-system design approaches. The environmental factors which require more in-depth study than has heretofore been undertaken include the effects of the following on early warning detection system performance: ventilation; room size, ceiling height, configuration and construction; area congestion; background radiation; and, none the least, the different types of combustibles common to nuclear power plants. Thus, even skilled interpretation of recommendations and requirements in present National Fire Protection Association (NFPA) Standard 72E(2) which may provide a basis for better than minimums may be, as yet, inadequate.

Consequently, designers for fire protection systems in nuclear power plants have, in the past, resorted to approaches that include interpretations of various fire codes and test laboratory standards, recommendations from fire consultants and architectural engineering firms, suggestions by various fire detector vendors, and requests from insurance agencies to formulate a fire detection system that may adequately meet the defense-in-depth posture for fire safety.

Indeed, evaluations of these various detection system approaches taken, in concert, with current state-of-the-art technology and research in fire detector test methods and site determinations may then lead to a unified treatment in fire detection system appraisal. Accordingly, the purpose of this report is to present an interim guide whereby (1) the reliability of existing installations can be more effectively assessed and deficient systems modified, (2) provide guidelines for types and locations of fire detection devices for new power plants, and (3) provide, as background material, the most recent information to date on detector selection and siting criteria.

At this juncture, it must be emphasized that further research is imperative, especially directed to the needs of fire safety in nuclear power plants; and that only by good sound engineering judgement by engineers competent in areas of fluid dynamics, heat and mass transfer, and fire protection to evaluate the overall hazard in conjunction with the various subjects discussed herein can an interim acceptance criteria be formulated.

1.2 General Considerations: Early Warning

Any detection system should be carefully and properly engineered to provide the degree of protection desired for the particular hazard present. Usually the system may be needed primarily for life safety, for property protection, for protection of specific pieces of equipment or a combination of these needs. Fire safety in nuclear power plants, from a detection viewpoint, is more restrictive since detection of appropriate capability and suppression systems of adequate capacity must be provided where the potential fire hazard may jeopardize safe plant shutdown. Thus, safety-related systems must be operative during the detection/suppression stages of the fire protection system and/or the detection system must alarm before redundant safety-related systems become impaired.

Thus, the purpose of a fire detector, in particular, and a fire detection system, in general, is simply to detect and usually to activate some system, whether it is an alarm, an extinguishing system, or other device. This definition really circumvents the issue, however, on what should be the criteria for a detector installation. The criteria must vary depending upon the occupancy and the design situation. For example, for life safety, detection systems must be designed to activate prior to the attainment of untenable conditions occurring within the safe egress path. This criterion may be the time that the interface between the upper (hot and/or smokey) layer and lower (clear air layer) layer drops to a preassigned level to permit safe egress before the effects of smoke and/or thermal radiation reach levels beyond human tolerance. Also, if the purpose of detection is to permit the extinguishment of the fire either manually or automatically, a threshold of the heat release rate of the fire at the moment of detection must be selected such that the energy absorption rate of the suppression system be greater than the heat release rate of the fire at the time of suppression. Note that for manual fire fighting systems, knowledge of brigade response time must be factored into the quantification of early warning. Such a criterion is mainly required for property protection. For nuclear power plants where safe shutdown is crucial, operation of safety-related systems during the <u>initial</u> stages of fire development also requires that early warning systems should activate alarm and/or suppression systems before the fire damages the cables that supply power and control to these particular items of equipment. Thus, in addition to determining the initial convective flow of the fire, one must also have knowledge of the mass pyrolysis rate of the generic cables so that times to electrical short may be assessed. This report will discuss how these factors may be used to determine response time.

1.3 General Considerations: Acceptance Criteria

Acceptance of an early warning fire detection system, in the context of nuclear power-plant safety requires, as a minimum, that the detection system criteria effectively consider the following general topics:

- classification of protection requirements - area protection, equipment protection, smoke movement control
- degree of protection requirements - consideration of detection speed as a function of risk; allowances of a certain number of false alarms to increase overall detection speed; amount of damage one could sustain.
- detector selection requirements - the fire signature should possess a measurable change, i.e., a good fire signal-to-background noise ratio; detector sensitivity parameters must relate to this fire signature.
- detector location - optimum grid spacing and/or spot location should account for room height, heat release rate, nature of the fire plume, its spread, threshold fire size, and environmental factors.
- properties of the combustibles - size distribution of aerosol particles, etc.
- installation testing and maintenance requirements - establishment and implementation of procedures to ensure that testing is performed and verified by inspection and audit to demonstrate conformance with design and system readiness requirements.

Each of these factors will be discussed in more detail in the following sections of this report.

The key point in formulating a general acceptance criteria is that establishment of definitive design rules and quantification of what constitutes "early warning" is still, as yet, beyond present-day technology in detection analysis. Indeed, present research, as this report will show, can provide better guidance in such matters; and as such, an acceptance criteria should be based upon an intelligent application of a system design approach accounting for all the factors enumerated herein. Thus, the answer to the question as to what detector and system arrangement are necessary must be based upon a logical decision process by individuals qualified in fire protection or system designers familiar with all types of detection equipment.

1.4 General Considerations: Verification Criteria

Verification of acceptable early warning detection systems is, at best, determined through their use in practice under the most diverse conditions. Obviously, fire detection system designers cannot wait for this experience to accumulate in order to verify the adequacy and safety margin of an installed system. Presently, testing of automatic fire-detection devices can be divided into two phases. The first is the standardized testing of devices submitted by manufacturers to the approval laboratories. The second is the research testing of the performance of fire detectors in simulated full-scale experiments.

Ideally, the response of a detection system should be confirmed using a test fire under environmental conditions anticipated to occur normally in the area being protected. The test fire should produce the type and degree of flame, heat, smoke, and combustion products characteristic of combustibles found in the protected area. Environmental conditions should also be representative.

Detector studies have made recommendations of augmenting existing qualification test methods incorporating procedures used in several European countries, notably West Germany. This procedure involving fifteen different tests of three fire sizes for each of five combustibles does indeed represent a broad spectrum of fire types, detector sensitivities and test combustibles. For nuclear plant operations, this procedure has some shortcomings since the effects of ceiling heights, ventilation conditions, and some combustibles common to reactor facilities are not within the realm of this type of test procedure. However, this latter deficiency can be circumvented, if guidelines suggest that prospective bidders of fire detection systems run qualification tests like those to be described using combustibles, notably cables, generic to the specific plant.

Understandably, there still is a great deal of difficulty in characterizing the adequacy of a fire detection system because of numerous room configurations and environmental conditions which can affect detector performance. In this regard, recommendations made by Berry,[3] who thoroughly reviewed the fire detection codes, standards, detection literature, and nuclear regulatory guidelines, in the use of in-place testing of detectors under conditions expected to occur normally in areas being protected is logical but unfortunately impractical for verification in existing operating facilities. For newer plants under construction this approach, in conjunction with the European concept cited above, should require further consideration since such tests will not affect the normal operation of the plant. Granted all effects on detector performance cannot be addressed in this early stage of plant construction but at least the effect of room size, ceiling configuration and height, threshold fire size, and combustible can, to some degree, adequately assess the performance of selected detectors.

For existing facilities general considerations for verifying early warning detection systems can only be addressed by indirect, albeit consistant, means. These considerations must include:

- threshold fire testing in large scale test enclosures including effects of ventilation;
- determination of an acceptable fire size;
- sources of ignition: open flame, heat conduction, convection
- determination of sensitivity range of detector using electrical cables as combustibles;
- determination of room ventilation patterns using tracer gas techniques or other site survey methods;
- in-place testing of units using commercially available particle source generators.

Factored into the above is also design criteria for performing installation testing and maintenance. Detector installation test procedures must be addressed by the plant's overall fire detection analysis and should include the factors listed in Section 1.3.

A detector maintenance procedure must also be developed. This procedure should identify the maintenance details and maintenance intervals required for each installed detector type. Recent U.L. standards (U.L. 268)[4] offer some guidelines on the basis of analyses or testing that demonstrate a detector's reliability.

This introduction has, in general terms, touched upon the necessary aspects for determining the acceptability of an early warning fire detection system. Broad areas which the licensee must address in their fire detection analysis should include (1) establishment of area detection requirements, (2) selection of specific detector types, (3) location and spacing of detectors, and (4) performance of installation tests and maintenance.

Because of the myriad of factors that can affect system performance, the key point in the design of a given early warning system should be the intelligent application of a systems design approach accounting for the factors cited above and detailed subsequently. Although this approach will emphasize the use of a technically sound deterministic method in preference to a purely subjective evaluation, it is also recognized that for some of the relevant factors a lack of theoretical or experimental precedents will require that one rely on subjective judgement. Accordingly, this process should always involve qualified individuals familiar with all aspects in detection systems and the factors that influence their operation.

2.0 SYSTEM DESIGN PARAMETERS

At the present time there are no recommended, unified guidelines covering system design requirements for early warning fire and smoke detection systems. In the past, information pertinent for designing an effective system has been scattered and difficult to locate. Recent research, discussed by Benjamin[5] Bukowski and Mulholland[6] and Bright [7] has uncovered many factors to take into consideration in the design of that type of system. Phillips[8] also furnishes a compilation of current information and concepts that should be of assistance in the design, installation and acceptances of detection systems. The following attempts to consolidate and augment these new findings and guidelines for direct application to nuclear facility designer's fire protection needs; but first, some preliminary groundwork is necessary to outline basic principles which should be recognized in the design and layout of an acceptable early warning detection system.

2.1 Stages of Fire Development

Most fires in solid combustibles develop in four stages: incipiant, smoke, flame, and intense heat. In the incipiant stage, invisible particles are produced with little or no visible smoke, heat or flame. In the smoldering stage invisible particles of combustion as well as visible smoke are present with however still no measurable quantity of heat or flame produced. The flaming stage, which depending upon the combustible can be the first stage present, occurs with no visible smoke or significant energy release but, by the combustion process, can produce measurable quantities of gaseous products.

The final stage of the fire develops with the production of both visible (smoke) and invisible (gas) products of combustion, as well as measurable quantities of flame radiance and heat. Thus, from the moment of its initiation, a hostile fire produces a variety of changes in the surrounding environment. Any product of a fire that changes the ambient conditions can be referred to as a "fire signature."

2.2 Fire Signatures

To be useful from a detection viewpoint, a fire signature should possess a measurable change of sufficient magnitude so as to be greater than normal background variations, i.e., the fire signature must have a good fire signal-to-background noise ratio. All other factors being equal, the preferred signature will be that which generates the highest ratio, in the earliest period of time, and for a wide variety of fuels.

Three broad categories of fire signatures are

- aerosol signatures, such as smoke
- energy release signatures, such as flame and heat, and
- gas signatures, notably CO and CO_2

2.2.1 Aerosol Signatures

Both solid and liquid particles in the size range from about 0.01 to 10 micrometers, released into the atmosphere through the combustion process, are normally called aerosols. Aerosols, from a detection standpoint, are divided into those which are less than approximately 0.3 micrometers and do not readily scatter light; and those that are larger, scatter light and therefore considered as visible. The visible aerosol, or smoke, ranges in particle sizes from 0.1 to about 2.0 micrometers. Aerosol-type or smoke detectors are designed to operate in this range noting, however, that size distribution can vary depending upon the stage of fire development; i.e., smoldering fires generally produce larger size particles than flaming fires. Size distribution can also change with time.

2.2.2 Energy Release Signature

A fire is constantly releasing energy into the surrounding environment in the form of both light and thermal energy. The light band of energy includes the visible as well as the infrared and ultraviolet spectrum. The low and high wavelength spectrum constitute the earliest energy signatures detectable with existing hardware. Convective thermal energy from a fire, i.e., heat causes an increase in the air temperature of the surrounding environment. The time required for release of sufficient energy to produce a significant convective energy signal can vary from the order of minutes for rapidly developing fires to hours for deep seated fires.

2.2.3 Gas Signatures

Many changes can occur in the gas content of the atmosphere during the course of a fire. Some examples of gases added to the atmosphere are H_2O, CO, CO_2, HCl, HF, H_2S, and NH_3, etc. Amounts of such gases produced are fuel-specific with CO being present in nearly all fire situations. Its rate, however, varies considerably with fuel type, ventilation, and fire stage. For electrical cables, composed mainly of PVC, Bright[9] has indicated that initial breakdown from overheating generates only hydrogen chloride (HCl) gas which cannot be readily detected. As breakdown due to electrical overload proceeds, then the platicizers and filler material in the cable insulation become involved in the overall fire signature.

2.3 Classification of Detectors

Fire detectors may be classified in several ways: on the basis of placement, by functional characteristics, or by operating principle. Detectors may also be classified by the geometry of the area they cover. Spot detectors are devices whose detecting element responds to conditions at a single point. A line detector senses conditions along a continuous linear path. Volume detectors are those which monitor conditions within a specified volume responding to conditions anywhere within that volume. Classification by operating principle is discussed below; further information can be obtained from the articles coauthored by Bright, Bukowski, and Custer [References (7) and (10)]

2.3.1 Convected Energy Detectors

Heat detectors respond to the convected thermal energy of a fire. They may respond either at a predetermined fixed temperature or at a specified rate of temperature change. Generally, heat detectors are designed to sense a prescribed change in a physical or electrical property of a material that is exposed to the heat.

Fixed temperature detectors are designed to alarm when the temperature of the operating element reaches a specified point. The air temperature at the time of operation is usually higher than the rated temperature due to the thermal inertia of the operating elements. Fixed temperature heat detectors are available to cover a wide range of operating temperatures ranging from 57°C (135°F) and up. Higher temperature detectors are necessary so that detection can be provided in areas which are normally subjected to high ambient (nonfire) temperatures. These also include the eutectic metal type, glass bulb type, continuous line type and bimetal type.

One effect which a fire may have on the surrounding environment is to generate a rapid increase in air temperature in the area above the fire. While fixed temperature heat detectors must wait until the gas temperature near the ceiling reaches or exceeds the designated operating point before sounding an alarm, the rate-of-rise detector will function when the rate of temperature change exceeds a predetermined value, typically around 15°F (8.33°C) per minute. Detectors of the rate-of-rise type are designed to compensate either mechanically or electrically for normal changes in ambient temperature which are expected under nonfire conditions.

The increased pressure of a gas when heated in a closed system can be used to generate a mechanical force which will operate alarm contacts in a pneumatic fire detection device.

Also, various thermoelectric properties of metals have been successfully applied in heat detection devices. Accordingly, heat detection devices operate basically on the convective heat transfer rate produced by the fire.

2.3.2 Radiant Energy Detectors

Flame detectors optically sense either the ultraviolet (UV) or infrared (IR) radiation given off by flames or glowing embers. Flame detectors have the highest false alarm rate but the fastest detection times of any type of fire detector. Detection times for flame detectors are generally measured in milliseconds from fire ignition.

Flame detectors are generally only used in high hazard areas such as fuel loading platforms, industrial process areas, hyperbaric chambers, high ceiling areas, and any other areas where hazardous atmospheres in which explosions or very rapid fires may occur. Flame detectors are "line of sight" devices as they must be able to "see" the fire and hence are subject to being blocked by objects placed along their sight-path. However, the infrared type of flame detector has some capability for detecting radiation reflected from walls. In general, the use of flame detectors is restricted to areas where highly flammable materials are stored or used.

Infrared detectors basically consist of a filter and lens system to screen out unwanted wavelengths and focus the incoming energy on a photovoltaic or photoresistive cell sensitive to the infrared. Infrared radiation can be detected by any one of several photocells such as silicon, lead sulfide, indium arsenide and lead selenide. The most commonly used are silicon and lead sulfide.

The ultraviolet component of flame radiation is also used for fire detection. The sensing element may be a solid state device such as silicon carbide or aluminum nitride, or a gas-filled tube in which the gas is ionized by UV radiation and becomes conductive, thus sounding the alarm.

Flame detectors are designd for volume supervision and may use either a fixed or scanning mode. The fixed units continuously observe a conical volume limited by the viewing angle of the lens system and the alarm threshold. The viewing angles range from 15° to 170° for typical commercial units. One scanning device has a 400 foot (122 m) range and uses a mirror rotating at 6 revolutions per minute through 360° horizontally with a 100° viewing angle. The mirror stops when a signal is received. To screen out transients, the unit alarms only if the signal persists for 15 seconds.

2.3.3 Aerosol Detectors

Aerosol detectors are usually classified according to their operating principle, and are of two main types: photoelectric and ionization.

The presence of suspended smoke particles generated during the combustion process affects the propogation of a light beam passing through the environment. This effect can be utilized to detect the presence of a fire in two ways: (1) attenuation of light intensity over the beam path length, and (2) scattering of light both in the forward direction and at various angles to the beam path.

The basic detection mechanism of an ionization detector consists of a radiation source in a chamber containing positive and negative electrodes. The radiation within the chamber ionizes the air between the electrodes causing a small current to flow when voltage is applied. When a smoke aerosol enters the chamber, it reduces the mobility of the ions, and therefore the current flow between the electrodes. The resulting change in the current is used to trigger an alarm at a predetermined level of smoke in the chamber.

In addition to the above mentioned detectors, there are other special types of detectors, using such techniques as particle ionization concentration, measuring of condensation nuclei, fiber optics, ultrasonic and laser devices. These devices are adequately described in the references cited above.

2.4 Detector Selection Criteria

Identification of the major combustibles present in a given fire area from a fire hazards analysis performed in accordance with draft Regulatory Guide 1.120[11] determines, to some extent, what type of detector principle, or combination thereof as described above is most suitable. Recall that these types of detectors operate on a specific, or a combination of, physical properties of a developing fire. The basic criteria for detector selection is that any postulated fire should, ideally, be detected in its incipiant stage such that appropriate fire suppression measures can be taken to protect equipment necessary for safe shutdown. As such, detector selection criteria should, as a minimum, acknowledge the following factors on detector choice, viz,

- combustion products
- fire development and size
- ventilation/stratification
- room congestion and geometry
- ceiling height and construction

2.4.1 Combustion Products

Both photoelectric smoke detectors (PSD) and ionization detectors (ID), which are used to respond to the aerosol signature of a fire, have different capabilities that a fire detection system designer should acknowledge. The sensitivity of the detectors depends strongly on the physical properties of the aerosol. Some of the important physical characteristics of fire smokes are opacity, particulate mass quantity or concentration, and particulate properties (size distribution, shape, and phase state). The response of the light scattering-type detector is roughly proportional to the six power of the particle diameter for particles smaller than a few tenths of a micrometer; whereas the ionization-type-detector response is approximately a linear function of particle diameter.[6]

Commercial light scattering-type detectors are practically insensitive to particles less than 0.1 micrometer, compared to the ionization type which can respond to particles two orders of magnitude smaller. This variation in sensitivity is illustrated in Figure 1 for a monodispersed aerosol which depicts the response of a PSD and ID detector as a function of particle size. Noting

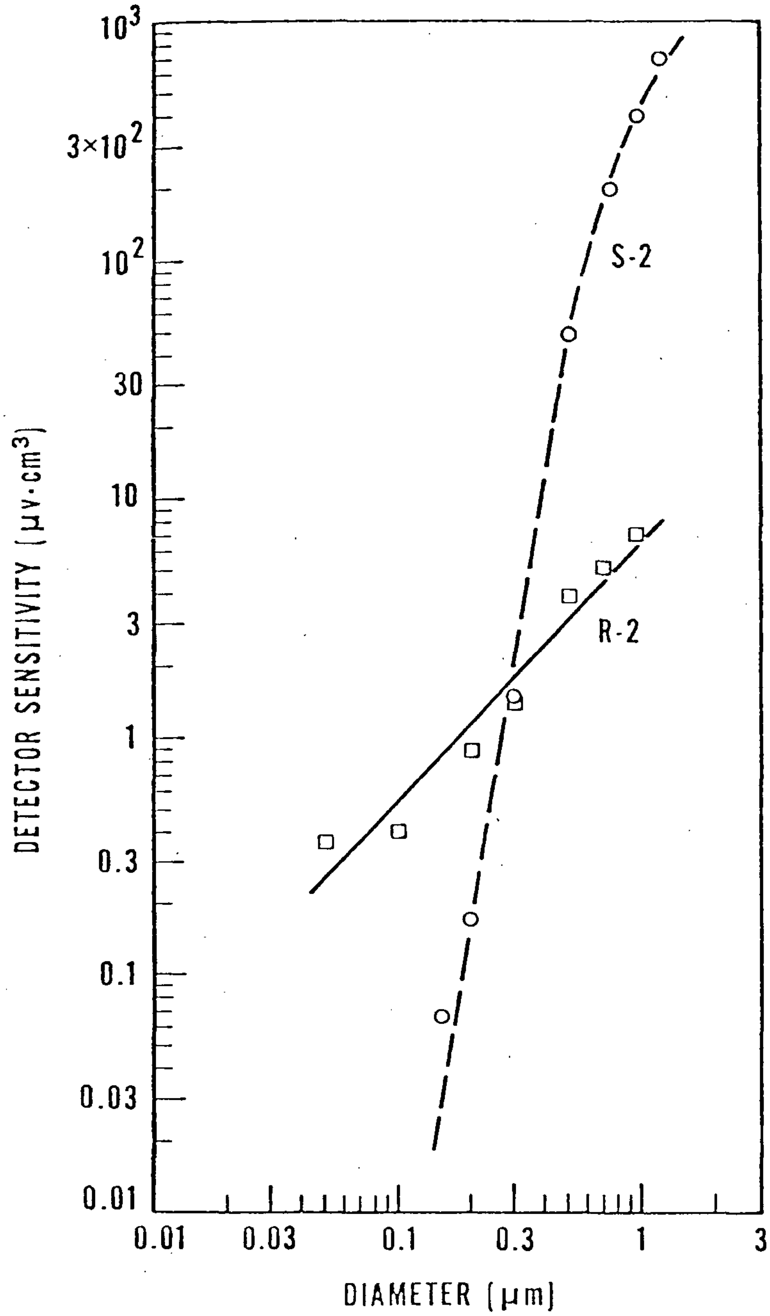


Figure 1. Detector sensitivity versus particle size for a light-scattering type detector (S-2) and for an ionization type detector (R-2) Reference (6)

that 0.3 micrometers is about the lower limit of visability indicates that the ID is more sensitive below this level and that the PSD becomes more sensitive above this level. Research(6,12) on the properties of smoke generated from many combustibles has shown significant differences in the particle sizes for smoldering and flaming material. From Figure 1 it is apparent that if one were designing only for smoldering fires, generally the photoelectric device would be preferable, whereas if one were designing only for flaming fires, it appears as if the ion chamber-type would be preferable. This conclusion has also been verified in studies of detector responses to real fires; albeit it should be noted that the various models of detectors have a wide range of responses to fires. Thus, particular detectors may present an exception to this general statement.

