Fire Safety Journal, 2 (1979/80) 191 - 211

Fire Hazard Analysis for Fusion Energy Experiments*,**

NORMAN J. ALVARES and HARRY K. HASEGAWA
Lawrence Livermore Laboratory, University of California, Livermore, California 94550 (U.S.A.)

SUMMARY

We used the 2XIIB mirror fusion facility at Lawrence Livermore Laboratory (LLL) to evaluate the fire safety of state-of-the art fusion energy experiments. The primary objective of this evaluation was to ensure the parallel development of fire safety and fusion energy technology.

Through fault-tree analysis, we obtained a detailed engineering description of the 2XIIB fire protection system. This information helped us establish an optimum level of fire protection for experimental fusion energy facilities as well as to evaluate the level of protection provided by various systems. Concurrently, we analyzed the fire hazard inherent in the facility using techniques that relate the probability of ignition to the flame spread and heat-release potential of construction materials, electrical and thermal insulations, and dielectric fluids. A comparison of the results of both analyses revealed that the existing fire protection system should be modified to accommodate the range of fire hazards inherent to the 2XIIB facility.

INTRODUCTION

In 1977, the U.S. Department of Energy funded us to research and evaluate the fire safety of state-of-the-art fusion energy experiments. The primary objective of the project was to ensure the parallel development of fire safety and fusion energy technology.

In general, fusion energy experiments fall into two categories: magnetic confinement- and inertial confinement- of plasmas. Many magnetic confinement experiments are housed in structures designed for previous applications, and are protected by existing fire protection systems. This does not mean that the system is inadequate for the experiment but rather that it was designed with other applications in mind. Most inertial confinement experiments generally have contemporary fire protection systems, the design for which is included in the construction package of the experiment and its enclosure.

At Lawrence Livermore Laboratory (LLL), both magnetic and inertial confinement experiments are being conducted: the 2XIIB mirror fusion experiment (magnetic), which is housed in the main bay of Building 435, and the Shiva laser fusion experiment (inertial), which has its own structure. These experiments are the models for the fire safety research project. Our analysis of them should eventually yield a methodology and criteria for evaluating the fire safety of a range of fusion energy facilities. In this paper, we describe the initial findings for the 2XIIB facility.

Through fault-tree analysis, we obtained a detailed engineering description of the 2XIIB fire protection system. This information helped us identify an optimum level of fire protection for experimental fusion energy facilities as well as to evaluate the level of protection provided by various systems. Concurrently, we analyzed the fire hazard inherent in the facility using techniques that relate the probability of ignition to the flame spread and heat-release potential of construction materials, electrical and thermal insulations, and dielectric fluids. The results of this study were incorporated into a fire growth analysis based on large-scale fire test

*Based on a paper presented at the International Symposium on Fire Risk Evaluation in Industry, Stockholm, Sweden, May 7 - 9, 1979.

**Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

data and exponentially increasing heat-release rates derived from several existing fire growth models.

The analysis maps the development of the fire with time and the status of the fire protection system. The reliability for the fire protection system, which was obtained through the fault-tree analysis, is then incorporated to produce an overall fire safety evaluation of the main bay housing the 2XIIB experiment.

PROGRAM OBJECTIVES

The objectives of the fire safety analysis of fusion energy facilities are:

(1) Parallel development of fire safety and fusion energy technology.

(2) Establishment of state-of-the-art fire protection for fusion energy experiments.

(3) Development of rational methods for assessing fault modes in fire protection systems.

(4) Development of techniques for defining the fire hazard of fusion energy experiments.

(5) A fire hazard analysis coupled with an analysis of the 2XIIB fire protection system.

(6) Identification of areas where practical and fundamental research is needed to enhance fire protection of fusion systems.

(7) Development and validation of survey protocol for other fusion energy facilities.

(8) Analysis of survey results and evaluation of fire safety for fusion energy facilities.

(9) Conducting research to solve identified problems.

So far we have progressed through item (5) and are in the preliminary stages of item (6). The Fire Science Group at LLL performed the first five tasks with the aid of the Econ, Inc. (Econ Inc. (Systems Analysis firm) 4 020 Moorpark Ave., Suite 216, San Jose, CA 95117) and Dr. Howard Lambert (TERA Corp., Berkeley, CA). Basically, Econ, Inc. and Dr. Lambert were responsible for the quantitative reliability evaluation of the 2XIIB fire protection system, while the Fire Science Group was responsible for developing techniques to define the potential fire hazards (Table 1). The Fire Science Group was also responsible for a fire safety evaluation. Hence, it had to:

- Develop a procedure for matching potential fire hazards to the fire protection systems.
- Develop a procedure for fire risk analysis based on logic.
- Analyze statistics on the performance of fire protection systems.

TABLE 1

Responsibilities of Econ, Inc. and the LLL Fire Science Group in the fire hazards analysis of the 2XIIB facility

Econ, Inc.	LLL Fire Science Group
1. Identify the specific fire protection system in selected enclosures of the 2XIIB facility. Discriminate between detection, isolation, alarm, and suppression.	1. Identify potential ignition sources and fire spread potential.
2. Describe the sprinkler system and the detection system individually and in concert.	2. Survey potential fuel load and ventilation characteristics.
3. Identify fault modes	3. Describe the maximum potential fire scenario with and without the fire protection system (develop fire growth model).
4. Perform fault-tree analysis of the sprinkler system and the detection system and describe their interaction with the total fire control system.	4. Describe the damage to apparatus, enclosure, experimental area, and the total facility based on the design fire in each locality.
5. Provide survey protocol for evaluating and describing a fire protection system based on the results of the LLL study.	5. Describe the potential hazard to personnel.
	6. Coordinate the fire hazards analysis with an analysis of fire protection systems.

- Identify areas where additional data are needed to increase the accuracy of the statistical analysis.

FIRE HAZARD ANALYSIS OF THE 2XIIB FACILITY

Figure 1 shows the basic framework we developed for the fire growth analysis. It describes potential fire growth in the 2XIIB facility and the response of the facility's automatic detection/suppression system. (It also serves as a general outline for this portion of the paper.) The heart of the analysis, the

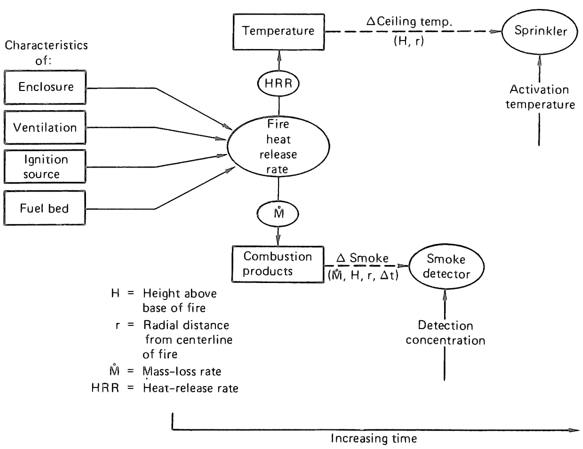


Fig. 1. Framework for fire growth analysis.

heat-release rate of the postulated fire, is determined by surveying the enclosure's ventilation, ignition source(s), and fuel elements. Automatic fire protection response is determined by correlating the heat-release rate to the temperature rise at the ceiling. The mass concentration of combustion products at the ceiling is then determined by the mass-loss rate (M) of the pyrolyzing fuel.

2XIIB Enclosure

The area of building 435 devoted to the 2XIIB experiment is shown in plan and transverse section in Fig. 2. Except for the control room, the diagnostics room and various shops, which are in separate enclosures, the main bay housing the experimental apparatus is primarily one large, continuous volume (Fig. 3). The mezzanines containing the pulse-storage networks (capacitor banks) on the north and south sides of the main bay are open platforms with wood-framed, wire-screened partitions. The main bay is approximately 15 m (48 ft) from floor to ceiling, 18.3 m (60 ft) wide, and 30.5 m (100 ft) long, which produces a total volume of approximately 8 000 m^3 (288 000 ft^3).