Not only is the size of the particle generated of importance but also its shape and reflectivity will influence detector response. Also, we must keep in mind that an aerosol particle size distribution is dynamic, varying with time and distance from the generation source and therefore not monodispersed. The particle diameter will tend to increase due to coagulation effects that are related principally to time and concentration. The particle size distribution generated from the combustion process can also change as a function of temperature of combustion, material and its density, moisture content, and other factors. Thus quantifying combustion products and how it relates to aerosol detector response is indeed complex. Some inroads in correlating these smoke properties with detector response thresholds have been made. For one, the work by Heskestad(13) of Factory Mutual Research Center (FMRC) for NBS has focused on classifying aerosol detectors through a Detector Material Response number (DMR); a classification that has not as yet received wide acceptance by approval laboratories. Simply put, a particular smoke detector is expected to respond when the local mass concentration of smoke particles reaches a threshold level, assuming a given fire source defined in terms of the identity of the combustible material and the mode of fire spread. Heskestad's results have indicated that, for a given flaming fire source, the mass concentration of particles is proportional to the local temperature rise (relative to ambient) of the fire gases. It follows that a given aerosol detector can be said to respond at a given temperature rise of the fire gases; a temperature rise that depends upon the particular detector model and the fire source. Thus it is conceivable that an aerosol detector can be classified not directly by the complex properties of the smoke but more simply by the gas dynamics of the fire plume that results when a given material is undergoing combustion. Thus far, this work indicates that there may be a general correlation between the temperature rise of the gas surrounding the detector and the measured optical density. This correlation reflects the fact that the magnitude of the buoyant force which carries the smoke to the detector is related to the temperature rise. Similarly, the amount of smoke produced and the temperature rise are both a function of burning rate. This relation between temperature rise, buoyant force, and smoke production has been demonstrated empirically in (13) and discussed further in (14). Some of the values of the detector material responses that have been measured thus far are given in Table 1. It should be noted, however, that this table represents selected values for only a few materials and a few selected ion chamber (ID) and photoelectric (PSD) detectors. The table has no other significance other than that it indicates the values of DMR that might be found for a given combination of detectors and materials. In general, however, for a given burning material a detector with a lower DMR number can be considered more responsive than one having a higher DMR value.

TABLE 1

Some DMR Values
(Representative Temperature Rise, °F, to Detection ($\triangle$Tr) for Smoke Detectors with Flaming, Spreading Fires)

Fire Source	ID	PSD
Wood Cribs	25	75
Polyurethane Foam	13	13
Cotton Fabric	3	50
PVC	13	13

	DMR Numbers (Temperature Rise to Detection, °F)
DMR 1	$\lesssim$ 20
DMR 2	21-40
DMR 3	41-80

*From Reference 14

Work in establishing DMR values for other materials is continuing. Tewarson (15) has evaluated the flammability properties of several cable samples (see Table 2) using a laboratory-scale apparatus. The data for the average peak values of the optical density, D, during the combustion of cable samples in air at a radiative exposure flux of 60 kw/m^2 are presented in Table 3; data for $D/\Delta T$ are also listed where ΔT is the average peak value of gas temperature above ambient measured in the sampling duct. Note that for PVC (granular) $\Delta T = D/[D/\Delta T] = 10°K$ (18°F) which is fairly close to the DMR value for PVC (13°F) given in Table 1.

Research is, however, continuing to quantify and correlate the important physical aspects of smoke particulates including light scattering and absorption, particle size distribution; and settling, sticking, and agglomeration rates. With respect to light obscuration, work at the University of Utah by Seader[16] has shown that the ratio of optical density per meter (%/m) to mass concentration (mg/m^3), termed the Particulate Optical Density (POD), is an intensive property independent of concentration. The results, summarized in Figures 2 and 3, depict that the light obscuring property of many smokes to white light can be placed in two categories depending on the mode of smoke generation, i.e., flaming or nonflaming. With the use of POD, the rate of change of the specific optical density with time for small scale testing may be assessed. Application to large-scale fires, as Seader notes, is under way. He also adds that the success thus far, in developing techniques for applying rate equations involving the POD number should stimulate studies to incorporate the relationships between smoke opacity and particulate mass into complete fire models for applications to large scale situations.

The basic point to be made here is that research in the sensitivity of a detector and hence its selection, although in generally a complex function

TABLE 2

CABLE SAMPLES USED IN THE STUDY

Number	Insulation/Jacket Materials[a]	Conductor No.	Size (AWG)	Outer Cable Diameter in. (m)	Insulation/Jacket Materials (% of total cable weight	Insulation Jacket Materials remaining as char (% of initial wt. of insulation/jacket materials)	IEEE-383 Rating
				Polyethylene (PE)/No Jacket			
1	Low density PE (ℓdPE), no jacket	1	14	0.128(0.003)	23.9	0.10	-
				Polyethylene/Polyvinyl chloride (PE/PVC)			
3	PE/PVC	1	-	0.945(0.024)	15.6	21.9	
4	PE/PVC	1	12	0.164(0.004)	26.5	0.6	Fail
5	PE/PVC	3	-	0.438(0.011)	49.9	20.8	Fail
6	PE/PVC	5	-	0.748(0.019)	51.0	25.6	
7	PE/PVC	12	-	1.000(0.025)	57.8	24.4	
				Polyethylene, Polypropylene/Chlorosulfonated Polyethylene (PE, PP/Cℓ·S·PE)			
8	PE,PP/Cℓ·S·PE (silicone coating)	1	-	0.445(0.011)	23.2	41.6	Pass
9	PE,PP/FRCℓ·S·PE[b]	1	6	0.368(0.009)	40.2	46.4	Pass
10	PE,PP/Cℓ·S·PE	1	12	0.192(0.005)	42.9	45.6	Pass
11	PE,PP/Cℓ·S·PE	5	14	0.668(0.017)	77.1	48.3	Pass
12	PE,PP/Cℓ·S·PE	2	16	0.426(0.011)	77.4	40.5	Pass
				Cross-Linked Polyethylene/Cross-Linked Poyethylene (XPE/XPE)			
13	XPE/FRXPE[b]	3	12	0.458(0.012)	61.4	44.9	Pass
14	XPE/XPE	2	14	0.377(0.010)	73.5	-	Pass
				Cross-Linked Polyethylene/Chlorosulfonated Polyethylene (XPE/Cℓ·S·PE)			
15	FRXPE/Cℓ·S·PE[b]	4	16	0.368(0.009)	56.2	29.5	Pass
16	XPE/Cℓ·S·PE	4	16	0.442(0.011)	62.1	31.0	Pass
				Cross Linked Polyethylene/Neoprene (XPE/Neo)			
17	XPE/Neo	3	16	0.369(0.009)	73.2	43.9	Pass
2	XPE/Neo	7	12	0.630(0.016)	53.6	-	
				Polyethylene, Nylon/Polyvinyl chloride, Nylon (PE, Ny/PVC, Ny)			
18	PE, Ny/PVC, Ny	7	12	0.526(0.013)	39.9	-	
19	PE, Ny/PVC, Ny	7	12	0.520(0.013)	43.5	-	
				Teflon			
20	Teflon	34	-	0.516(0.013)	48.9	3.9	Pass
				Silicone			
21	Silicone, glass braid	1	-	0.363(0.009)	34.0	-	
22	Silicone, glass braid/asbestos	9	14	0.875(0.022)	70.5	59.4	Pass

[a] Generic class as given by the suppliers. Cable samples belonging to similar generic class may not be similar because of different types and amounts of unknown additives in the cable samples.

[b] FR - with fire retardant chemical

*From Reference (15)

TABLE 3

D/ΔT FOR THE COMBUSTION OF CABLE SAMPLES IN NORMAL AIR AT 60 kW/m^2 [a]

Cable Sample	$D (m^{-1})$	$D/\Delta T\ (mK)^{-1}$
XPE/Neo (#2)	17.9	0.647
PE, PP/Cℓ•S•PE (#12)	17.4	0.630
FRXPE/Cℓ•S•PE (#15)	16.6	0.563
PVC (granular)[b]	5.5	0.550
PE/48%Cℓ (granular)[b]	4.0	0.395
PE/36%Cℓ (granular)[b]	4.8	0.387
PE, Ny/PVC, Ny (#19)	17.8	0.357
XPE/Neo (#17)	6.6	0.294
PE, Ny/PVC, Ny (#18)	8.2	0.269
PE/25%Cℓ (granular)[b]	5.4	0.250
PE/PVC (#4)	5.5	0.185
PE/PVC (#7)	6.5	0.166
PE/PVC (#6)	4.8	0.160
Silicone, glass braid (#21)	1.4	0.133
XPE/XPE (#13)	2.8	0.127
XPE/XPE (#14)	3.3	0.126
Silicone, glass braid/asbestos (#22)	2.8	0.125
XPE/Cℓ•S•PE (#16)	3.1	0.107
ℓdPE (#1)	2.8	0.082
PE, PP/Cℓ•S•PE (#11)	2.4	0.080
PE/PVC (#3)	2.4	0.069
Nylon (granular)[b]	2.6	0.062
ℓdPE (granular)[b]	2.1	0.039
Teflon (#20)	0.3	0.013

[a] Average peak values, $D = \frac{1}{\ell} \ln (I_o/I)$; ℓ = optical path length (m); I_o = optical transmission through air; I = optical transmission through the mixture of products and air; $\Delta T = T_d - T_a$, T_d = gas temperature (K); T_a = ambient temperature (K)

[b] Research samples, data from Ref. (9)

*From Reference (15)

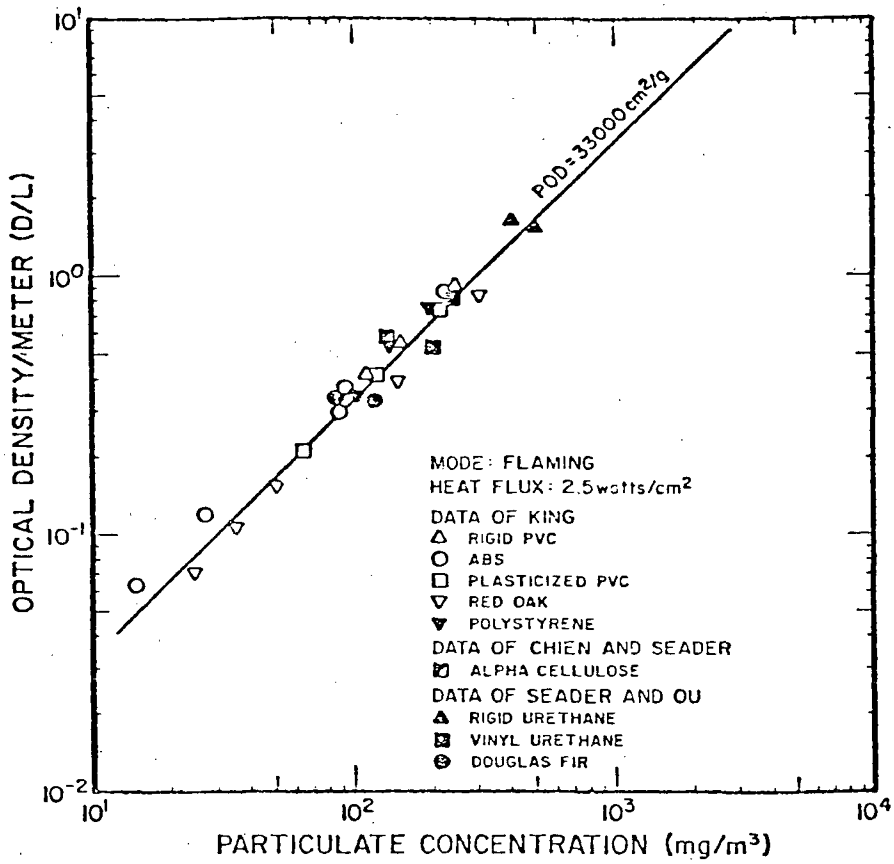


Fig. 2. Correlation of experimental data on particulate optical density for flaming mode. ( )

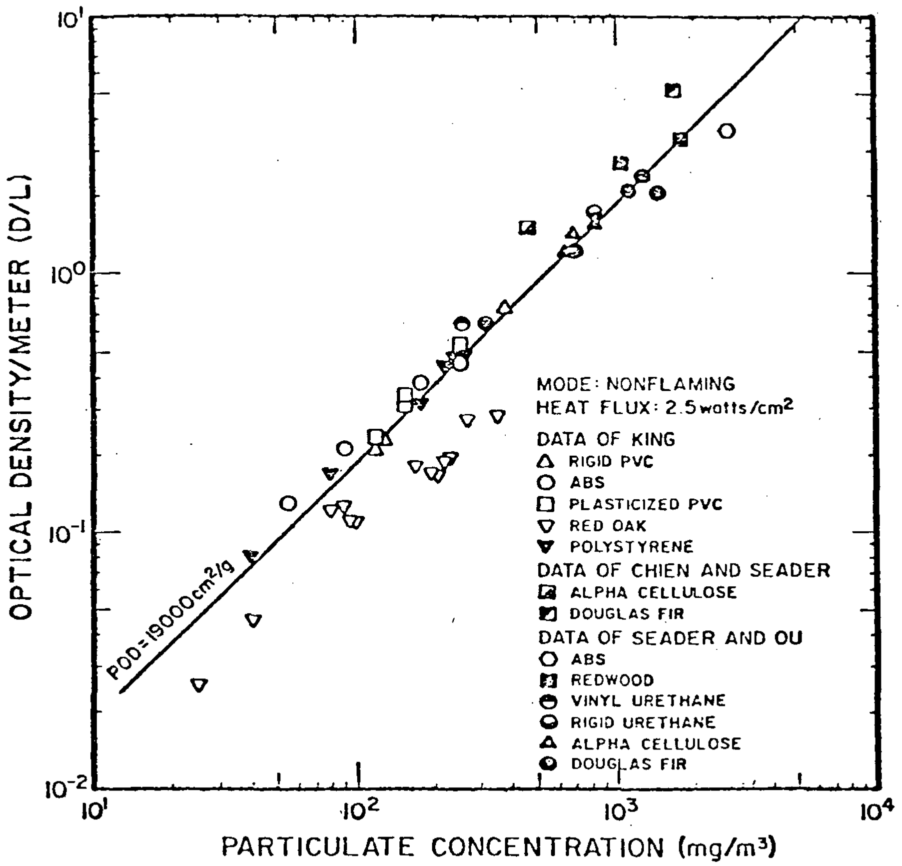


Fig. 3. Correlation of experimental data on particulate density for nonflaming mode. (16)

between the burning material and the inherent characteristics of the detector has, and is, establishing techniques through which such interrelationships may be quantified.

2.4.2 Fire Development

Detector response time (and hence selection) should be consistent with the nature and type of fire to which the detector should respond. The growth rate of the fire will vary depending upon the orientation, occupancy, and nature of the fuel. A flaming fire grows in an accelerating pattern after ignition and, as already discussed, a fire should be detected during this initial growth stage. Fires can be sized by the rate of heat released. For example, a small fire (such as a small waste basket) has a heat release rate of approximately 100 kw (100 BTU/sec) while a large fire (such as a 4 ft^2 heptane pool) has a heat release rate of approximately 1000 kw. The detector design must reflect the size of the fire that one wishes to detect. Understandably, the smaller the critical fire the more sophisticated will be the detection selection requirements.

Thus, in addition to fire size, the rate of growth of the anticipated fire also affects the detection selection process. The critical time required for the fire to reach a specific burning rate will determine detector selection and location. For purposes of subsequent discussion, fast and slow burning fires will be based upon the time for the fire to reach a heat release rate of 1000 kw. A "fast" fire is usually defined as taking 150 seconds to reach this level; a "slow" fire is usually defined as requiring 600 seconds to reach the same level. This is further depicted in Figure 4. Of course, detector systems should respond before the fire achieves this rate.