We chose to study the main bay for two reasons. First, because of a lack of significant fire stops and barriers in this space, we felt that a fire could spread with little obstruction. Second, we felt that the extensive ceiling

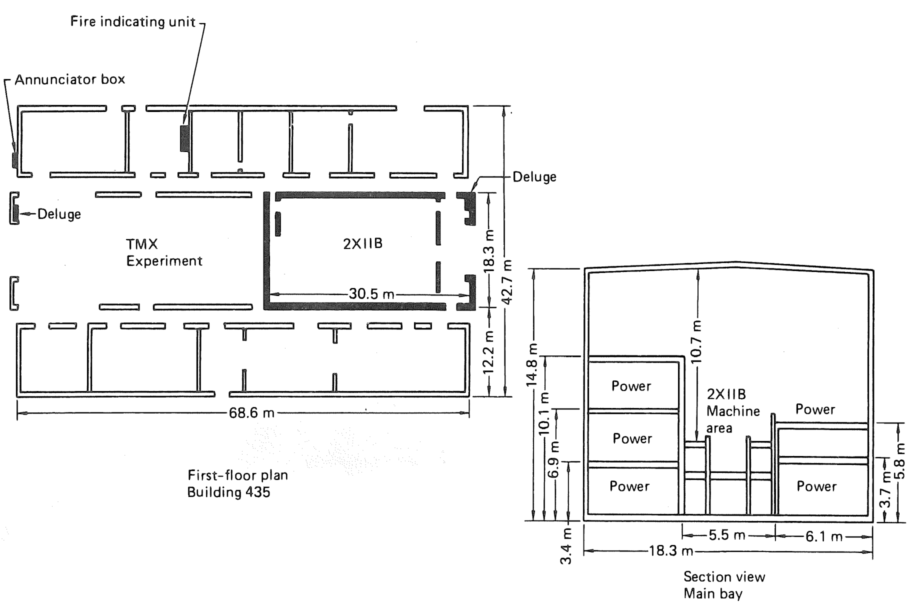


Fig. 2. Plan and transverse section of building 435 devoted to the 2XIIB experiment.

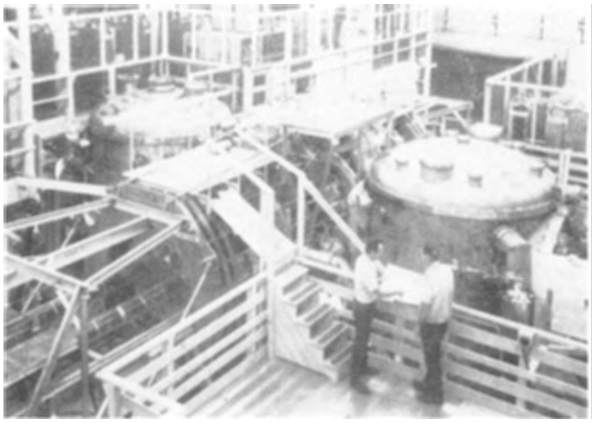


Fig. 3. 2XIIB Main Bay.

height would result in maximum automatic fire detection and suppression response times.

Fuel load and ventilation survey

The fuel load survey is an estimate of the primary fuels that exist in the 2XIIB facility. These estimates are based on visual surveys and analyses of generic physical and chemical properties, such as density and heat of combustion. Although there is a wide variety of combustibles in the experimental area (for example, acrylic sheets, polyethylene films, fiber reinforced polyester, etc.), only those present in significant quantities or posing fire hazards were quantified.

The primary fuel loads included (1) extensive wood structures, such as platforms, stairways, partition frames, and wall and ceiling finishes; (2) a myriad of power, control, and diagnostic cables, the majority of which have either polyvinyl chloride (PVC) or neoprene jackets and polyethylene dielectric material. The total fuel quantities are tabulated below:

• Cables:	PVC insulation	≃ 1 180 kg
	polyethylene dielectric	≃ 1 575 kg
	neoprene insulation	≃ 55 kg
• Wood structures		≃ 6 170 kg

The total mass of combustibles in a building is only significant in terms of total fire duration and only if the fire is allowed to burn out completely. A more vital concern in this study is the rate of fire growth. In terms of fuel bed characteristics the rate of fire spread is essentially dependent on

(a) Material properties:
- heat of combustion
- heat capacity, specific gravity
- thermal conductance, water content
- ignitability

(b) Geometry:
- thickness or depth of fuel elements
- exposed surface areas
- orientation (*i.e.*, vertical, horizontal)
- location and proximity to other fuel elements
- other fuel element shape parameters

(c) Adequate ventilation

Although the bulk of the wood construction in the 2XIIB facility is heavy timber, it is arranged so that all wood surfaces have nearly optimal surface area exposure. Similarly, a large number of power cable bundles are loosely packed, resulting in obtuse and vertical runs. If ignition were established, these factors would enhance fire spread and growth.

The main bay contains approximately 8 000 m^3 of air (ignoring volume of experiment). In addition, two rooftop fans provide ventilation at a rate of 680 m^3 of air/min. The following approximate calculations, in which H_c is the heat of combustion, show that the 8 000 m^3 alone is sufficient to support the combustion of 1 556 kg of polyvinyl chloride (PVC) or 1 848 kg of wood:

PVC: $H_c = 46.6$ mJ/kg.
This material requires 5.14 m^3 of air to burn 1.0 kg.
8 000 m^3/5.14 = 1 556 kg of PVC.

Wood: $H_c = 16.6$ mJ/kg.
This material requires 4.33 m^3 of air to burn 1 kg of wood.
8 000 m^3/4.33 = 1 848 kg of wood.

In other words, the growth of a fire in the main bay would probably not be limited by the availability of oxygen.

Automatic fire protection system

Because we describe the automatic fire protection system in detail in a later portion of this paper, we give only a brief description here. The 2XIIB experiment is protected by a preaction sprinkler system with a preaction valve. The valve requires two electrical impulse signals, from the smoke detector circuit and the air pressure circuit, to release water.

Figure 4 shows the fire protection system from a functional viewpoint. Link-actuated sprinkler heads, fusible at 74 °C (165 °F), are located throughout the 2XIIB experimental area (Fig. 5). Heads over the main bay area are laid out on a 3.65 × 3.05 m (12 × 10 ft) grid. Positioning of the sprinkler heads is predominantly upright.

Eight central supply sources at the laboratory complex provide the building with compressed air at 552 kPa (80 psi). Air pressure is reduced to 138 kPa (20 psi) before entering into the preaction system. A controlled leak between the high- and low-pressure circuits allows small amounts of air to enter the system to replace the air potentially lost from leaks. In the event of a sudden pressure drop to about 103 kPa (15 psi) from a fused sprinkler head, the pressure detection switch signals.

Ionization type, ceiling-mounted smoke detectors make up the other part of the fire protection system. Their placement is shown in Fig. 6. Both the signal from the air pressure detection switch and the signal from the smoke detector circuit are necessary to energize the solenoid that opens the preaction valve. This voting circuit will not operate without both inputs unless the valve is opened manually with a resident pull handle.

Probable ignition sources

We studied the 1972 - 1977 "Activity Reports" from the Emergency Operations Section of the LLL Hazards Control De-

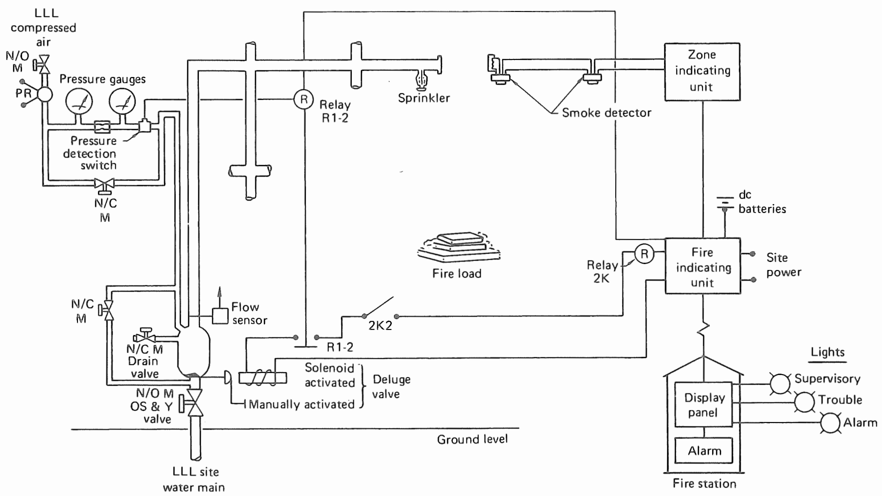


Fig. 4. Functional block diagram of the 2XIIB fire protection system.