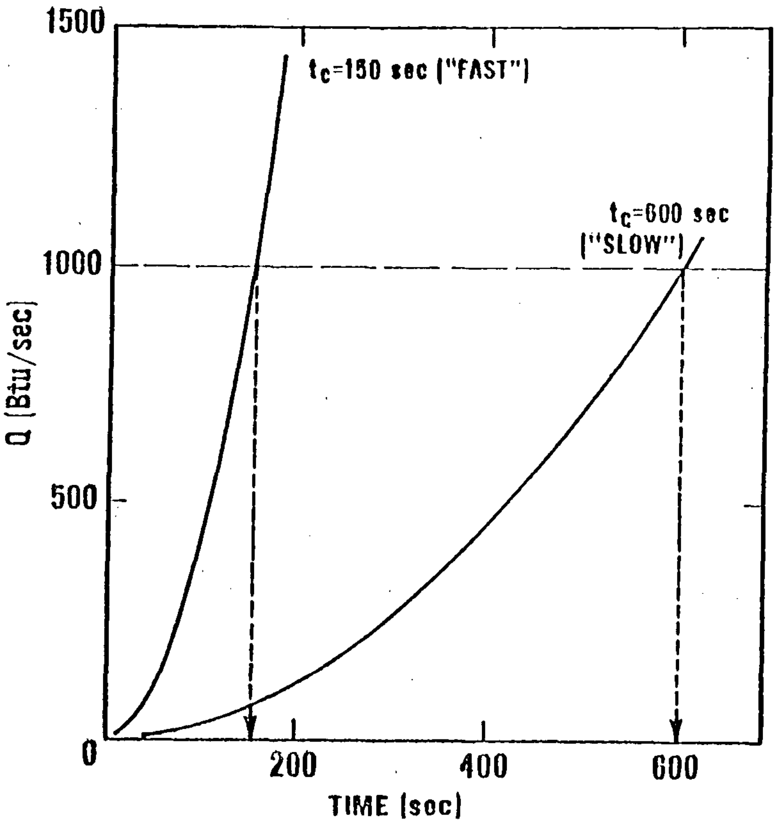


Fig. 4. Idealized Heat Release and Fire Growth Rates. (5)

The work done at FMRC[15] for the Electric Power Research Institute (EPRI) on measuring cable flammability parameters using a laboratory scale apparatus and the large scale cable tray fire tests[17] conducted at Sandia Laboratories for the Nuclear Regulatory Commission are noteworthy for the determination of the heat release and growth rate of electrical cable fires. In addition, the data reported by Bhatia[18] for time to electrical failure and total time of fire involvement in a variety of control and power cables can also be used to determine the nature of electrical cable fires. Heat release rates for select small samples of cables (.09m x 0.09m), summarized in Table 4, indicates that cables that pass the IEEE-383 tests have actual heat-release rates less than about 350 kw per square meter of cable surface area under an imposed external radiative heat flux of 60 kw/m^2.[15] These data as well as other piloted ignition data tend to substantiate the results reported in Reference (17), namely, that for XPE/XPE cable the critical surface temperature for ignition is about 750°K. Electrical failure time (detector selection and siting should be such that detector response time is much less) collected by Bhatia and summarized in Table 5 as well as cable involvement reported by Klamerus can also be used to assess relative growth rates of cable fires. These data indicate that a slow-growing cable fire reaches 1000 kw in 20 minutes and a fast-growing fire reaches 1000 kw in half as much time. For example, for XPE/XPE cable (cable #13 in Table 4), the actual heat release rate measured is approximately 500 kw/m^2; and according to the data in Table 5 this cable maintains circuit integrity for approximately 10 minutes. Assuming an involvement area of approximately 0.4 m^2 as reported by Klamerus and a heat release rate that grows parabolically with time (as indicated in Figure 4) one can show that such cable material will reach a 1000 kw heat release rate in approximately 20 minutes. Non-IEEE rated cables will reach

Table 4

HEAT RELEASE RATE PER UNIT AREA FOR FLAMING FIRE OF CABLE SAMPLES IN NORMAL AIR AT 60 kW/m^2 [a]

Cable Sample	IEEE-383 Rating	Heat Release Rate Per Unit Area (kW/m^2) Actual	Convective	Radiative
ℓdPE (#1)	NK	1071	398	673
PE/PVC (#5)	Fail	589	325	264
XPE/FRXPE (#13)	Pass	475	207	268
PE/PVC (#4)	Fail	395	175	220
PE/PVC (#6)	NK	359	228	131
XPE/Neoprene (#2)	NK	354	166	188
PE, PP/Cℓ•S•PE (#12)	Pass	345	131	214
PE/PVC (#3)	NK	312	185	127
XPE/Neoprene (#17)	Pass	302	144	158
PE, PP/Cℓ•S•PE (#8)	Pass	299	160	139
PE, PP/Cℓ•S•PE (#11)	Pass	271	172	99
FRXPE/Cℓ•S•PE (#15)	Pass	258	112	146
PE, Nylon/PVC, Nylon (#19)	NK	231	120	110
PE, Nylon/PVC, Nylon (#18)	NK	218	107	111
XPE/Cℓ•S•PE (#16)	Pass	204	135	69
Silicone, glass braid, asbestos (#22)	Pass	182	152	30
XPE/XPE (#14)	Pass	178	107	71
PE, PP/Cℓ•S•PE (#10)	Pass	177	114	62
Silicone, glass braid (#21)	NK	128	89	39
Teflon (#20)	Pass	98	82	16

[a] Average peak values

NK - Not known

From Reference (15)

TABLE 5

DATA REPORTED IN THE LITERATURE ON FIRE TESTING OF CABLE TRAYS[a]

No.	Cable Insulation/Jacket[b]	No. of Conductors	Size (AWG)	Time (min) Electrical Failure	Time (min) Total Fire Time after Electrical Failure
	Control Cables (600v)				
40	Special rubber/armored	4	14	2.0	9.5
39	Special rubber/armored	3	14	2.5	9.5
16	PVC/Neoprene	4	12	3.0	7.5
25	PVC/Neoprene	7	12	3.0	10.0
33	PVC/Neoprene	12	12	3.0	9.5
2	Special rubber/armored	4	14	3.5	10.0
37	Special rubber/armored	3	14	4.5	5.0
36	Special rubber/Neoprene	4	14	5.0	5.5
41	XPE/asbestos	7	12	5.5	6.0
24	PE/PVC	7	12	6.0	9.5
38	Special rubber/Neoprene	7	14	6.5	5.0
3	Cℓ•S•PE/Cℓ•S•PE	4	14	6.5	8.5
20	PE•PP/Neoprene	5	12	7.0	9.0
5	XPE/Neoprene	5	14	7.5	9.5
1	XPE/PVC	4	14	8.5	6.5
7	Cℓ•S•PE/Cℓ•S•PE	7	14	8.5	4.5
11	Special rubber/armored	7	14	8.5	6.0
4	XPE/Neoprene	4	14	9.0	8.0
8	XPE/Neoprene	7	14	9.0	5.5
12	Cℓ•PE/Cℓ•S•PE	12	14	9.0	5.5
21	PVC/PVC	7	12	9.5	6.5
10	XPE/PVC	12	14	10.0	6.5
15	PVC/PVC	2	12	10.5	6.0
30	PE•PP/Neoprene	7	12	10.5	6.0
32	PE•PP/Neoprene	9	12	10.5	3.5
34	PE•PP/Neoprene	12	12	10.5	4.0
9	XPE/Neoprene	7	14	11.0	3.0
27	PE•PP/PVC	7	12	11.0	4.0
29	PE•PP/PVC	7	12	12.0	3.5
28	PE•PP/Neoprene	7	12	12.5	7.5
6	XPE/PVC	7	14	13.0	4.5
23	XPE/PVC	7	12	13.0	0.5
13	XPE/Neoprene	12	14	13.5	7.0
19	Silicone/Asbestos	5	12	15.0	0.5
14	XPE/Neoprene	12	14	15.5	3.5
18	Silicone/Asbestos	5	12	No	23.0
44	Silicone/Asbestos	4	14	No	24.0
45	Silicone/Asbestos	5	12	No	25.0
42	Silicone/Neoprene	7	12	No	25.0
43	Silicone/Asbestos	7	12	No	27.0

From Reference (18)

TABLE 5 (Cont'd)

No.	Cable Insulation/Jacket[b]	No. of Conductors	Size (AWG)	Time (min) Electrical Failure	Total Fire Time after Electrical Failure
	Power Cables (600v)				
50	PVC/Neoprene	3	6	5.0	8.5
46	XPE/Neoprene (triplexed)	3	6	8.0	6.5
52	Special rubber/armored	3	6	8.0	1.5
54	XPE/Neoprene (triplexed)	3	4	8.5	6.0
56	Special rubber/Neoprene	3	4	8.5	2.0
57	Special rubber/Neoprene	3	4	9.0	2.0
48	Rubber/Neoprene (triplexed)	3	6	10.0	6.0
49	XPE/Neoprene (triplexed)	3	6	10.5	5.0
51	PE·PP/Neoprene	3	6	14.5	4.5
55	Special rubber/armored	3	4	No	9.0

[a] Data taken from Ref. (10). Tray configurations not known. Tray loading - one cable layer, one-half cable diameter spacing between cables; number of cables per tray < 15; ignition source - transil (transformer) oil, 5-gal open can at ~1800°F, oil level, 2 in. below the rim of the can. The top of the can, 4 in. below the center of the cable tray; exposure time - 5 min with flame at a constant temperature of about 1800°F, and extinguished after 5 min by placing a metal cover over the pan; times to electrical failure and total fire time measured beginning with extinguishment of the oil flame.

[b] XPE - cross-linked polyethylene; PE - polyethylene; PVC - polyvinyl chloride; Cl·S·PE - chlorosulfonated polyethylene; PE·PP - polyethylene·polypropylene.

this threshold value in a shorter time since heat release rate as well as its flame spread may be higher. A good estimate for the critical time is 10 minutes. Of course, this example is only illustrative since as the data show there are a variety of cables of different sizes, size of conductors, and varying contents of flammable materials in the cabling jackets. But it does tend to indicate how data gathered from large and small scale tests may be used to help approximate fire development and growth.

Thus, for example, a nuclear power plant fire detection system designer may consider a large threshold size, slowly developing fire as a design basis fire for detector selection and siting in plant storage areas; whereas a small threshold size, fast developing fire may be considered as a design basis fire for fire detection plans in computer and switchgear rooms.

2.4.3 Ventilation

It is difficult to predict how severely ventilation conditions can degrade a particular detector's operation. Some aerosol detectors become more sensitive in higher air velocities; other less sensitive. In areas of high flow rates it is expected that ionization detectors would perform better than photo-electric detectors. Various manufacturers of ionization detectors give recommendations as to what generic model to use or what sensitivity setting to adjust for several ranges of air flow. Detectors sensing radiant energy signatures are not affected by ventilation factors; devices responding to convective energy signatures are only slightly affected since the convective energy of the fire which is sufficiently large to actuate these units can overpower ambient circulation patterns. Continuous line detectors which can be located closer to the fire source should also be considered. For aerosol detectors, standards recently established in UL 268 -- "Smoke Detectors for Fire

Protective Signaling Systems" has attempted to assess this effect by utilizing several air flow rates ranging from 0.15 to 0.76 m/sec. (30 to 150 fpm). However, the effects of both high and low air flow rates are still not completely understood. It is therefore stressed that potential bidders of aerosol detection systems be informed of the possible room flow rates and "in house" tests be conducted by the manufacturers using conbustibles common to the specific fire area.

2.4.4 Congestion

In fire areas containing large amounts of piping, ductwork, cable trays and other equipment, detectors which depend on the line-of-sight "viewing" of a fire may be ineffective. Fixed temperature, or rate-of-rise detectors may also be ineffective because of possible heat transfer from the fire plume to the intervening obstacles. Detectors should be selected based upon their placement in accessible locations with no large items of congestion between the detector and the major combustible hazard in the detector area. It is expected that the effects of congestion would increase the time for smoke to reach a given detector and also increase smoke aging. Work reported by Bukowski and Mulholland(6) on the behavior of aerosol detectors with smoke coagulation (or aging) indicates that the sensitivity of a light scattering type detector, with a near forward scattering angle, increases with aging while the sensitivity of an ionization detector decreases with aging. The coagulation phenomena tends to create two opposing effects on aerosol detector response. The decrease in the number concentration (particles/unit vol) tends to decrease detector output while the increase in particle size accompanying particle coalescence tends to increase detector response. Which effect will predominate is determined by the size sensitivity characteristics for the detector. However, it appears that in highly congested areas photo-electric detectors are preferred if, of course, assurances have been made that the detector is located in the path of the smoke.

2.4.5 Other Environmental Factors

Atmospheric pressure changes, humidity, and temperature variations can influence detector sensitivity and therefore selection. Other factors that also require consideration in detector selection are corrosive and dust laden atmospheres, background radiation affects and operational activities within the fire area.

All aerosol detectors are influenced to some degree by altitude. In certain ionization devices, this influence can be significant. Most aerosol units are also only slightly affected by normal air humidity; however the affect increases as the moisture content approaches the dew point. Since increase humidity increases particle coagulation then ionization detectors become less responsive while photoelectric detectors become more responsive.[8]

Dust and dirt in the air can have a major affect on detector sensitivity. It can make a detector completely insensitive in some cases and hypersensitive[8] in others. Aerosol detectors will become less sensitive if dust or debris partially seal the smoke entry chamber unit. If debris insulates the radioactive foil of ionization detectors, they become hypersensitive due to reduction in ionization rate. For photoelectric detectors, sensitivity decreases.

Background radiation affects ionization rate and thus ionization detectors become less sensitive. One manufacturer indicates that for levels of radiation at about 20 R/hr smoke concentration must increase by a factor of two for the detector to alarm. The optical components of photoelectric devices can also be affected by background radiation.

Recently published U.L. 268, "Smoke Detectors For Fire Protective Signaling Systems," calls for tests which deal with most of the aforenoted effects. Thus, detector selection can be better appraised as a result of this standard.

2.4.6 Room Geometry

Rooms with high ceilings may render heat, photoelectric, and ionization detectors ineffective because the buoyant effect of the rising combustion gases may be insufficient to overcome ceiling height and may stratify the aerosol signatures of the fire especially if ventilation rates are low. Accordingly, the degree of ambient thermal stratification should be determined in each fire area during plant operations. With this, together with an assessment of the buoyant flux of the anticipated fire, one can approximate where the aerosol may stratify. Plume rise formula in stratified environments, usually associated with problems in meteorology, can be used to determine distance below the ceiling where smoke detectors may be installed. This procedure will be discussed in the section dealing with detector siting. The need for baffles over each detector may also be required in areas containing draft diffusing ceilings (metal grate ceilings). These baffles should be as large as practical. Baffle sizes of approximately 0.6 to 0.9 m^2 (6-9 sq. ft) are usually recommended. However, subsequent analysis will show that a more realistic approach is to determine the half-width of the fire plume as a function of buoyant flux and height above the source. This idea can also be extended to areas having some horizontal movement of ambient air using analysis which deal with a "bent-over" plume configuration.

2.4.7 Response Time Lag

Inherent in any detection system is the response time lag. The time lag for heat detectors is caused by the thermal inertia of the sensing device which is a function of the mass, specific heat, conductivity, and the surface area of the device. Response time for heat detectors is typically calculated or assessed in a similar fashion as sprinkler head response time is calculated. The U.L. approval for heat detectors provides information for determining the response time lag. For approving detectors, fire tests are conducted in a 18.3 x 18.3 m room having a 4.80 m high smooth ceiling. The detectors are compared to the response of sprinklers using a pan of denatured alcohol located approximately 0.91 m above the floor and of such intensity that the sprinkler operates in approximately 2 minutes. How this U.L. data can be used to develop the transfer from the U.L. approval spacing to the time constant for heat detectors accounting for ceiling height, heat release rate, and fire growth rate will be discussed in Section 2.5.

The time lag for aerosol-type detectors, somewhat more complex than that associated with heat detectors, is attributable to the time it takes for the aerosol around the detector to infiltrate into the sensing chamber and activate the detection mechanism. At response, the mass concentration outside the detector is higher than the threshold concentration by an amount that depends upon the geometric detector design, the rate-of-rise in aerosol concentration and the gas velocity surrounding the detector. The problem of entry, as reported by Heskestad(19) indicates that the smoke entry resistance of a given detector is defined as the ratio of the difference between the smoke density (% obscuration/meter) needed around the detector to get response $[(Du)_r]$, and the smoke density that is actually needed within the sensing volume of the detector to trigger the mechanism, $[(Du)_0]$ and the rate-of-rise in optical density d/dt(Du). This ratio, measured experimentally, has dimensions of time and implicit in its absolute value is the sensitivity of the smoke detector and the velocity of smoke surrounding the detector. Thus multiplying this time lag factor by a characteristic velocity, namely smoke velocity, yields a quantity with dimensions of length. This characteristic length, L, is then an intrinsic parameter of the geometry of a particular detector.

Extending the concept of a detector material response number, DMR, discussed in Section 2.4.1 dealing with combustion products, where it has been indicated that for a given fire source, the mass concentration of particles (and hence optical density) is proportional to the local temperature rise of the fire plume gases, then it can be shown(19) that this characteristic length can be determined by measuring the gas dynamic (instead of the optical) properties of the aerosol at detector threshold response.

Values of L among approved aerosol detectors vary from less than 3 m to more than 24 m. The smaller the L value the less resistance to smoke entry. Thus, in effect, aerosol detector selection can be appraised if each detector has an L value listing and a DMR rating for the various combustibles tested.

2.4.8 Reliability

Although detailed reliability data are lacking for most detection devices, some general statements can be made regarding certain critical components based on field or laboratory experience and manufacturers' literature.

Heat sensing detectors are generally the most reliable type in terms of component life since these devices respond directly to the presence of heat by a thermal or physical change in the detector operating elements. Heat detection systems may fail due to mechanical damage or abuse to the detectors after installation or by failure of components or circuitry in peripheral equipment such as power supplies or alarm indicating equipment.

Detection devices for fire signals other than heat employ electronic circuitry of varying complexity to sense the presence of a fire signal and to monitor the output of the sensing element. The reliability of such devices is related to the reliability of its components as they are used in each type of circuit and generally decreases with increasing complexity.

However, U.L. has recently modified U.L. 268, the system connected detector standard, to apply the concepts of electronic circuit failure rate predictions. This technique for predicting reliability has been in use for several years in military and space design programs and has been effective in cutting down failures by extending the mean time between failures by improving the quality of the components.

2.4.9 Maintenance

The sensitivity of some detectors may degrade more dramatically with age than that of others. Maintenance problems also affect detector reliability particularly in photoelectric and ionization types. Accumulations of dust and films on the bulbs, lenses and photocells will reduce the intensity of light within the detection element. The effect of this varies with the type of detector. Projected beam-type photoelectric detectors will become more sensitive with contamination increasing the possibility of false alarms. Light scattering detectors, on the other hand, may become less sensitive as light intensity is decreased unless some internal compensation is provided. Ionization detectors are also affected by contamination. Deposition of dust and films inside the ion chamber will decrease the current flow across the chamber and raise the sensitivity. This can result in an increase in the false alarm rate. Also, collections of dust, particles of lint and other large airborne contaminants can often be trapped in the protective screens or light shields of smoke detectors. This can block smoke entry and prevent or delay an alarm. Proper cleaning and maintenance are important to retain the designed operating characteristics of these detectors.

Detector selection criteria should consider the frequency of maintenance schedule that is required to ensure satisfactory performance.

2.4.10 Detector Selection Summary

One phase of the acceptance criteria requirements is how well the detection system design engineer has addressed the factors dealing with the operating characteristics of detector types and how they relate to the area being protected. Factors discussed above which should be considered in the overall detector selection criteria are the type and quantity of the fuel, its anticipated heat release rate and growth rate, possible ignition sources, ranges of ambient conditions, room geometry and congestion and ceiling height, configuration and construction, detector maintenance and reliability, and most importantly, the relevance of the area protected to safe shutdown systems.

Heat detectors have the lowest cost and false alarm rate but are the slowest in response. Since heat tends to dissipate fairly rapidly (for small fires), heat detectors are best applied to the protection of confined spaces, or directly over hazards where flaming fires could be expected.

Aerosol detectors are higher in cost than heat detectors but are faster responding to fires. Due to their greater sensitivity, false alarms can be more frequent, especially if they are not properly located.

Since smoke does not dissipate as rapidly as heat, smoke detectors are better suited to the protection of large open spaces than heat detectors.

TABLE 6

Summary of Detector Application Considerations

Detector Type	Response Speed	False Alarm Rate	Cost	Application
Heat	Slow	Low	Low	Confined Spaces
Smoke	Fast	Medium	Medium	Open or Confined Spaces
Flame	Very Fast	High	High	Flammable Material Storage
Particle Counter	Fast	Medium	High	Open Spaces - High Value

From Reference (10)

Smoke detectors are more subject to damage by corrosion, dust, and environmental extremes than the simpler heat detectors since smoke detectors contain electronic circuitry. They also consume power, so the number of smoke detectors which can be connected to a control unit is limited by the power supply capability.

Photoelectric smoke detectors are particularly suitable where smoldering fires or fires involving PVC wire insulation may be expected. Ionization smoke detectors are particularly suitable where flaming fires involving any other materials would be the case.

Flame detectors are extremely fast responding but will alarm to any source of radiation in their sensitivity range, so false alarm rates can be high if improperly applied. Flame detectors are usually used in hyperbaric chambers and flammable material storage areas where no flames of any sort are allowable.

Flame detectors are "line of sight" devices, so care must be taken to insure that they can "see" the entire protected area and that they will not be accidentally blocked by stacked material or equipment. Their sensitivity is a function of flame size and distance from the detector, and some can be adjusted to ignore a small flame at floor level. Their cost is relatively high, but they are well suited for areas where explosive or flammable vapors or dusts are encountered as they are usually available in "explosion proof" housings.

Table 6 contains a brief summary of information contained in this section on detector selection. In an effort to define more concisely the types of detectors most appropriate to different nuclear plant areas, Berry[3] has developed a table relating the physical characteristics of selected safety-related plant areas with detector selection; Table 7 and Figure 5 have been reproduced from this effort and can be used as a guide in the overall selection process.

TABLE 7

Physical Characteristics of Selected Safety-Related Plant Areas as Related to Detector Selection

Plant Areas	Predominant Combustibles	Anticipated (a) Fire Development	Room Congestion (b) for Detection	Room (d) Ceiling Height	Other Factors	Suitable Detector Choice
Control Room	Cable Insulation	Slow	Low	Low	False Ceilings Continuously Manned	Ionization or Photoelectric
Cable Spreading Room	Cable Insulation	Slow	High	Low	None	Ionization or Photoelectric or Line Type
Switchgear Rooms	Cable Insulation	Initially Fast - High Voltage Short Slow - Propagation	Low	Medium	High Temperature Potential	Ionization or Photoelectric
Decontamination Areas	Plastics, Cloth, Cable Insulation	Fast or Slow	Variable (c)	Variable (c)	Transient Fire Loads, Background Radiation	Photoelectric
Battery Rooms	Hydrogen Gas Cable Insulation	Explosive or Slow	Low	Low	Corrosive Atmosphere	Photoelectric (plus hydrogen sensor or ventilation)
Diesel Rooms	Lube Oil Diesel Fuel Oil Cable Insulation	Fast or Slow	Low	High	Diesel Combustion Products	Heat - Rate of Rise or Ultraviolet or Infrared
Computer Rooms	Plastics, Paper Cable Insulation	Fast or Slow	Low	Low	False Ceilings & False Floors	Ionization or Photoelectric
Safety Pump Rooms	Cable Insulation Lube Oil	Fast or Slow	Low	Variable	None	Ionization or Photoelectric
Nuclear Fuel Areas	Plastics Cable Insulation	Fast or Slow	Variable	High	Transient Fire Loads, Background Radiation	Photoelectric
Primary Containment	Cable Insulation Lube Oil	Fast or Slow	Medium	Variable	Background Radiation	Photoelectric
Relay Rooms	Cable Insulation	Slow	High	Medium	None	Ionization or Photoelectric
Remote Shutdown Rooms	Cable Insulation	Slow	Medium	Variable	None	Ionization or Photoelectric
Instrument Rooms	Cable Insulation	Slow	High	Medium	None	Ionization or Photoelectric
Other Electrical Equipment Areas	Cable Insulation	Slow	Variable	Variable	None	Ionization or Photoelectric

(a) Based on cable burning tests performed at Sandia Laboratories (References 7 and 8) cable fires, involving IEEE - 383 approved cables, develop slowly, in the time span of minutes. In this table, fires, such as oil which can fully develop in time spans of seconds, were rated as "fast".

(b) The influence of room congestion on detector selection is a factor only in those cases where line-of-sight detectors are satisfactory from the standpoint of all other characteristics being considered.

(c) "Variable" refers to those situations in which there are either transient fire conditions within an area or significant variations of physical characteristics between different power plants.

(d) The terms low, medium, and high ceilings were arbitrarily chosen as rooms having real or false ceilings: low, less than 10 feet high; medium, 10 to 30 feet high; high, greater than 30 feet high.

*From Reference (3)

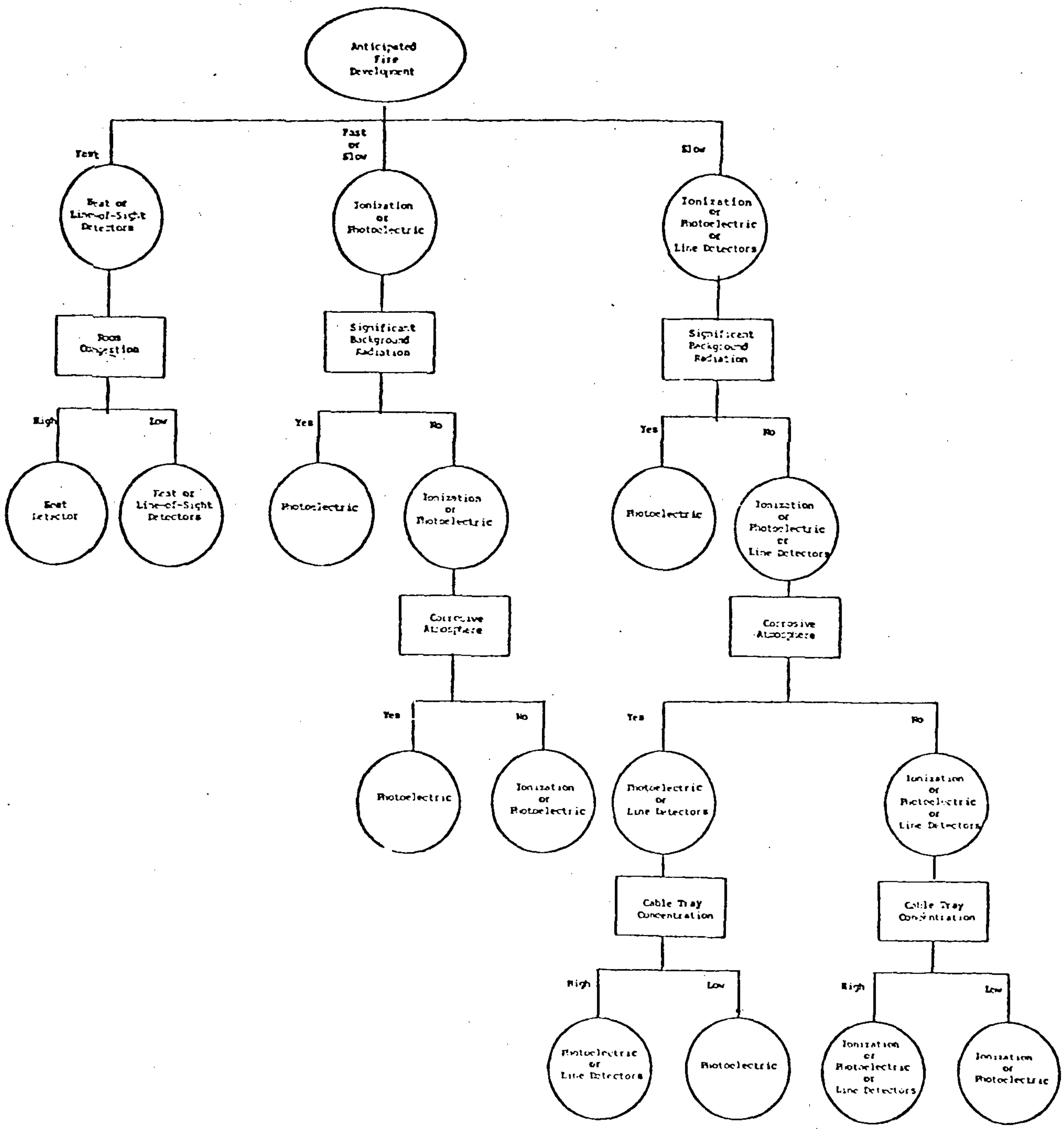


Fig. 5. Detector Selection Guide Flow Chart (3)

2.5 Acceptable Detector Location and Spacing Criteria

Once plant areas requiring fire detection have been established and appropriate detector types chosen, it is necessary to locate and space the detectors* in a manner consistant with the environment in which the detector must function accounting for (1) fire development and growth, (2) fire signatures produced, (3) combustible materials involved, (4) ceiling height and configuration, (5) ventilation and stratification, and (6) fire area geometry and congestion.

As has already been noted, no definitive design criteria exists for locating and spacing fire detectors in nuclear power plants. In fact, only through reference to NFPA 72E "Standard for Automatic Fire Detectors" does draft Regulatory Guide 1.120 acknowledge the influence of locating and spacing on detector performance. Also, only tacit acknowledgement of detector spacing is given in Appendix A of USNRC BTP 9.5-1. The proposed rule, Appendix R of USNRC 10 CFR Part 50, only indicates requirements for automatic fire detection systems in specific areas to provide "...prompt notification and alarm in the event of fires..." but does not submit guidance for detector selection and spacing.

Current efforts by NBS, FMRC, UL, and the Fire Detection Institute have directly addressed some of the shortcomings in fire detection analysis that have been reviewed by Berry. This section will deal with these current approaches which should be used as a basis for detector siting acceptance.

The basis for acceptable detector siting analysis will be the acknowledgement to tie the spacing of detectors to realistic fire situations recognizing the effects of the factors numerated above on optimum location. Some of these factors have already been discussed regarding acceptable detector selection criteria; they will not be addressed regarding detector siting criteria.

*Once detector siting has been established, it may be necessary to reevaluate detector selection.

2.5.1 Initial Convective Flow in Fire

Heskestad and Delichatsios, under the auspices of the Fire Detection Institute, have considered the physical modeling of the initial environment generated by a fire in an enclosure that persists up to the time when recirculation of products of combustion begins to influence the further yield of products. This is an important fire interval for fire detection problems dealing with determining optimum spacing configurations of fire detectors.

Proposed modeling relations[20] pertaining to idealized, yet realistic, classes of unsteady fires and referred to as "power law" fires have been corroborated with experiments. These "power law" fires are by definition defined as

$$Q_c = \alpha_c t^p \tag{1}$$

which indicates that the convective heat release rate, Q_c (watts) varies with some power, p, of time, t, from ignition. For example, p=2, is often a good representation of flaming and radially spreading fires in low fuel piles. The coefficient, α_c, determines the fire growth rate for a given power law fire. For parabolic growing fires, p=2, as illustrated in Figure 4, the coefficient, α_c, takes on the values of 4.44 $(10)^{-2}$ kw/sec^2 for a "fast" fire and 2.79 $(10)^{-3}$ kw/sec^2 for a slow fire. These values reflect arbitrary rate criteria but they do define within a practical range, the types of slow and fast developing fires that might be expected from common burning materials. Also, since heat release rate can be represented by the product of the mass burning rate and the heat of combustion of the fuel, then the fire intensity coefficient, α_c, is directly proportional to the heat of combustion of the fuel.

Thus, fires can be sized by the rate of heat released, Q_c. The detector site location must be related to the size of the fire that one wishes to detect. The size of the fire at threshold response, (Q_{cr}), must reflect the amount of damage equipment can sustain before safety systems become impared. Obviously, the smaller the critical fire the more sophisticated will be the detection requirements. To have a detector system respond before a fast developing fire grows to, say, 100 kw requires a idealistic response time of approximately 50 secs (i.e. $t = [(Q_c)_r/\alpha c]^{1/2} = [100/4.44(10)^{-2}]^{1/2}$). Increasing the threshold fire size by an order of magnitude indicates that the detector response time could be delayed by a factor of 3.

For fast (non-IEEE rated) or slow developing (IEEE rated) cable fires, the intensity coefficient can be estimated using the data of Tewarson,[15] Klamerus,[17] and Bhatia.[18] As indicated in Section 2.4.2, fast cable fires may reach 1000 kw intensity in roughly 600 seconds whereas slow cable fire development may require twice as much time to reach the same intensity level. These estimates are indeed approximate since there are a variety of cables of different sizes and varying contents of flammable materials in their jackets.

However with these data as idealistic examples, if a detector system is designed to respond to a cable fire before a 100 kw intensity ($\approx$100 BTU/sec) is achieved requires that the criteria for early warning be approximately 190 secs for a fast developing fire and approximately twice this value for slow developing fires.

Integrating Equation 1 with time and assuming that the only contribution to the fire is from these hypothetical cables, the consumed cable material up to detection can be determined, viz,

$$m_c = \int_0^{t_r} (Q_c)\,dt/Hc \qquad (2)$$

where Hc is the heat of combustion of the cable (J/gr), a value that can be determined from small scale tests. For a parabolically growing fire the mass loss is

$$m_c = [(Q_c)_r]^{3/2} \;/\; 3\alpha_c^{1/2} \;/Hc \qquad (3)$$

Data on the total mass loss of generic cables before electrical short can also be used to determine approximately the range for early warning. The question that must be answered is how this concept can be translated into detector spacing. This requires knowledge of the dynamics of the fire plume generated by the aforenoted, power law, transient fire within an enclosure.

Heskestad does provide scaling relationships relating plume temperature rise and plume velocity as a function of radial distances from the fire axis and time with fire intensity and clearance distance between the ceiling and the fire source as parameters. These correlations were verified by experiments(13).

Briefly, for fires growing with the second power of time explicit relations for a nondimensional temperature and velocity in the hottest layer under large flat ceilings is given by

$$\Delta T^* = \left\{ \left[t^* - 0.954(1+r/H) \right] \;/\; \left[0.188 + 0.313(r/H) \right] \right\}^{4/3} \qquad (4)$$

$$U^*/(\Delta T^*)^{1/2} = 0.59(r/H)^{-0.63} \qquad (5)$$

where the ( )* are nondimensional quantities defined as

$$\Delta T^* \equiv \left[A^{-2/5}\, T_\infty^{-1} g \right] \alpha^{-2/5} H^{3/5}\, \Delta T \qquad (6)$$

$$U^* \equiv \left[A\, \alpha\, H \right]^{-1/5} U \qquad (7)$$

$$t^* \equiv \left[A_\alpha^\alpha / H^4 \right]^{1/5} t \qquad (8)$$

where $A \equiv g/CpT_\infty\rho_\infty$; Cp is the specific heat; ρ_∞, T_∞ are the ambient density and temperature; g is gravity, and H is the clearance height between the ceiling and the combustible. These relations together with Equation (1) can be used to predict temperature and velocity histories for arbitrary combinations of ceiling clearance and fire growth rate.

This cited work of Heskestad and Delichatsios has been used, under the auspices of the Fire Detection Institute, NBS, HUD, US. Bureau of Mines, Navy Department and the Veterans Administration, to develop design siting information for aerosol and heat detectors.[13-14]

Before proceeding, it must be emphasized that this design information is strictly applicable for flaming, parabolically growing fires in quiescent enclosures having smooth ceilings.

2.5.2 Aerosol Detector Spacing Criteria: Flaming Fires, Smooth Ceiling, Quiescent Environment

In addition to modeling the initial fire environment generated within an enclosure, the aforenoted research has shown that the mass concentration of aerosol particles generated from a given source is proportional to the local temperature rise above ambient of the fire gases. It follows then that a particular smoke detector, which is expected to respond when the local mass concentration of smoke particles reaches a threshold value, can be equated to a determinable gas temperature rise; a temperature rise which depends on the particular detector model and the fire source.

The temperature rise at detection, already discussed in Section 2.4.1, is defined as the Detector Material Response (DMR) number; a number which intrinsically relates the properties of the detector with the burning material. This concept may also be refined, as discussed in Section 2.4.8, where it is noted that because of smoke entry resistance the mass concentration of particles inside the sensing chamber lags behind the smoke concentration buildup outside the given detector. Thus, since there is a one-to-one correspondence between smoke concentration at threshold response to local gas temperature rise, this lag time, τ, can be expressed as

$$\tau = \left[\Delta T - (\Delta T)r\right] / \langle dT/dt \rangle \qquad (9)$$

where ΔT is the actual temperature rise of the fire gases at response (or the actual smoke concentration at response); $(\Delta T)r$ is the temperature rise at response for zero resistance to smoke entry; and $\langle dT/dt \rangle$ is the average rate-of-rise at detection. Note that the specific value of τ is intrinsically related to the particular characteristics of the detector and the gas dynamics. By defining τ as the ratio between a characteristic length and a characteristic velocity, taken as the average gas velocity at detection, $\langle u \rangle$, i.e., $\tau \equiv L/\langle u \rangle$ an additional parameter associated with a given detector, namely its "characteristic length," L, emerges.

Thus, in practice implementing the above equations for aerosol detector siting along a given ceiling with clearance height, H, requires realistic values of

- the threshold fire size, $(Q_c)r$, at detector response (Sec. 2.5.1).
- the gas temperature rise, $(\Delta T)r$, at detector response, i.e., the DMR number (Sec. 2.4.1) of the <u>given</u> detector and combustible material.
- the characteristic length, L, of the detector (Sec. 2.4.8).
- fire growth coefficient (Sec. 2.4.2, 2.5.1).

Knowing H, and considering that by definition of detector response $\Delta T = (\Delta T)r$, Equation (6) can be used to determine ΔT^*. With a specified $(Q_c)r$

and α, Equation (1), for $p=2$, determines t, i.e., the response time of the detector. Thus, from Equation (8), t^* can be calculated which together with the previously calculated T^*, allows the ratio r/H to be evaluated using Equation (4). Since detectors are usually spaced on a square array pattern, the detector spacing, S, is simply $\sqrt{2}\ r$.

This example assumes, for simplicity, that the smoke entry resistance of the given detector is zero, i.e., L=0. If $L \neq 0$, but given, additional calculations using the above equations would be required since now $\Delta T \neq \Delta Tr$ which can be determined using Equation (9) after the quantity $(dT/dt)/\langle u \rangle$ has been evaluated.

The results of calculations of this type are summarized in the report prepared for the Fire Detection Institute by an ad hoc committee with I. Benjamin of NBS as chairman.[14] Figure (6) is an example of one of many design charts found in Reference (14). Thus, for example, using this figure and Table 1, for siting of smoke detectors for optimum response to PVC burning ($(\Delta T)r$ = 10°F, therefore DMR=1) at a "slow" rate when the fire intensity reaches a threshold value of 100 Btu/sec (100 kw) in a room having a smooth ceiling with a clearance height of 20 feet requires aerosol detector spacing on a grid of 10 ft x 10 ft with detectors having zero smoke entry resistance (L=0). The grid spacing decreases if the detectors have a non-zero smoke entry resistance.

Also cross plotting detector spacing with threshold fire size, for a given ceiling height, in effect, determines the percent change in response time if detectors are located at spacing distances different than the "optimum" value. In essence increasing the grid spacing from 10 ft x 10 ft, using the same detectors requires the threshold fire size, $(Q_c)r$,

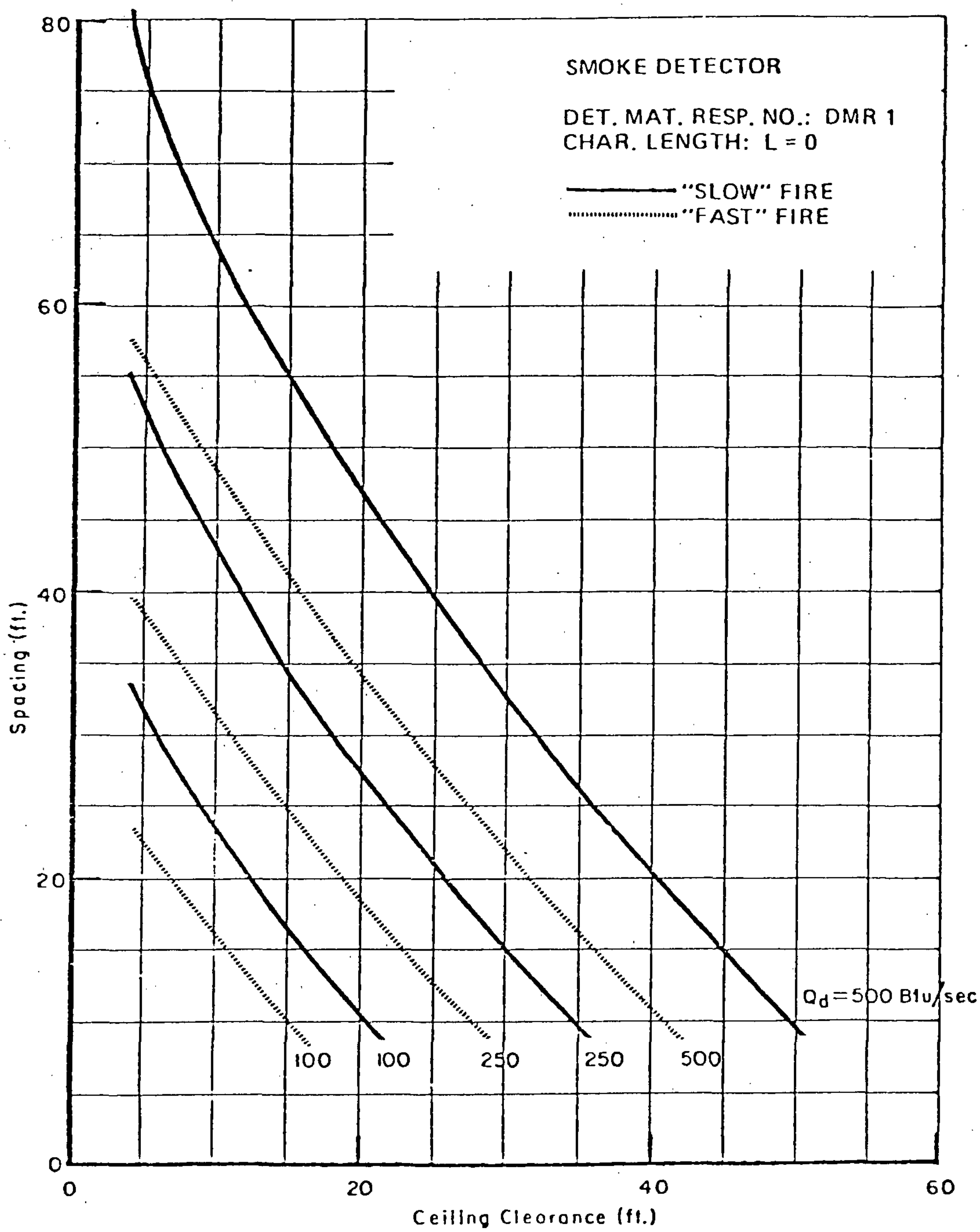


Fig. 6. Typical smoke detector spacing design curves for smooth ceiling and flaming fire conditions. (14)

at response to increase. Thus one can analytically assess the sensitivity of actual detector locations to a given fire and combustible material.