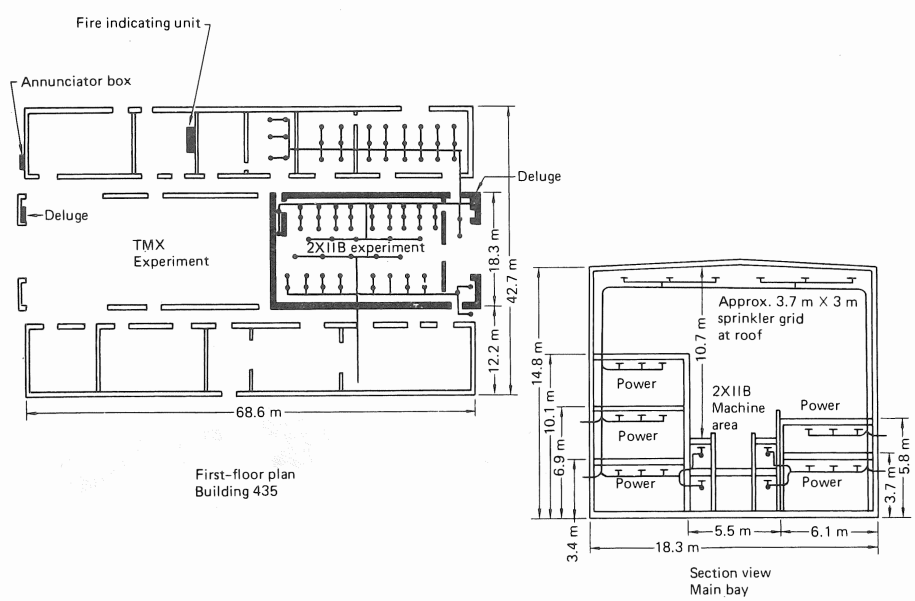


Fig. 5. Sprinkler layout.

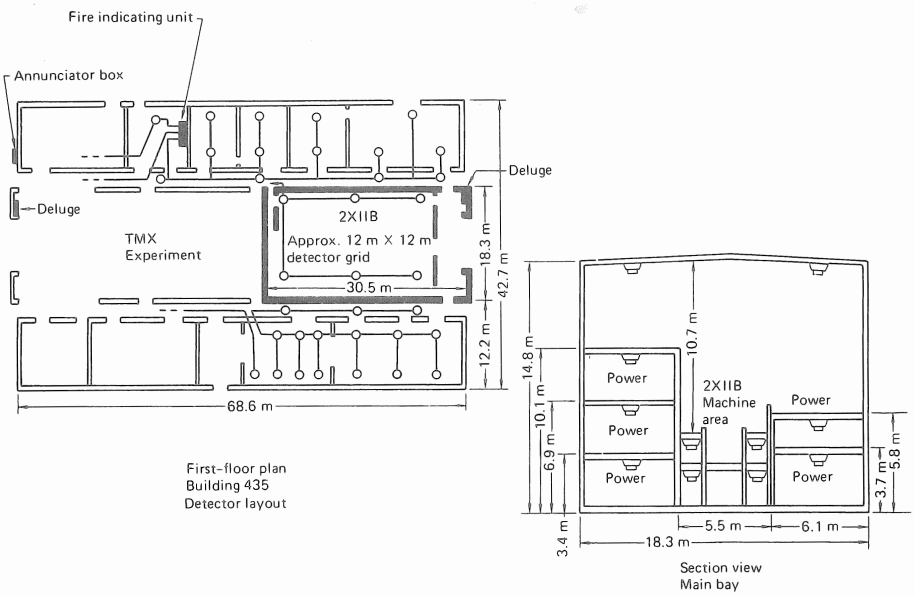


Fig. 6. Detector layout.

partment to determine probable causes of fire in Building 435. Historically, the data reveal that the majority of ignitions was caused by overloaded electrical components that either arced, overheated, or exploded. In most cases combustibles close to the component ignited and provided fuel for the fire. In relative terms, none of these incidents developed into a serious fire; most of them were terminated in their incipient stages by building occupants.

Survey of fire growth models

Analytical models defining the course of ventilation-controlled, or postflashover, fires in residential-scale rooms have been developed for a number of years. Through the use of thermodynamic and heat-transfer relationships, these models (the majority of which are computerized) describe the dynamic states of a fire with reasonable accuracy. This is possible in a ventilation-controlled regime because many of the variables involved can be disregarded or considered to be in a quasi-steady-state condition.