It is important, also, to note that the use of the design charts found in Reference (14) means that the fire detection system designer must make some decisions on the character and nature of the fire. Also the design data for aerosol detectors are based upon a material response number and L value, both of which are not currently available but should be obtained from the detector manufacturer. For cables, estimates on the DMR values can be obtained using the results of Tewarson. It is believed however, that L values among approved smoke detectors vary from less than 10 feet to more than 80 feet. Thus the design charts are given for six L values (L=0, 5, 10, 20, 40, 80), three DMR numbers, and threshold fire intensities ranging from 100-1000 Btu/sec under both "fast" and "slow" developing conditions. Thus a rather broad range of fire conditions, detector types, and combustible materials are included in these design charts.

2.5.3 Thermal Detector Spacing Criteria: Flaming Fires, Smooth Ceiling, Quiescent Environment

Having expressions for the radial variations of temperature and velocity along the ceiling, as highlighted in Section 2.5.1, the thermal response of heat detectors due to convective heating can also be calculated.[20] However implementing this analysis and correlation for both the fixed-temperature and rate-of-rise detectors, the "time constant" reflecting the thermal inertia of the heat detector (Sec. 2.4.8 and Eq. 9) must be known. Heskestad and Delichatsios have related the UL spacing schedule to this time constant. They have, by using data from the Underwriter's acceptance tests on these types of detectors, in connection with the above analysis, devised a response value or sensitivity for these types of detectors.

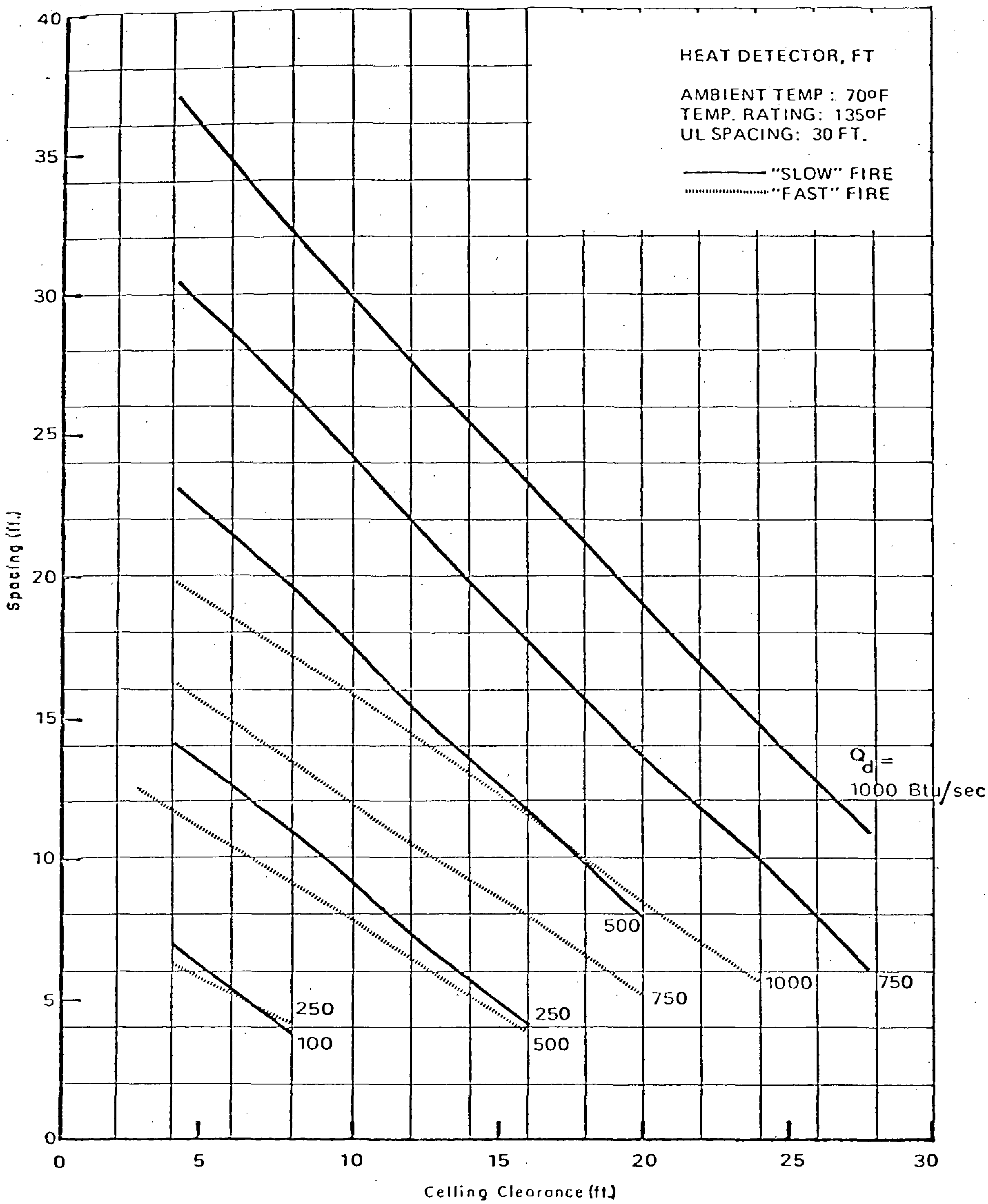


Fig. 7. Typical heat detector spacing design curves for smooth ceilings and flaming fire conditions. (14)

Design charts for a 135°F fixed temperature rating detector and a 15°F/minute rate-of-rise detector at three UL spacings (20, 30, 50 ft) are also presented in Reference (14). Figure (7) is a typical example of these charts and shows fixed-temperature heat detector spacing as a function of ceiling heights for fires ranging in intensity at response time from 100-1000 Btu/sec and growing at either a slow or fast rate. Note that the fire intensity coefficient for the charts presented is for "fast" fires reaching 1000 Btu/sec in 150 seconds and for "slow" fires reaching 1000 Btu/sec in 600 seconds. For combustibles in nuclear reactors these values may in some instances have to be reevaluated, and hence, the design charts modified accordingly. However, it is expected that direct use of the cited charts can give some realistic indication of the number and approximate spacing of detectors in a given area. Also, it must be emphasized that spacing need not be on a regular geometric pattern. Accordingly, these charts may be used to determine the minimum number of detectors required in a given fire area; their actual placement (not necessarily on a grid pattern) requires a site survey of the area.

2.5.4 Aerosol Detector Spacing Criteria - Beamed Ceilings, Flaming Fires Quiescent Environment

The presence of beams on the ceiling affects detector spacing. NFPA 72E considers beams 8 inches or less in depth equivalent to a smooth ceiling due to the "spill over" effect of the smoke. For beam depths greater than 8 inches in depth, movement of heated air and smoke may be slowed by the pocket or bay formed by the beams. NFPA 72E calls for reduced spacing but does not indicate percent reduction. Also the code suggests that beams exceeding 18 inches in depth and more than 8 feet on centers shall be treated as a separate area requiring at least one detector. However, the effect of beams on smoke movement is proportional to the ratio of the depth of the beam to the ceiling

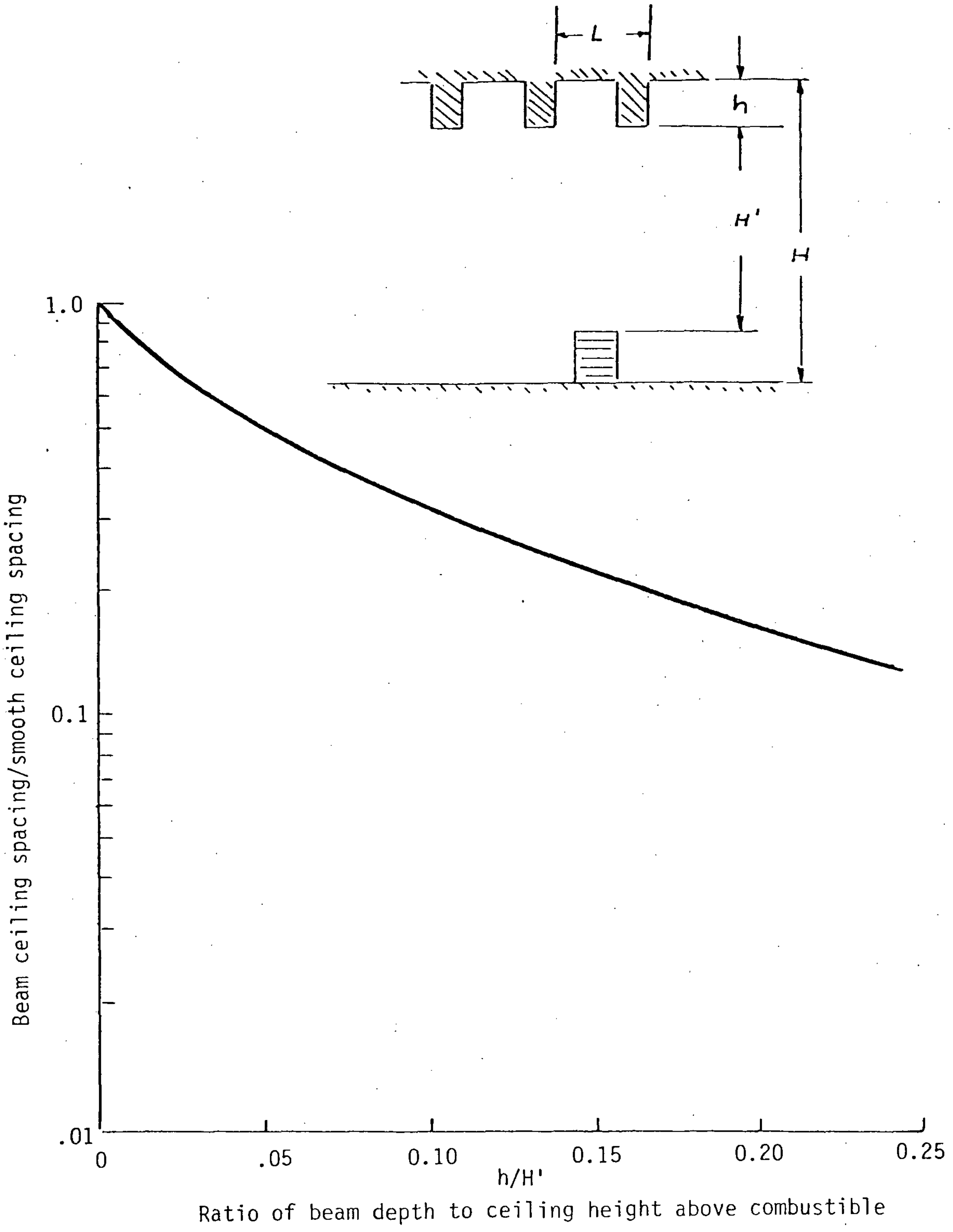


Fig. 8. Comparison of cross-beam spacing of smoke detectors under beamed ceilings with spacing under flat ceilings. (21)

clearance height above the combustible and also the spacing of the beams in relation to their depth. For example, an 18-inch beam depth in a room with a 60-foot clearance height may be considered "smooth" when compared to the same beam depth found in a room having a 20-foot clearance height.

Also because of the channel effect of the beam bays, gas temperatures and smoke decrease very rapidly from the fire source across the beam direction but decrease slowly along the beam direction. Heskestad and Delichatsios[21] have extended their work on smooth ceilings to determine the effect of beam depth and bay width on detector response and spacing; Benjamin has also reported on the results of this work. The effect of the spacing of detectors across the beam channels, as compared with that for a flat ceiling, is shown in Figure 8, which indicates the relative reduction in cross beam spacing as the beam depth increases for a given clearance height, H', above the combustible. Use of this figure, together with the design charts for smoke detector spacing over smooth ceilings, can lead to an approximate method of determining spacing configurations for smoke detectors under extensive beamed ceilings. The approach requires the following variables: ceiling height above the combustible to the bottom of the beam (H'); the beam depth (h); the beam spacing (L); and the gas temperature at response for the detector $(\Delta T)r$. From Figure 8 determine $Sx/(Sx)_{FLAT}$ at H'=8 ft and $(Sx)_{FLAT}$ at H'=8 ft from the smooth ceiling design charts. Assume Sx is independent of H'; hence, Sx at the ceiling height of the problem equals Sx at H'=8 as determined above. Form the ratio Sx/L and choose the nearest lower integer to represent the number (n) of beams between detectors (note $n \geq 1$).

An approach for determining parallel beam spacing (Sy) is also described in Reference (21). Maximum spacing along the beams is estimated as $(Sy)_{max} = (70/8)(H')$.

TABLE 8

NUMBER OF BEAMS BETWEEN CHANNEL-MOUNTED DETECTORS (n)
FOR VARIOUS BEAM CONFIGURATIONS AND SELECTED COMBINATIONS
OF FIRE GROWTH PARAMETER (t_c), TEMPERATURE RISE TO DETECTION (ΔT_r),
AND CEILING CLEARANCE TO BOTTOM OF BEAM (H')

Note: 1) Power-law, p=2 fires; 2) Detection threshold of Q_d= 1000 Btu/sec;
3) S_y conservatively limited to 70 ft for H' = 8 ft, 140 ft for H' = 16 ft, and 210 ft for H' = 24 ft, <u>except</u> as stated explicitly in parentheses.

Beam Config.				n (S_y in parentheses)		
h/H'	L/h	t_c(sec)	ΔT_r(°F)	H' = 8 ft	H' = 16 ft	H' = 24 ft
1/8	2	150	80	4	2	1 (34 ft)
"	"	"	40	6	2	2
"	"	"	20	8	4	2
"	"	"	10	10	6	4
"	"	300	80	6	2	1 (34 ft)
"	"	"	40	8	4	2
"	"	"	20	12	6	4
"	"	"	10	14	8	4
"	"	600	80	?	2	1 (60 ft)
"	"	"	40	?	4	2
"	"	"	20	?	6	4
"	"	"	10	?	8	6

Beam Config.				n		
h/H'	L/h	t_c(sec)	ΔT_r(°F)	H' = 8 ft	H' = 16 ft	H' = 24 ft
1/8	4	150	80	2	1 (104 ft)	1 (22 ft)
"	"	"	40	4	2	1 (168 ft)
"	"	"	20	6	2	2
"	"	"	10	6	4	2
"	"	300	80	4	1 (120 ft)	1 (22 ft)
"	"	"	40	4	2	1 (168 ft)
"	"	"	20	6	2	2
"	"	"	10	8	4	2
"	"	600	80	?	1	1 (22 ft)
"	"	"	40	?	2	1 (204 ft)
"	"	"	20	?	4	2
"	"	"	10	?	4	2

Beam Config.				n		
h/H'	L/h	t_c(sec)	ΔT_r(°F)	H' = 8 ft	H' = 16 ft	H' = 24 ft
1/8	6	600	80	?	1 (72 ft)	1 (21 ft)
"	"	"	40	?	1	1 (84 ft)
"	"	"	20	?	2	1
"	"	"	10	?	4	2

From Reference (21)

TABLE 8 (Cont'd)

Beam Config.				n		
h/H'	L/h	t_c(sec)	ΔT_r(°F)	H' = 8 ft	H' = 16 ft	H' = 24 ft
1/8	6	150	80	2	1 (48 ft)	1 (12 ft)
"	"	"	40	2	1	1 (66 ft)
"	"	"	20	4	2	1
"	"	"	10	4	2	2
"	"	300	80	2	1 (48 ft)	1 (16 ft)
"	"	"	40	2	1	1 (78 ft)
"	"	"	20	4	2	1
"	"	"	10	4	2	2
1/4	2	150	80	1	1 (132 ft)	1 (24 ft)
"	"	"	40	2	1	1 (192 ft)
"	"	"	20	2	1	1
"	"	"	10	2	2	1
"	"	300	80	2	1	1 (12 ft)
"	"	"	40	2	1	1 (202 ft)
"	"	"	20	2	1	1
"	"	"	10	4	2	1
"	"	600	80	?	1	1 (24 ft)
"	"	"	40	?	1	1
"	"	"	20	?	2	1
"	"	"	10	?	2	1
1/4	4	150	80	1	1 (32 ft)	1 (6 ft)
"	"	"	40	1	1	1 (36 ft)
"	"	"	20	1	1	1
"	"	"	10	1	1	1
1/4	4	300	80	1	1 (32 ft)	1 (6 ft)
"	"	"	40	1	1	1 (54 ft)
"	"	"	20	1	1	1
"	"	"	10	1	1	1
"	"	600	80	?	1 (52 ft)	1 (12 ft)
"	"	"	40	?	1	1 (60 ft)
"	"	"	20	?	1	1
"	"	"	10	?	1	1
1/4	6	150	80	1	1 (20 ft)	1 (6 ft)
"	"	"	40	1	1 (124 ft)	1 (30 ft)
"	"	"	20	1	1	1 (168 ft)
"	"	"	10	1	1	1
"	"	300	80	1	1 (24 ft)	1 (6 ft)
"	"	"	40	1	1	1 (36 ft)
"	"	"	20	1	1	1 (198 ft)
"	"	"	10	1	1	1
"	"	600	80	?	1 (40 ft)	1 (6 ft)
"	"	"	40	?	1	1 (42 ft)
"	"	"	20	?	1	1
"	"	"	10	?	1	1

Some typical results using this approach are shown in Table 8 which have been taken directly from the above cited references. It is important to note that this information is based upon experiments conducted in an enclosure configured with a large uninterrupted ceiling with beams at reasonably regular spacing. The effects of walls crossing this space have not been assessed, but Heskestad[22] notes that the above steps constitute a conservative approach and should serve as a base for starting out the siting design.

2.5.5 Heat Detector Spacing Criteria - Beamed Ceilings, Flaming Fires, Quiescent Environment

The theory developed and verified previously for fixed temperature and rate-of-rise detectors has also been extended in the above cited work for heat detector location within beam ceiling enclosures. These results have also shown that there is little difference between placing detectors beneath the beam or in the channel between the beams, except for very close beam spacing where in-channel detector array is better.

Recall, that the approach used requires that the time constant, τ, at some reference velocity be known. Also, the temperature rating of the fixed-temperature device and the rate-of-rise set value for the rate-of-rise device be specified. Time constants, which represent the thermal inertia of the detector and are measurable, are not generally available for commercial detectors. A remedy, discussed in Reference (13), has been devised where τ is related to the spacing limitations issued by U.L. for listed detectors.

Some results are presented in Table 9. The first part of the table pertains to fixed-temperature detectors; the latter part deals with rate-of-rise detectors. For each U.L. spacing, the number of beams, n, between channel-mounted detectors is listed at three ceiling heights for each of six beam configurations. Further details can be found in Reference 21.

TABLE 9

HEAT DETECTORS: NUMBER OF BEAMS BETWEEN CHANNEL-MOUNTED DETECTORS (n) FOR VARIOUS BEAM CONFIGURATIONS (h/H';L/h) AND CEILING CLEARANCES (H')

Notes: 1) Fire growth time constant at t_c = 300 sec; 2) Power-law, p=2 fires;
3) Ambient temperature of 75°F; 4) Detection threshold of Q_d = 1000 Btu/sec;
5) S_y conservatively limited to 70 ft for H'=8 ft, 105 ft for H'=12 ft, and 140 ft for H'=16 ft, except as stated explicitly in parentheses.

FIXED TEMPERATURE — n (S_y (ft) in parentheses)

UL Spacing (ft)	T_s (°F)	h/H'=1/8;L/h=2 H'=8ft	12 ft	16 ft	h/H'=1/8;L/h=4 8 ft	12 ft	16 ft	h/H'=1/8;L/h=6 8 ft	12 ft	16 ft	h/H'=1/4;L/h=2 8 ft	12 ft	16 ft	h/H'=1/4;L/h=4 8 ft	12 ft	16 ft	h/H'=1/4;L/h=6 8 ft	12 ft	16 ft
10	128	1	1(77)	1(19)	1	1(23)	1(15)	1	1(16)	1(12)	1	1(26)	1(14)	1(40)	1(15)	1(11)	1(29)	1(14)	1(8)
	145	1	1(78)	1(19)	1	1(24)	1(15)	1	1(17)	1(12)	1	1(31)	1(14)	1	1(15)	1(11)	1(33)	1(14)	1(8)
	165	1	1(80)	1(18)	1	1(23)	1(15)	1	1(17)	1(12)	1	1(34)	1(14)	1	1(14)	1(10)	1(37)	1(14)	1(8)
12.5	128	2	1(95)	1(32)	1	1(43)	1(18)	1	1(19)	1(15)	1	1(73)	1(19)	1	1(19)	1(13)	1(62)	1(17)	1(11)
	145	2	1(97)	1(32)	1	1(46)	1(17)	1	1(20)	1(15)	1	1(77)	1(18)	1	1(19)	1(13)	1	1(17)	1(11)
	165	2	1(95)	1(24)	1	1(45)	1(16)	1	1(23)	1(14)	1	1(77)	1(17)	1	1(17)	1(12)	1	1(16)	1(10)
15	128	2	1	1(62)	1	1(67)	1(20)	1	1(32)	1(17)	1	1	1(23)	1	1(22)	1(15)	1	1(20)	1(13)
	145	4	1	1(64)	1	1(76)	1(20)	1	1(31)	1(17)	1	1	1(23)	1	1(22)	1(15)	1	1(20)	1(13)
	165	4	1	1(48)	1	1(75)	1(18)	1	1(30)	1(16)	1	1	1(21)	1	1(22)	1(14)	1	1(19)	1(12)
20	128	4	1	1(111)	1	1	1(32)	1	1(57)	1(25)	1	1	1(42)	1	1(37)	1(21)	1	1(29)	1(18)
	145	4	1	1(102)	1	1	1(28)	1	1(57)	1(22)	1	1	1(36)	1	1(37)	1(19)	1	1(28)	1(17)
	165	4	1	1(93)	1	1	1(21)	1	1(56)	1(20)	1	1	1(32)	1	1(36)	1(17)	1	1(26)	1(16)
30	128	4	2	1	2	1	1(99)	1	1	1(40)	1	1	1	1	1	1(31)	1	1(65)	1(26)
	145	4	2	1	2	1	1(65)	1	1	1(30)	1	1	1(101)	1	1(79)	1(26)	1	1(50)	1(22)
	165	4	2	1(133)	2	1	1(38)	1	1	1(27)	1	1	1(66)	1	1(71)	1(21)	1	1(44)	1(19)
40	128	6	2	1	2	1	1	2	1	1(55)	1	1	1	1	1	1(38)	1	1(99)	1(30)
	145	6	2	1	2	1	1(94)	2	1	1(38)	1	1	1	1	1	1(31)	1	1(72)	1(26)
	165	6	2	1	2	1	1(60)	2	1	1(33)	1	1	1(108)	1	1(95)	1(26)	1	1(72)	1(22)
50	128	6	2	1	2	1	1	2	1	1(69)	1	1	1	1	1	1(45)	1	1	1(32)
	145	6	2	1	2	1	1(114)	2	1	1(46)	1	1	1	1	1	1(35)	1	1(90)	1(28)
	165	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

RATE OF RISE — n (S_y (ft) in parentheses)

UL Spacing (ft)	R(°F/min)	h/H'=1/8;L/h=2 H'=8ft	12ft	16 ft	h/H'=1/8;L/h=4 8 ft	12 ft	16 ft	h/H'=1/8;L/h=6 8 ft	12 ft	16 ft	h/H'=1/4;L/h=2 8 ft	12 ft	16 ft	h/H'=1/4;L/h=4 8 ft	12 ft	16 ft	h/H'=1/4;L/h=6 8 ft	12 ft	16 ft
10	15	1	1(86)	1(22)	1	1(25)	1(15)	1	1(19)	1(13)	1	1(39)	1(16)	1	1(17)	1(12)	1(33)	1(16)	1(10)
	20	1	1(86)	1(22)	1	1(25)	1(15)	1	1(20)	1(12)	1	1(37)	1(16)	1	1(16)	1(12)	1(35)	1(16)	1(9)
	25	1	1(83)	1(22)	1	1(25)	1(15)	1	1(20)	1(12)	1	1(35)	1(15)	1	1(15)	1(11)	1(36)	1(15)	1(9)
12.5	15	2	1(101)	1(54)	1	1(50)	1(19)	1	1(25)	1(15)	1	1	1(20)	1	1(21)	1(14)	1	1(20)	1(12)
	20	2	1(98)	1(33)	1	1(43)	1(18)	1	1(24)	1(14)	1	1	1(18)	1	1(19)	1(14)	1	1(18)	1(11)
	25	2	1(97)	1(31)	1	1(41)	1(17)	1	1(23)	1(14)	1	1(77)	1(18)	1	1(18)	1(13)	1	1(18)	1(10)
15	15	4	1	1(88)	1	1(96)	1(22)	1	1(32)	1(18)	1	1	1(25)	1	1(26)	1(17)	1	1(23)	1(15)
	20	4	1	1(79)	1	1(75)	1(21)	1	1(30)	1(16)	1	1	1(22)	1	1(24)	1(16)	1	1(22)	1(13)
	25	4	1	1(71)	1	1(73)	1(19)	1	1(29)	1(16)	1	1	1(22)	1	1(22)	1(15)	1	1(22)	1(13)
20	15	4	1	1(119)	1	1	1(32)	1	1(70)	1(24)	1	1	1(41)	1	1(40)	1(21)	1	1(32)	1(19)
	20	4	1	1(119)	1	1	1(30)	1	1(64)	1(23)	1	1	1(38)	1	1(41)	1(21)	1	1(32)	1(18)
	25	4	1	1(115)	1	1	1(36)	1	1(56)	1(22)	1	1	1(32)	1	1(35)	1(19)	1	1(32)	1(17)
30	15	6	2	1	2	1	1(90)	2	1	1(39)	1	1	1	1	1	1(31)	1	1(93)	1(27)
	20	6	2	1	2	1	1(68)	2	1	1(32)	1	1	1	1	1	1(28)	1	1(71)	1(24)
	25	6	2	1	2	1	1(36)	2	1	1(28)	1	1	1(80)	1	1(68)	1(24)	1	1(57)	1(21)
40	15	6	2	1	2	1	1	2	1	1(57)	1	1	1	1	1	1(38)	1	1	1(31)
	20	6	2	1	2	1	1(104)	2	1	1(43)	1	1	1	1	1	1(32)	1	1	1(28)
	25	6	2	1	2	1	1(66)	2	1	1(32)	1	1	1	1	1	1(28)	1	1	1(24)
50	15	6	4	1	2	1	1	2	1	1(53)	1	1	1	1	1	1(40)	1	1	1(32)
	20	6	4	1	2	1	1(135)	2	1	1(55)	1	1	1	1	1	1(36)	1	1	1(30)
	25	6	4	1	2	1	1(86)	2	1	1(34)	1	1	1	1	1	1(32)	1	1	1(25)

From reference (21)

Again, it must be emphasized that, since this design data does not account for the effects of walls or other major interruptions in the beam channels, such as cross girders of considerable depth, these values could be considered as conservative.

2.5.6 Stratification Criteria

From the field of meteorology, dealing with plume dynamics in stratified or stable ambients, it is known that a hot plume can only penetrate a thermal inversion and continue to rise if at that elevation the plume is warmer than the air above the inversion. Similarly, for detector system design, stratification of combustion products below the ceiling can delay the response of ceiling-mounted aerosol and heat detectors until a fire has grown to dangerous proportions. The analysis previously described cannot account for this effect. However criteria can be developed for plume rise in still air to reach the ceiling using the results of plume rise formula found in meteorological applications.[23] Such approximate analysis indicates that plume rise, h, above a virtual source can be related to the buoyancy flux parameter, F and stability parameter, s, viz

$$h = 5.0\ F^{1/4} s^{-3/8} \qquad (10)$$

where

$$F \equiv gQ/\pi cpT \approx 8.84(10)^{-3}\ Q\ \frac{m^4/sec^3}{kW} \qquad (11)$$

and

$$s \equiv (g/T_\infty)(dT/dz) \qquad (12)$$

Assuming a linear stratification (s = constant) from the level of the fire source to the ceiling, the convective heat release from the source required for the plume to reach the ceiling can, with the above expressions, be estimated using:

$$Qc > 1.11(10)^{-3} H^{5/2} (\Delta T)^{3/2} \qquad (13)$$

where Qc is the convective heat release rate (KW); H is the clearance between the top of the ceiling and the fuel source (m); and (ΔT) is the ambient gas temperature difference (°K) from ceiling level to the fuel. For example, considering Qc = 10 KW ($\approx$10 Btu/sec) and H = 18 meters ($\approx$60 feet) then

$$Ts < 3.5°C\ (6.3°F)$$

Thus, a floor to ceiling ambient temperature rise greater than approximately 4°C would cause a thermal plume generated from a 10 KW source to stratify before reaching a height of 18 meters. This example indicates how stratification effects may be assessed once ambient temperature profiles and realistic fire size have been determined.

If the above guidelines on stratification indicate that aerosol detectors must be suspended from the ceiling, baffles should be placed around the detector. Down draft or draft diffusing ceilings also require a baffle over each detector to collect a substantial fraction of the particulate matter. Recommended size for these baffles are 0.6-0.9 square meters. However, estimates on baffle width with height can be determined knowing that the plume width, b, can be approximated by $b/z \approx 0.2$ for Gaussian plumes. Thus, the characteristic length of the baffle should be approximately 20% of the installed smoke detector height.

The effects of room ventilation may cause the fire plume to bend; thus negating the effect of smoke baffles situated directly above the fire. However, if the detector is required for equipment protection and if the room flow pattern is fairly uniform, the detector along with its baffle may be offset slightly from the fire source using the formula

$$(H'/r) = (1.8)(F/u^3/r)^{1/3} \qquad (14)$$

where r is now the offset distance of the baffle located directly above the detector situated at a vertical height, H', above the combustible and u is the room flow velocity.

2.5.7 Congestion Criteria

Since there exists no proven methodology for assessing the relationship between the degree of congestion and detector effectiveness, the only guideline one can suggest is to install detectors in accessible locations with no large item of congestion between the detector and the major combustible hazard in the fire zone area. For a cable spreading room this suggestion is indeed inappropriate since the entire room can be considered fully congested. Under these circumstances, four factors to be considered are the effects of congestion on (1) resistance to smoke movement, (2) accumulation and/or condensation of the aerosol on obstructions, (3) dilution effects due to enhanced mixing, (4) reduction in gas temperature due to enhanced heat transfer to the barriers. Based upon the various siting criteria already discussed, a conservative approach may be to additively consider the effects of congestion together with ceiling beam geometry. Thus, congestion in terms of flow blockage area may be translated as having beams of greater depth for a given ceiling height. Resistance to plume flow may, in practice, be determined using instantaneous release of tracer gas. Measurement of tracer gas concentration with time at a particular detector location may provide some information as to flow resistance.

2.5.8 Ventilation Criteria

The effects of high flow rates on detector response are not completely understood. Manufacturer's data suggest that optimum detector performance can be expected at 5-7 air changes per hour. Berry notes that in a power plant,

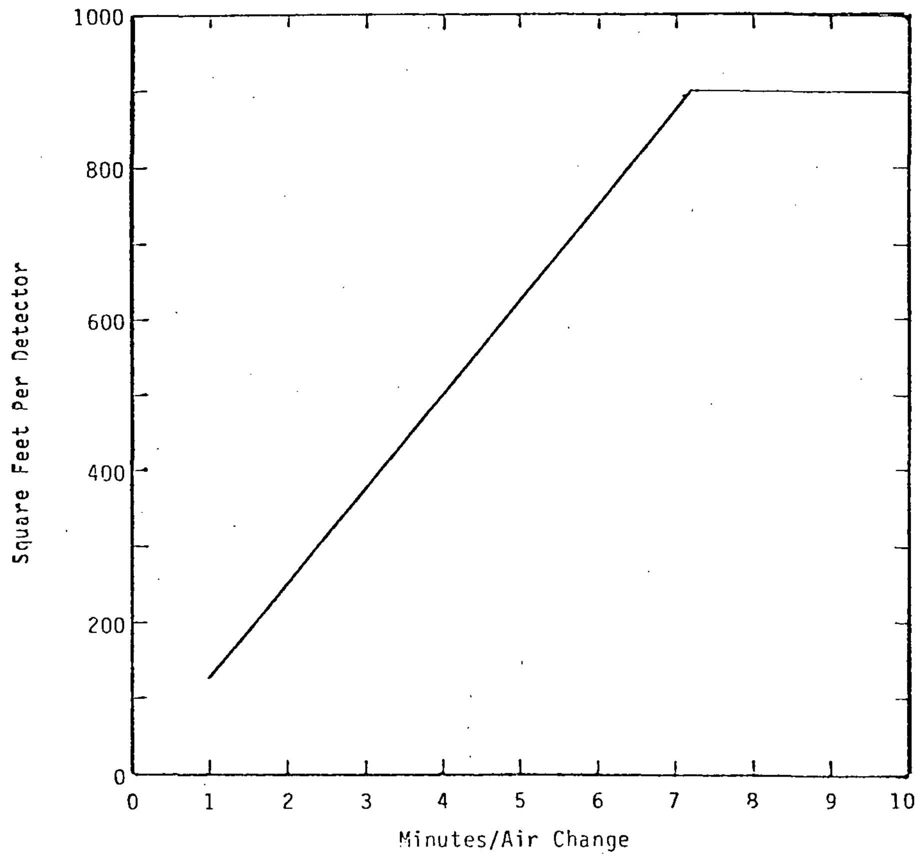


Fig. 9. NFPA 72-E Quide on effects of room ventilation on detector spacing. (2)

air flow rates through portions of a ventilated room can exceed 100 feet/min. (5.5 m/sec) while rates in the vicinity of supply and return registers can reach values an order of magnitude larger. Since criteria applicable within these flow environments do not exist, it is suggested that detector location should not be in the direct path of ventilation supply registers.

In addition, a possible interim measure, although not verified, to assess global air movement on detector spacing is to use Figure A-8-3-5.1A (Figure 9 here), found in Appendix A of NFPA 72-E[2] in conjunction with the detector spacing curves already discussed. For example, in Figure 9 an upper level of 900 square feet of detector spacing is reached at air change rates greater than 7 minutes/air change (or less than 8.6 air changes per hour). This indicates that a quiescent environment can be considered for rates greater than 7 minutes/air change (or lower than 8.6 air changes per hour). Now, considering a detector threshold fire size of 250 Btu/sec, burning at a "fast" rate, Figure 6 indicates that this 30 foot x 30 foot spacing (900 ft^2) is required in a quiescent room having a ceiling height of approximately 11 feet.

If one now presumes that the linear variation of detector spacing with air change rate shown in Figure 9 still applies regardless of ceiling height and that for all ceiling heights a quiescent environment is defined as one having an air change rate greater than 7 minutes/air change, then a set of curves, typified in Figure 10, can be generated using Figures 6 and 9 for any predetermined threshold fire size (we used in this example, 250 Btu/sec. and a slow-growth rate.) It must be emphasized that there is no experimental justification to this approach, in fact, if one utilizes "complete" mixing analysis one would expect an exponential variation of detector spacing with volumetric flow rate rather than the linear variation indicated. However, the approach appears conservative.

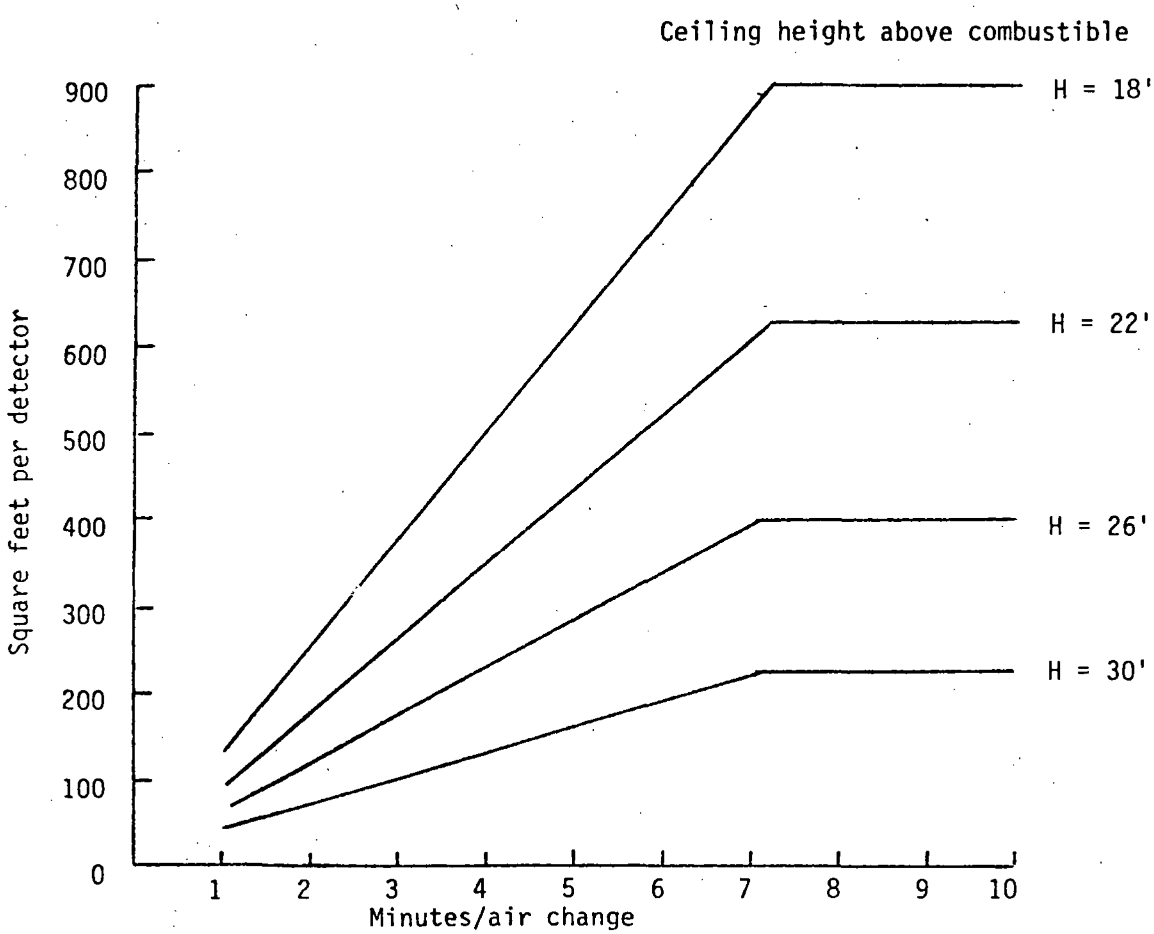
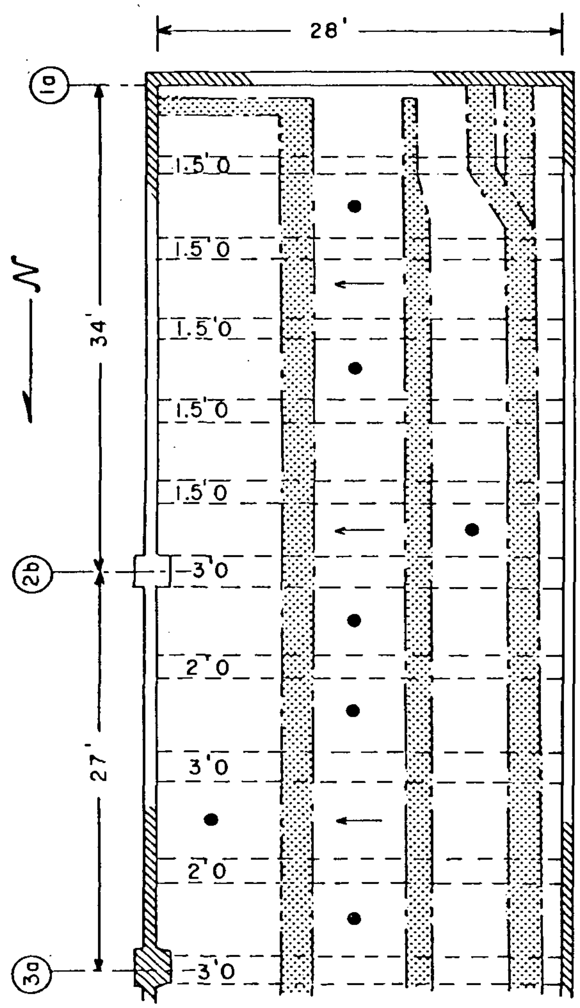


Fig. 10. Possible effect of room flowrates on detector spacing; threshold fire size, Q_D = 250 BTU/sec.; growth rate, slow; detector material response, DMR = 1

2.5.8 System Design Parameters - An Overview

The purpose of this section (Section 2) has been to give a broad review of some of the current work in smoke detector siting. Of primary concern, this section addressed the need for consideration of the nature and type of fire to which a detector should respond. It indicates that information and design criteria are available which can make engineering judgements less subjective and hence more acceptable since these criteria now take into account, more fully and realistically, some of the parameters that affect detector selection and location.