A fully involved compartment, or ventilation-controlled, fire can be considered a volume process in which average temperatures and heat fluxes within the compartment are meaningful concepts. In direct contrast to the ventilation-controlled fire is the fuel surface-controlled, or preflashover, fire. During this type of fire flames either remain localized to stationary sources or advance by flame fronts along the surfaces, and gas temperatures have extreme spatial variation. In some areas, gas temperatures will be near flame temperature; elsewhere they may be near ambient temperature.

Intuitively, an unwanted fire in the high-bay structure housing the 2XIIB would be a surface-controlled fire of long duration because of the abundance of air. Consequently, we needed a predictive model for fire growth in the preflashover or surface-controlled regime to determine the fire scenario. Furthermore, the sensitivity and vulnerability of electronic components indicated that there would be extensive fire damage before the fire fully involved the enclosure. Hence, we had to keep in mind that the automatic detection and suppression devices would be most effective in the incipient stage of fires and would have to be evaluated accordingly.

Table 2 lists a number of state-of-the-art fire growth and fire risk models. These models fall into three general categories: (1) probabilistic models, (2) modular models, and (3) differential field-equation models. Pape and Waterman [1] defined the categories. Probabilistic models generally describe fire development as a sequence of states or realms (*e.g.*, ignition, initial item development, spread to other items, etc.) and consider the transitions between these states in terms of probabilities of occurrence and time. Modular models show a compartment consisting of discrete volumes (the

TABLE 2

Fire growth and fire risk models

Probabilistic	Modular (or control volume)	Differential field equation	Statistical fire risk
*Development of engineering models and design aids to predict flame movement and fire severity within a room NBS & HEW	(1) *Quantification of threat from a rapidly growing fire, in terms of relative material properties. R. Friedman, FMRC	UNDSAFE-I A computer code for buoyant flow K. T. Yang and L. C. Chang, Univ. of Notre Dame	*The du method of evaluating residential fire danger E. L. Gallagher
*Building fire safety model: a systems approach to the evaluation of residential fire safety. NFPA & GSA	(2) *Update times and logic for the DTNSRDC fire spread model for FG-7. R. S. Alger and S. J. Wiersma, SRI Int'l.	Numerical simulation of the natural convection in fire compartment. Y. Hasemi, Bri, Japan	*The evaluation of the fire risk as a basis for planning automatic fire protection systems. G. A. Purt
*Probabilistic analysis of fire risks for the design of fire protection systems in nuclear power facilities. Engineering Analysis Co., Inc.	(3) *Enclosure fire hazard analysis using relative energy release criteria. C. D. Coulbert, JPL		*Fire risk assessment classification system. ASTM Subcommittee E5. 15 Task Group F
*An introduction to the fire safety design method. Rexford Wilson	(4) *Estimating fire hazards within enclosed structures as related to nuclear power stations. I. I. Pinkel		
*Fire growth and testing. R. B. Williamson	(5) *Fire protection — a re-evaluation of existing plant design features and administrative controls. Florida Power and Light Company		
	(6) A study of the development of room fires. T. E. Waterman and R. Pape, IITRI		
	(7) Computer code (II). H. W. Emmonds, Harvard University		
	(8) Dayton aircraft cabin fire model, Volume I — Basic mathematical model. J. B. Reeves and C. O. MacArthur, FAA		
	(9) The growth of fire in building compartments. J. Quintiere, ASTM-NBS Symposium		
	(10) Model of the developing fire in a compartment. E. E. Smith and J. J. Clark, ASHRAE		
	(11) Computer modeling. R. Luoto		
	(12) A mathematical model of a compartment fire. T. Tanaka, Bri, Japan		

lower spaces, the burning item, the plume, the upper spaces, and the heating surfaces). Conservation relations are applied to each control volume. Differential field-equation models divide an enclosure into numerous finite volume elements and, by means of the governing differential conservation equations, consider the exchanges of mass, momentum, and energy between the elements.

Probabilistic models do not rely heavily on the physics and chemistry of the fire. Modular models, however, rely heavily on the physics: the entire field is viewed as the same state, *i.e.*, the thermodynamic/fluid dynamic situation at any given time. Differential field-equation models rely very heavily on both the chemistry and the physics of the fire.