Guidelines employing quantitative determination for smoke and heat detector siting for flaming fires in quiescent environments have been described with (1) fire size, (2) growth rate, (3) combustion products, (4) ceiling height and (5) detector characteristics as requisite input factors. Use of this approach by qualified individuals will necessarily lend more credance, and therefore acceptability, to their detector siting analysis since now various effects on detector performance and sensitivity can be appraised.



For example, the accompanying sketch depicts part of an enclosure that requires an early warning detection system. Superimposed is a fire detector location plan submitted for review comprising seven ionization detectors at the locations indicated and based upon considering cable insulation as the major combustible. The room under discussion is approximately 61 feet long, 28 feet wide, having a beamed ceiling height of 30 feet with beam depths ranging from 3 feet to 1.5 feet as shown. Air is distributed through supply registers along the west wall and is exhausted through return grills at the east wall. Ventilation flows throughput is such that the air change rate is approximately 13.5 minutes/air change. The air flow velocity in the detector areas ranges from 10-30 feet/minute. The shaded area depicts the location of cable trays.

For purposes of subsequent discussion in appraising the submitted detector plan consider that the detector system should respond when a "slow-growing" cable fire reaches a threshold value of 250 BTU/sec. Also, assume that the aerosol detectors chosen have a negligible entry resistance to smoke, which implies a charateristic length, L, of zero and a detector material response, DMR, number of 1. With this information the following steps are taken:

(1) With $(Qc)_r$ = 250 BTU/sec, DMR = 1, L = 0, H = 30 ft., and a slow fire growth rate, Figure 6 indicates that detectors should be spaced at 15 foot intervals if the enclosure has a smooth ceiling. In addition according to Figure 10 the room can be considered quiescent.

(2) To account for the beamed ceiling consider the room divided into two sections separated by columns (2b). In the section between columns (3a) and (2b), the average beam depth, h, is 2.5 feet; thus the ratio of beam depth to height above the combustible, H', is approximately 2.5/(30-2.5) = 0.09 which from Figure 8 indicates a reduced cross-beam spacing $S_x/(S_x)_{flat}$ = 0.35. From Step 1 above,

$(S_x)_{flat}$ = 15 feet indicating that cross beam detector spacing in this section should be 5.25 feet ($S_x = (0.35)(S_x)_{flat}$). Within this area beam spacing, L, is approximately 7 feet; thus S_x/L = 0.75 < 1 indicating that the number of beams between channel-mounted detectors, n, is 1. Thus detectors should be installed in every beam bay. The room width is sufficiently small, and the smoke-channeling effect of the beams is such that one detector in each bay area is sufficient. Thus the number of detectors shown in the sketch, based upon these interim guidelines is acceptable.

For the area between columns (2b) and (1a), 1.5 foot depth beams are indicated. Thus h/H' = 1.5/27.5 = 0.05 and Figure 8 indicates $S_x(S_x)_{flat}$ = 0.5. With beams in this area spaced approximately every 6 feet apart, detectors should again be mounted in every beam bay and thus the number of detectors shown in the sketch is unacceptable. Thus a minimum of 10 detectors, one each installed in every bay constitutes an acceptable number. The actual location should be based upon a site survey of the area keeping in mind the flow patterns within the room. Note that if the air change rate had been less than 7 minutes/airchange then $(S_x)_{flat}$ would first be reduced according to a trend depicted in Figure 10 before the above steps are taken.

Although the above procedure is still considered highly idealized it indicates to some extent how engineering judgement may be augmented with recent detector siting analysis.

Important problem areas still remain, the environmental factors (congestion, ventilation, stratification) together with the factors describing the fire signature on detector selection/siting are highly coupled. The above discussions have treated, to some extent, each of these factors by themselves, using analyses from other disciplines, to make judgements on detector siting. Indeed, these require validation; but, at least, it may provide some initial basis for detector siting.

3.0 INSTALLATION TESTS & MAINTENANCE

Effective performance of fire detection systems requires that the system be inspected, tested and maintained properly. At the completion of the installation, acceptance tests should be conducted in order to demonstrate that the system and devices will meet the performance specifications of the design criteria. To insure that the original performance capability of the fire detectors is maintained after the system is made operational, periodic tests and maintenance procedures should also be performed.

Each type of fire detector has different requirements for testing and maintenance based on the type of fire signature required for detector alarm. Most detector manufacturers supply installation manuals for their equipment which include recommendations for installation, operation, maintenance and trouble shooting.

NFPA 72D, Standard on Proprietary Protective Signaling Systems, provides code requirements for fire alarm systems including those incorporating fire detection devices. This standard outlines the requirements for the system installation with specific performance requirements for functions such as circuitry, power supplies, supervision, signal initiation, transmission and alarm annunciation. NFPA 72E, Standard on Automatic Fire Detectors, provides guidance on detector selection and installation.

It also includes requirements for initial acceptance tests and periodic inspection tests.

The technical specifications which form a part of every nuclear power plant operating license contain limiting conditions for operation as well as surveillance requirements for fire detectors. As the technical specifications must be adhered to by the licensee, the inspection test and maintenance procedures developed should, as a minimum, conform to the inspection and test requirement of the technical specifications, as well as the required frequency in performing these actions.

Various other guidelines suggest that detector installations be tested initially and periodically with smoke from punk sticks, tobacco smoking materials or other particulate matter producing devices. Some criteria including manufacturers' guides recommend detector sensitivity set point checks using special instruments.

Maintenance procedures for fire detectors will vary due to the specific type of detector, the environment it is installed in and the variations in design between models and between manufacturers. In nuclear power plants the conditions affecting detector operability and sensitivity in some locations may be severe. These conditions may include vibration, dust, high air flows and exposure to radiation. Different types or models of detectors may become inoperable or become less or more sensitive when subjected to these various environmental conditions. In developing a plan for maintenance of fire detectors all the conditions that could affect detector operation should be determined and the recommendation of the manufacturer should be followed.

3.1 Design Details for Performing Installation Tests and Maintenance

The following details in testing and maintenance requirements have been culled from the fire detection literature.

3.1.1 General

- Each automatic detector should be continuously maintained in reliable operating condition at all times, and such periodic inspections and tests should be made as are necessary to assure proper maintenance as specified.

- Detectors should be under the supervision of a responsible person who shall cause proper tests to be made at specified intervals and have general charge of all alterations and additions.
- In any tests, all persons who would automatically receive an alarm should be notified, so that an unnecessary response shall not take place.
- After installation, a visual inspection of all detectors should be made to be sure that they are properly located.
- After installation, each detector should be checked to insure that it is properly connected and powered in accordance with the manufacturer's recommendations.

3.1.2 Initial Installation Tests

- Heat Detectors:

  A restorable spot-type detector should be tested with a heat source, such as a hair dryer or shielded heat lamp, until it responds. After each heat test, the detector shall reset.

  A pneumatic tube line-type detector should be tested either with a heat source (if a test chamber is in the circuit) or tested pneumatically with a pressure pump. The manufacturer's instructions should be followed.

  Line- or spot-type detectors of nonrestorable type should not be heat tested.

  Detectors with a replaceable fusible alloy element should be tested by:

  1. removing the fusible element to determine that the detector contacts operate properly, and then
  2. reinstalling the fusible element.

- Smoke Detectors:

To assure that each smoke detector is operative, it should be tested, in place, in accordance with the manufacturer's instructions.

Instruments for checking the sensitivity of some detectors are available from the manufacturer. When using these, the manufacturer's recommended test instructions should be followed.

- Flame Detectors and Other Fire Output Detectors:

Flame detectors and other fire output detectors should be tested for operation in accordance with instructions supplied by the manufacturer.

- Periodic Tests:

1. Detectors should be periodically tested as described in the following paragraphs.
2. For nonrestorable spot-type detectors, after the fifteenth year, at least two detectors out of every hundred, or fraction thereof, should be removed every five years and sent to a nationally recognized testing laboratory for tests. The detectors that have been removed should be replaced with new detectors. If a failure occurs on any of the detectors removed, additional detectors should be removed and tested as a further check on the installation until there is proven to exist either a general problem involving faulty detectors or a localized problem involving only one or two defective detectors.
3. For restorable spot-type heat detectors, at least one detector on each signal initiating circuit should be tested semi-annually and different detectors should be selected for each test.
4. Pneumatic line-type detectors should be tested for leaks and proper operation semi-annually.

5. Line-type fixed-temperature detectors should have their loop resistance measured and recorded in the control cabinet at least semiannually.
6. Smoke detectors should be tested semiannually in accordance with the manufacturer's instructions.
7. Flame detectors and other fire output detectors should be tested at least semiannually as prescribed by the manufacturer and more often if found to be necessary for the applications in question.
8. A permanent record showing all details of the test including the name of the inspector, type, number, location, and the results of detectors tested on a specific date should be kept on the premises for at least five years.

NFPA 72E also gives limited requirements for maintenance of fire detectors consisting of:

- Cleaning and Maintenance:
  1. Ionization and photoelectric smoke detectors may require periodic cleaning to remove dust or dirt which has accumulated. The frequency of cleaning will depend on the local ambient conditions. For each detector, the cleaning, checking, operation, and sensitivity adjustment should be attempted only after consulting the manufacturer's instructions.

Manufacturer's guidelines for testing and maintenance of fire detectors varies with the manufacturer and specific types and models. In general, manufacturers recommend that fire detectors be cleaned and tested at least yearly and more often in areas that have more severe than normal environmental conditions. Testing usually consists of testing the operability and sensitivity of the detector. Most manufacturers recommend testing heat detectors with an electric heat gun similar to a hair dryer. Flame detectors are usually recommended to be tested by special test meters that check the sensitivity set point of the detector or actual smoke simulation tests which include the following methods:

- Photo-electric devices of the spot-type may have a built-in reflector (usually a wire) or similar mechanism that, when actuated, simulates smoke slightly above the minimum required to actuate the photo-sensor.
- Photo-electric devices of the long beam-type may be tested with "screens" or films that simulate a specific degree of smoke obscuration.
- Some manufacturers allow the use of a freon gas to test their ionization detector; others specifically prohibit the use of freon as it may damage the detector circuitry. Freon is a gas and does not demonstrate a threshold test. It "suffocates" the ionization chamber by replacing the ionized air.

Other methods of performing installation acceptance and periodic tests include:

- Actual test fires.
- Smoke Bomb Release tests.
- Tobacco Smoking Materials test (cigarettes, cigars, pipes).
- Smoking Materials (punk sticks, smudge pots, bee smokers, etc.)
- Particulate Matter Release Tests.

Actual test fires give the most accurate results of the ability of fire detector to respond, but this method cannot be used in nuclear power plants because it violates the rule against open fires.

Smoke bomb release tests are very helpful in determining the air flows within an area which can assist in the siting of detectors. However, the material release from smoke bombs usually contain chlorides which may be deleterious to some materials and equipment found in some areas of nuclear power plants. Also, the use of smoke bombs for operation tests of detectors is not effective because the smoke released has no relationship to the type, density or quantity of smoke from an actual fire. Cigarettes and tobacco are often used as test for smoke detectors. This method will show that the detector will respond to small size particulate and does not produce any significant hazard or disagreeable conditions to systems and personnel. Blowing strongly across the glowing tip produces an abundance of small smoke particles that can trigger an ionization type detector from several feet away. Puffed smoke or inhaled smoke will not actuate an ionization detector as easily as the previous method because the smoke particles will tend to agglomerate forming larger less effective particles. Puffed smoke, because of its greater quantity and larger size particles will however, actuate a photo-electric type detector sooner. Other smoke producing materials such as smudge pots, bee smokers and punk sticks are usually unacceptable because of the disagreeable odors, discomfort caused to personnel and the possible harmful effects to equipment and materials in the plant. The problem with this form of test however, is that the aerosol properties, such as mass and number concentration, reflectivity, etc. that effect detector sensitivity cannot be appraised.

There are other problems associated with this form of testing, namely, that combustion generated aerosols used for small scale test purposes, and for periodic maintenance requirements, are too variable. Such properties as material, density, moisture content, thermal history and others have an effect on the characteristics of the aerosol generated. Accordingly, it is felt that a mechanically generated aerosol is the only practical solution to eliminating or minimizing these variables. In this regard, a portable instrument has been constructed and tested[24] to check the sensitivity response of installed smoke detectors. The unit which fits around the detector, can generate, using dioctyl-phthalate, a monodisperse aerosol at a given flow rate and concentration. This field unit could then be used to determine the sensitivity of an installed detector instead of just determining whether or not it is operating as is now done.

3.2 Qualification Test for Performing Installation Tests and Maintenance

A detector installation test procedure needs to be developed that is based upon confirmatory research, and is representative of the combustibles, environmental conditions and detector types normally found in nuclear plants. In this regard, considerations should be given to the following:

- Sensitivity Log - The sensitivity set point of each fire detector should be verified at the time of installation by the manufacturer or installer. If necessary, the set point should be adjusted or the detector replaced to meet design or recommended factory settings. The set point data should consist of firing point voltage, pulse rate, temperature or other determining characteristics of a detector's sensitivity. The readings should be recorded in a log and identified by detector number and location corresponding to a plan of the installation.
- Stability Test - The acceptance of the fire detection system should include a 30 day stability test with all room conditions in the normal operating mode. The detectors should experience no spurious alarms during this period. At the successful completion of the stability test, the set point of each detector should be checked and recorded in the log. All detectors should also be checked to determine that they

are electrically supervised as installed. This can be accomplished by possibly removing each detector from its base which should result in a supervisory, (trouble) signal at the control panel. After making the supervisory test, the detector should be reattached to the mounting base and retested for alarm function.

- Special Equipment - Any special equipment such as sensitivity meters, particulate matter test devices, heat guns, etc. necessary for the proper testing and maintenance of the detectors should be acquired. When testing and maintenance of the fire detectors is subcontracted to an outside firm, it should be determined that the contractor has the necessary equipment.
- Test Personnel Qualifications - The persons responsible for the fire detector testing and maintenance program should include a qualified fire protection engineer familiar with the problems of the specific location and with the problems associated with smoke detectors.

4.0 FIRE DETECTION SYSTEM ANALYSES - APPROACHES TAKEN BY SOME LICENSEES

The need for added research in the fire detection area or the lack of specific guidelines conducive to plant fire detection systems notwithstanding, licensees of nuclear facilities have been obliged to analyze and submit for review their fire detection programs. Brookhaven National Laboratory has undertaken an evaluation of several licensee submittals to the NRC with the possible aim that concerted reviews of these methods, coupled with the recent strides made in detector selection and siting as outlined in Section 2 of this report, may then lead to a more unified and systematic approach from which subsequent appraisals may be implemented.

To date, three fire detection system selection approaches have been reviewed; namely, the smoke simulation prototypic tests conducted by the NUTECH Corporation for Yankee Atomic Electric Company; the fire detection analysis performed by Stone & Webster Engineering Corporation for the Omaha Public Power District at the Fort Calhoun facility; and, the fire detection system selection criteria proposed by Wisconsin Electric Power Company for their Point Beach facility.

Briefly, the "NUTECH" method attempts to simulate the movement of combustible aerosols using a surrogate invisible tracer gas, specifically sulfur hexafluoride, together with electron-capture gas chromotography to measure gas concentration with time. The intent of these tests was to demonstrate that an acceptable method for conducting in situ tests with a suitable smoke generation device to verify that a fire would be promply detected by installed smoke detectors is readily available.

The "Fort Calhoun" method to all intents and purposes follows the guidance in NFPA 72E and relies heavily on sound engineering judgement, and field surveys for detector siting.

The "Point Beach" approach, recognizing that existing design and regulatory guidelines provide insufficient direction toward procurement of a suitable nuclear power plant fire detection system infers that its criteria will be based upon current resarch dealing with fire detectors as well as sound engineering practices. Also, recognizing that these current efforts, although able to quantify some of the particular items addressed in NFPA 72E, are still limited, the approach also makes use of consultations with several fire detection system suppliers. Table 10 compares the detector location and spacing criteria employed in each of these methods with the guidance offered in NFPA 72E.

Of the three approaches, the "Point Beach" method has been considered to be the most acceptable at this time. Under present limitations, the approach is adequate since it contains a more viable mix of sound engineering judgement, present day state-of-the-art smoke detector selection and siting technology, and the use of visual smoke for siting assessment. Most of the factors listed in Section 2 of this document are either directly considered or inferred which indicates that well-informed individiuals in fire detection technology have formulated the "Point Beach" approach.

Further details of each of the above approaches including the evaluations performed by BNL are given in the letter reports to the NRC by senior author dated November 30, 1979, February 12, 1980, and March 3, 1980.

Table 10

Comparison of Licensees Detector Location and Spacing Criteria with Governing Design Guidelines Quoted from NFPA 72E

Design Criteria	NFPA 72E Guidance	Comments	Point Beach	Ft. Calhoun	NUTECH
• Fire Development (growth rate and intensity)	Detection is dependent upon the size and intensity of fire to provide the necessary amount of required products and related thermal lift, circulation, or operation.	Guidance inadequate since fire intensity and growth rate not quantified.	Considers recent NBS research on detector environment.	No consideration	Considers a surrogate smoldering fire using a tracer gas. Excellent technique to determine global and detail smoke movement in areas where use of other visual aerosols visual aerosols are prohibited.
• Ventilation	Spacing of smoke detectors shall result from an evaluation based upon engineering judgement supplemented, if feasible by field test: Ceiling shape, ..., and ventilation are some parameters that shall be considered. Supplies curve of detector spacing with room air-change rate.	Guidance inadequate since fire intensity, growth rate, smoke production rate, ceiling height not quantified with air change rate.	Detector location will not be in direct path of ventilation supply registers,... air flow patterns, using chemical smoke, etc., will be checked and noted in general area of each detector	Uses NFPA 72E guidance and detector manufacturer suggestions.	Determines detector location using tracer gas technique.
• Ceiling Height	On smooth ceilings with no forced circulation, spacing of 30 feet may be used as a guideline. In all cases, the manufacturers recommendations shall be followed.	Guidance inadequate. Does not relate spacing with initial convective flow of fire and detector characteristics.	Utilizes fire protection consultants recommendations. Approach does not include fire intensity and growth rate but does infer implementation of recent research.	Uses NFPA 72E guidance.	Effect of ceiling height implicit in tracer gas technique. But relationship between gas concentration and actual aerosol concentration on detector performance cannot be assessed.
• Stratification (ceiling height)	For proper protection for buildings with high ceilings, detectors shall be installed alternately at two levels; one half at ceiling level; the other at least 3 ft. below ceiling.	"High" ceiling is not defined quantatatively. Estimate of stratification can be made by determining buoyant flux of fire and ambient temperature distribution in fire area.	Not directly addressed. But the field surveys using visible smoke can determine areas of stratification.	Not addressed but engineering judgement implied.	Effect of ceiling height implicit in tracer gas technique. But relationship between gas concentration and actual aerosol concentration on detector performance cannot be assessed. Test room is highly ventilated. Thus stratification not directly addressed.

Table 10 (Cont'd.)

Design Criteria	NFPA 72E Guidance	Comments	Point Beach	Ft. Calhoun	NUTECH
• Stratification (heating systems)	None	Laminar flows of room heating air may become significant barriers to combustion product movement.	Not directly addressed.	Not considered but use of engineering judgement implied.	Proper use and interpretation of results of tracer gas technique can effectively determine heating and ventilation effects on smoke movement.
• Ceiling construction (beamed ceilings)	Beams 8 in. or less in depth can be considered equivalent to a smooth ceiling......in beam construction over 8 in. in depth, movement of heated air and smoke may be slowed...by the beams. In this case spacing shall be reduced. If beams exceed 18 in. in depth and are more than 8 ft. on centers, each beam bay shall be treated as a separate area requiring at least one detector.	One should relate detector spacing with the ratio of beam depth to ceiling height above combustible.	Alludes to implementation of recent NBS research on effect of beams. As initial criteria detectors shall not be installed to provide area detection for more than one section of ceiling divided by beams.	• 18-24 in. and less than 8 ft. apart-alternate beam pocket. • over 18 in. in depth and more than 8 ft. apart-each beam pocket. • over 24 in. in depth-each beam pocket	Difficult to determine unless more site locations for concentration measurements are utilized.
• Room congestion	None	No specific guidance, recent research does not address this problem.	Detectors will be placed in accessible locations with no large item of congestion between detector and major combustible hazard. Path and capability for smoke migration evaluated using visible smoke.	Not directly addressed, but use of engineering judgement implied.	See first comment.

5.0 RECOMMENDED ACCEPTANCE CRITERIA

As yet, there does not exist an effective procedure for testing fire detectors in the in situ condition which has industry acceptance in general and NRC sanctions in particular. As such this report has been written to provide an interim guide of the basic factors that should be considered by the licensee in formulating a fire detection system selection criteria and which may be used by NRC in their review of the licensees approach.

The fire detection system selection criteria proposed here still requires a viable mix of good engineering judgement, the use of qualified investigators and excellent reporting and administrative procedures; all of which should be coupled to the results of current research that has been discussed herein.

The submittal by the licensee should address five major phases required in a fire detection analysis, viz,

1. Establishing area detector requirements.
2. Selection of specific detector types.
3. Location and spacing of detectors.
4. Installation tests and maintenance.
5. Administrative controls and reporting.

5.1 Detector Requirements

A fire hazards analysis performed by the licensee, in accordance with Draft Regulatory Guide 1.120, and subsequent review by the NRC staff, determines plant areas requiring detection needs based upon each area's safety importance or major combustibles present. In addition, it is advisable that for each area the type of fire expected and the response time required be determined. Research on cable flammability parameters, as reported above, can be used to quantify these particular variables.

5.2 Selection of Specific Detector Types

The fire hazards analysis, which identifies the major combustible present in each area, should give some initial indication of the specific type of detector or combinations thereof to be employed based upon the fire signature that has the greatest fire signal-to-background noise ratio. As such, detector selection criteria should acknowledge the following factors on detector choice:

- fire development and size
- combustion products, fire signature
- ventilation and stratification
- room congestion and geometry
- detector sensitivity

For safety of electrical cable systems, two types of fire risk may prevail. These are external exposure of the cable to a fire originating from other combustible materials or internal heating from overloads or short circuits in power cables. The type of fire exposure can affect the decision on the type of detection device used because each different type of exposure may produce different signatures. From the discussion found in Section 2.4, for example, the use of photo-electric smoke detectors for response to cable pyrolysis products resulting from internal electric breakdown is indicated; for external exposure fires ionization detectors may be sufficient. In cases where both fire risk prevail, a combination of the above types may provide the requisite mechanism for early warning. For areas involving low risk, electrical cables may be protected using line-type heat sensors. In any event, the licensee's detection system criteria should reflect the time required for a postulated fire to reach a certain threshold value, using recent data that can describe, within the limitations noted in the text, the initial convective flow of the fire.

For assessing the effects of the other environmental factors on detection sensitivity, it is suggested that prospective bidders of fire detection systems be obliged to conduct sensitivity tests, as described in UL-268, using cable samples indiginous to the particular facility. The use of two types of ignition sources are suggested in the UL-268 procedures.

- flaming fires - using a flammable liquid for the ignition source that in itself produces negligible smoke, such as acetones.
- smoldering fires - place cables on a temperature control hot plate (see details in UL-268).

5.3 Detection Siting and Location Requirements

With plant areas requiring fire detection having been established and appropriate detector types chosen then location and spacing of detectors in a manner consistant with the environment in which the detector must function and the qualification standard to which the detectors have been tested constitutes the next phase of overall selection criteria. It is believed that the suggestions and procedures, discussed in Section 2, which realizes the need to tie spacing (or specific siting) to realistic fire situations, including recognition of the effects of fire-growth rates, ceiling height, combustible material, room ventilation/ stratification/geometry/congestion will provide an interim measure of acceptability for this phase of the overall process.

For aerosol and heat detectors, the starting point for spacing criteria is the approach recently put forth by the Fire Detection Institute.

For cable fires these discussions indicate that a threshold fire size of 100 Kw be the starting point for detector siting. Parametric studies on changes in detector location (or response) with several select values of threshold fire size should be included in the overall analysis so that assessment of time-to-reach-response threshold can be made. Current work from the references cited on cable flammability can allow one to estimate the range of the fire intensity coefficient (needed in the aforenoted charts) described in Section 2.5.1. The described design data for aerosol detectors, is based upon detector/combustible characteristics, such as the detector material response number, and detector characteristics such as the characteristic length, both of which are not currently or completely available but should be obtained from prospective bidders of detection systems. For thermal detectors the spacing analysis discussed is based upon current U.L. sprinkler spacings, for determining response time.

Granted this approach is limited to flat and beam-type ceilings with flaming-type fires in quiescent enclosures; but, it provides a requisite datum from which other environmental effects also discussed in Section 2 can be factored. What is emphasized here is that a more technically sound deterministic method is stressed in lieu of a purely subjective evaluation. However, it is also recognized that under some circumstances a lack of either theoretical understanding or experimental precedents may require reliance on subjective judgement. This method should be considered since it may conceivably become an adjunct to NFPA 72E.

5.4 Initial Installation Tests, Periodic Tests and Maintenance

An acceptable early warning fire detection system analysis should also address the steps necessary for maintaining such a system. This facet of an acceptable system should identify the maintenance details, installation test procedures and maintenance intervals required for each installed detector in particular and the system as a whole. The following are some of the recommended steps required to meet this need.

5.4.1 Installation Test

At the completion of the installation, the fire detection system should be tested to insure that the system performs to the design parameters and is reliable in operation. These tests should include demonstrations confirming the sensitivity of the detectors, the adequacy of the placement and the stability of the components. Recommended initial installation tests include:

a. Testing should, in addition to the recommendations below, be in accordance with the plant technical specifications.

b. Detectors should be tested under the supervision of a responsible person who shall cause proper tests to be made at specified intervals. Guidance should be provided by a fire protection engineer familiar with the site and knowledgeable in the operation and maintenance of fire detectors.

c. Detector installation should be checked to insure that they are electrically supervised as required by the design criteria. Each detector should be removed from its mounting base which should initiate a supervisory trouble signal at the fire alarm system annunciator panel. After making the supervisory test the detector should be reinstalled into the circuit and retested for alarm function.

d. A 30 day stability test with all room equipment in normal operating mode should be made.

e. A log should be maintained in which the results of all sensitivity checks, and other tests are recorded.

5.4.2 Smoke Detectors (Ionization and Photoelectric)

a. The sensitivity set point of each detector should be checked to determine that the setting conforms to the design criteria or manufacturers recommended setting. (Note: this test may require the use of special instruments available from the detector manufacturer).

b. Each detector should be tested by being exposed in place to real smoke, (such as cigarette smoke), or to an aerosol particulate matter using a device specially designed for this application. Testing smoke detectors with freon gas is not considered an acceptable substitute to real smoke or particulate matter such as DOP. Present thinking is that the use of mechanically generated aerosol devices for in situ testing offer the best compromise.

5.4.3 Heat Detectors (line type, fixed temperature and rate-of-rise)

a. Restorable thermal detectors should be tested with a safe heat source. The detectors should go into the alarm state at the rated temperature with time compensation for the thermal lag of the device. Upon completion of the test the unit should automatically restore to the normal mode.

b. Fusible or other non restorable type heat detectors should not be tested with a heat source. Testing of these units should follow manufacturers recommendations.

5.4.4 Flame Detectors and Other Output Detectors

a. Flame detectors and other fire output detectors should be operationally tested in accordance with manufacturers instructions.

5.4.5 Periodic Tests

a. All detectors should be periodically tested to insure that they will operate as anticipated by the design criteria during the operating life of the installation.

b. Smoke detectors should be tested at least once after installation with real smoke or aerosol particulate matter.

c. All detectors should be tested for operation and sensitivity in accordance with manufacturers recommendations semiannually. In areas having severe environmental conditions such as dust, humidity and high radiation, testing should be more frequent. Detectors normally inaccessible due to operating conditions such as in inerted containments, testing may be performed during the refueling outage.

d. The results of periodic testing should be recorded in the log.

e. Detectors deviating in sensitivity from the initial setting should be readjusted or replaced.

5.4.6 Maintenance

Fire detectors should be visually inspected, cleaned and retested in accordance with manufacturers recommendations semiannually. Where installed ambient conditions are more severe than normal, more frequent cleaning may be required.

5.5 Administrative Controls and Reporting

Establishing an acceptable early warning fire detection system is a multi-step, iterative procedure which involves engineering, plant survey and approval. The following example typifies the steps involved in the "Point Beach" approach.

A responsible engineer reviews the utilities' fire protection hazard analysis and the building plans for each room/fire area where fire detectors are to be installed. The quantity of detectors deemed necessary to satisfy the early warning requirements for each room/area are determined. A fire detector location sheet for each detector is prepared with appropriate design

FIRE DETECTOR LOCATION SHEET PAGE 1

SHEET NO.

FPR SECTION

FIGURE NO.

ROOM NO. ________

LENGTH ________ FT.

WIDTH ________ FT.

HEIGHT ________ FT.

VOLUME ________ CU.FT.

AIR FLOW ________ CFM

AIR CHANGE/HR. ________

AMBIENT ________ F

RADIATION FIELD ________ MR/HR.

MAJOR COMBUSTIBLE

DETECTOR NO. ________

TYPE ________

SENSITIVITY ________

N

W E

S

1. ZONE NO.

2. REASON FOR DETECTOR:
GENERAL AREA; ________ CABLE TRAY; ________
EQUIPMENT; ________ ITEM; ________
OTHER: ________ DESCRIBE; ________

3. VENTILATION: INDICATE GENERAL AIR FLOW DIRECTIONS ON SKETCH
TURBULENT AIR FLOW (SMOKE DISSIPATES RAPIDLY); ________
CORRECTIVE ACTION; ________

MODERATE AIR FLOW (SMOKE MOVES IN A CLOUD); ________
LOCATE DETECTOR IN THE PATH OF AIR MOVEMENT.

CALM (NO LATERAL MOVEMENT OF SMOKE CLOUD); ________
CORRECTIVE ACTION; ________

SPECIAL NOTES; ________

4. CONGESTION:
HEAVY; ________ MODERATE; ________ LIGHT; ________
CABLE TRAYS; ________ DUCTWORK; ________ PIPING; ________
EQUIPMENT; ________ BARRIERS; ________ TANKS; ________
OTHER; ________ DESCRIBE; ________

FIRE DETECTOR LOCATION SHEET PAGE 2

4. CONGESTION: (CONTINUED)
WILL CONGESTION IMPEDE SMOKE REACHING THE DETECTOR? YES ______ NO ______
CORRECTIVE ACTION; ________

WILL SMOKE ACCUMULATE IN THE AREA OF THE DETECTOR? YES ______ NO ______
CORRECTIVE ACTION; ________

CAN THE DETECTOR BE EASILY REACHED FOR MAINTENANCE? YES ______ NO ______
CORRECTIVE ACTION; ________

SPECIAL NOTES; ________

5. CEILING HEIGHT: ________
ALLOWABLE DETECTOR AREA COVERAGE ______ SQ.FT. MAXIMUM RADIUS ______ FT.
INSTALLED DETECTOR AREA COVERAGE ______ SQ.FT. MAXIMUM RADIUS ______ FT.

6. CEILING CONFIGURATION:
SMOOTH UNOBSTRUCTED; ______ OPEN HATCH; ______ STAIRWELL; ______
CEILING BEAMS; ______ DEPTH; ______ IN.(LOCATE ON SKETCH)
OTHER DISCONTINUITY; ______ DESCRIBE; ________

WILL CONFIGURATION IMPEDE SMOKE REACHING DETECTOR? YES ______ NO ______
CORRECTIVE ACTION; ________

SPECIAL NOTES; ________

CONCLUSIONS:
WILL THE SELECTED DETECTOR LOCATION SUPPLEMENTED BY THE CORRECTIVE ACTIONS LISTED ABOVE PROVIDE A SUITABLE DETECTOR INSTALLATION? YES ______ NO ______
ADDITIONAL RECOMMENDATIONS; ________

ENGINEERED BY: ________ DATE: ________

PLANT SURVEY BY: ________ DATE: ________

APPROVED BY: ________ DATE: ________

Fig. 11. Typical Fire Detector Location Sheet - "Point Beach" Approach

information included. This should include a sketch of cabling system within the fire area, and where other major (or transient) items of combustion may be located. An accompanying sketch of the fire area should be provided indicating the layout of the ventilation ductwork, and other large items of congestion. Area flow patterns can be included on this sketch once a plant survey has been made. A sample fire detection location sheet is depicted in Figure 11. These location sheets are then forwarded to the utility for plant survey.

Following the plant survey, these sheets are returned to the responsible engineer for his review. If, in his judgement, the located detectors or types will not adequately satisfy the early warning requirements for the fire area, additional detectors and/or relocation should be indicated. Following the determination and location of the proper quantity of detectors, the responsible engineer will assign detector and zone numbers and forward the completed location sheets to the systems fire protection officer for approval.

The plant survey will be conducted in accordance with the requirements of Section 2.5. Each factor discussed which affects detector location is evaluated and the appropriate information entered on the aforenoted sheets. A suitable location for each detector is noted on the sketch. These sheets will again be returned to the responsible engineer.

Following completion of these two general activities, the completed fire detection location sheets are to be forwarded back to the system fire protection officer for final review and approval. Thus, the fire detector location sheet requires the signature of the person who engineers the evaluation, the person who performs the survey and the person approving the work. Overall, an acceptable multi-step, self checking procedure.

6.0 RECOMMENDED VERIFICATION CRITERIA

Although ongoing research has made significant inroads in (1) identifying the key parameters and conditions that must be considered when measuring the performance of individual detectors and (2) in providing quantitative guidelines for siting aerosol and heat detectors based upon idealized, yet realistic fire situations, there are no specific guidelines or test procedures which can verify the effectiveness of an installed early warning fire detection system. Granted this research should continue to specifically address fire protection in nuclear power plants so that a more viable approach in the design of an acceptable early warning system may be formulated.

The major problem for early warning fire detection system verification, simply stated, is the determination of the movement of smoke and heat produced by site-specific combustibles within a given fire area and the concentration required for alarm. This, at least, indicates that verification should be performed using an in situ test program; certainly a logical conclusion but considered impractical and, in some instances, in violation of other plant safety codes. The use of a tracer gas, such as SF_6 has been suggested as a alternate in situ approach. Indeed its conceivable that this technique, which has found wide application in assessing global smoke movement, may be refined to assess detailed flow patterns within an enclosure but in order for this approach to be an effective means for verification, a correlation must be first obtained between the tracer gas concentration and the quantity of smoke movement from actual fires likely to occur in a nuclear power plant facility. It can however be used to assess the overall ventilation patterns within a room to assist in detector siting and judgement on the local effects of congestion on detector siting.

In the interim, however, it is important to identify what minimum course of action can be followed by the licensee to provide some degree of assurance of adequate detector operation. Since direct verification of an acceptable early warning fire detection system, as a whole, is not practical, indirect means of verifying individual components are suggested.

Bright[25] has described a method currently used in West Germany for testing automatic fire detection devices which may be adopted within the International Standards Organization (ISO) procedures. The test method is composed of five types of fires involving cellulosic materials, plastics and flammable liquids which may either produce fire signatures resulting from flaming or smoldering forms of combustion. In addition the five test fires are divided into three sizes; each fire is about twice the size of the next smaller fire. The geometry of the test room (4 mH, 10-12 mL, 6-8 mW) is, as one would expect, crucial to the results obtained in the tests. Further details of the test procedure, the measurements, and the classification from the test data can be found in the cited reference. However, for nuclear power plant fire protection, it is suggested that the cellulosic smoldering and flaming (well ventilated crib fires) fires be replaced with fires from cable materials that are used within the facility. Based upon recently cable flammability data these cable fires should be sized to produce say 10, 50, and 100 Kw of heat intensity.

7.0 FURTHER RESEARCH

Although the capabilities of technology, as it applies to fire detection systems, have made significant strides due to increased public awareness and regulatory actions, these advances in (1) detector selection, (2) detector siting, (3) reliability, and (4) approval tests and standards have not substantially addressed the fire detection requirements within nuclear power plants. There are a number of environmental factors unique to these facilities, discussed in this report, which possibly preclude adequate assessment of fire detection devices that have been selected and already installed in accordance with existing requirements, standards, and recommendations. Accordingly the research, already cited, should be extended to directly address the effects of room sizes, ceiling heights, ventilation, congestion, radiation, and most notably combustibles indigenous to nuclear power plants.

In this regard, the purpose of this report is to provide an interim guide in determining an acceptable early warning fire detection system that the licensee and plant safety review teams may use. Its limitations are indeed apparent. However, its effectiveness can be enhanced if the following research is pursued:

1. An in situ test scheme, e.g., a tracer gas technique, should be reliably devised that can correlate gas movement with actual smoke movement and which can provide reliable field data of the movement of smoke within a single large compartment. Approaches to be investigated should include both electron-capture gas chromatography or condensation nuclei test devices. The latter concept may have more direct bearing on verification procedures since its operation depends directly on the properties of aerosols and not, as in the former, on selective gas diffusion principles.

2. Large scale room and corridor tests should be performed with realistic fires of varying magnitude using combustibles commonly found in nuclear power plants to assess the suitability of various types of fire detectors. Factors of immediate concern should be ventilation, congestion, and ceiling construction. Such tests should be performed by those organizations and research laboratories who have already studied these effects, although under conditions not directly related to nuclear power plant fire detection needs.
3. Recent developments in fire detection technology have indicated that the performance of aerosol detectors are based upon two empirically developed, detector/combustible-specific characteristics. One relates to the smoke entry characteristics of a particular detector, which is a function of the mechanical design of the detector sensing chamber and outer enclosure. The other factor corresponds to the characteristics of the smoke aerosol generated by a specific material under a particular mode and rate of combustion. These have been referred to, herein, as respectively the characteristic length and the detector material response number. Ideally, once these two factors are known, the necessary spacing for detector response prior to a given rate of heat release from a flaming fire can be determined for any ceiling height. Accordingly, testing should be extended to include determination of these two values for various commercial aerosol detectors using materials and combustion modes typical of nuclear power plants.

The above study programs, in conjunction with research currently underway in fire detection technology, are considered as short term programs. However, recent advances in mathematical modeling of fire development within enclosure is fast approaching a stage where direct implementation for NRC purposes should be investigated. Presently, the fire research community is studying two different types of mathematical models to describe fire growth scenarios. Zone models yield a set of algebraic and differential equations derived from unit problem analysis of bulk conservation principles; the field models deal directly with discretized partial differential equations that represent the relevant physical phenomena. The former approach is more simple yet flexible and in a higher stage of development; the latter is more detailed, requiring less empiricism and is more aptly suited for investigation of some of the nuances in fire development such as smoke stratification although inherently more opaque to parameterization. Preliminary efforts should commence on studying the suitability of these existing approaches for nuclear plant fire protection application.

The overall scope of this effort may then naturally lead to an interactive computer program operable from a terminal. By synthesizing the mathematics and detector information, the program can, by its interactive capacity, tell what information is needed, performs the requisite calculations and displays the final results. Understandably, this approach may be all to encompassing at this stage of plant fire protection development but, in conclusion, it must be stressed that present efforts in fire protection technology, in general, are being channeled for operator/computer interactive capability.

The ultimate requirements for nuclear power plant fire protection should keep close pace with and in some instances redirect efforts in these endeavors.

NOMENCLATURE

A	$g/C_pT_\infty\rho_\infty$
C_p	specific heat of air at constant pressure
D	optical density
F	buoyancy flux parameter
g	acceleration of gravity
H	characteristic ceiling height
H'	ceiling clearance above fire source
H_c	heat of combustion
L	characteristic length or beam spacing
p	fire-growth exponent; see Equation (1)
Q_c	convective heat release rate
$(Q_c)_r$	heat release rate at detector response
r	radius from fire axis
T	gas temperature
ΔT	$T-T_\infty$, temperature rise
ΔT^*	non dimensional temperature rise in ceiling layer
t	time
t_r	response time
t^*	non dimensional time for p-type fire growth rate
U	gas velocity in ceiling layer
U^*	non dimensional velocity in ceiling layer
α_c	fire-growth coefficient based on total heat release rate
ρ	gas density
τ	detector lay time
S	detector spacing
S_x, S_y	cross-beam and parallel-beam spacing
DMR	detector material response number; temperature rise range within which a given smoke detector would respond
ID	ionization detector
PSD	photo electric smoke detector
POD	particle optical density; ratio of optical density with aerosol mass concentration
$( )_\infty$	ambient conditions
$( )_r$	conditions at detector response

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