Because we do not completely understand the physics and chemistry of a fire, we cannot, at present, adequately understand or model fire growth inside an enclosure. Consequently, it is unlikely that we will use differential field-equation models as a practical tool in the near future. Furthermore, these models apply to moderate size enclosures; hence, an extrapolation to the extremely large and complex fusion energy facilities would not yield usable results.

Derivation of fire growth analysis

The modular models were the most reasonable fire growth models because they provided a convenient structure for describing fire growth inside an enclosure and because they relied heavily on full-scale fire test data. We therefore chose three semi-empirical modular models — the Friedman model [2], the Alger and Wiersma model [3], and the Coulbert model [4] (modular models 1, 2, and 3 in Table 2) to use as a basis for our own fire growth analysis.

Because we lacked the practical tools for conducting our analysis, we had to keep in mind the following limitations:

- The results of this analytical model would be accurate within orders of magnitude and would predict bounding conditions, not finite values.
- The model would be a synthesis of existing work; consequently, no new relationships would be developed.
- The governing equations and relationships would be based on large and full-scale fire test data. They would be derived by curve fitting for a large number of experiments related to industrial occupancies.
- Item-to-item fire spread (or contiguous fire growth) would be treated in gross terms, not in finite quantities.
- In order to perform the fire growth analysis, a sustained ignition in the enclosure would have to be assumed. However, in a final and realistic analysis, we would have to consider the probability of ignition.
- At present, fire hazard assessment is, at best, an approximate science. Data obtained under one set of circumstances have been applied to another, somewhat different set of circumstances. Despite this weakness, these data can be extremely useful assessment tools. Even the most advanced analytical model cannot accurately describe a burning object as a function of time from theoretical relationships. It must also rely heavily on empirical inputs.

The Friedman, Alger–Wiersma, and Coulbert models, which provide the framework for our analysis, all describe preflashover fire growth as a function of the heat-release rate of the burning fuel. The fire spread with time increases according to an exponential constant derived from experimental data. Figure 7 is

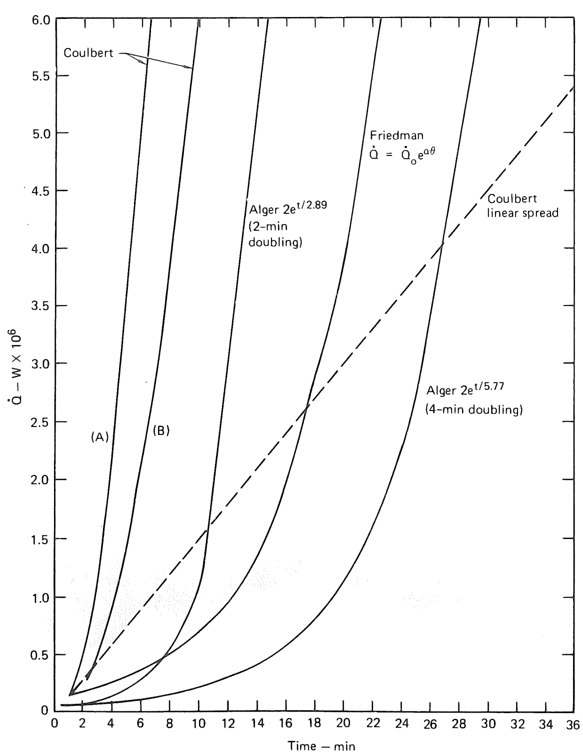


Fig. 7. Range of fire growth plots.

a graphic plot of the three models, which use wood as the primary fuel bed.

Coulbert considers two growth modes: radial flame spread and linear flame spread. Radial fire spread from an initial point ignition source is plotted as:

$$\dot{Q}_s = (\dot{Q}/A)\,(\pi V^2 t^2),$$

where:

$\dot{Q}_s$ = heat-release rate during flame spread
$\dot{Q}$ = heat-release rate (kW)
A = unit area (m^2)
b = flame front length (m)
V = flame spread velocity (m/min)
t = burning time (min)

Linear flame spread from an initial point ignition source is plotted as:

$$\dot{Q}_s = (\dot{Q}/A)\,bvt.$$

The values for these variables are obtained from applicable large-scale test data. In Fig. 7 curves A and B show the effect of flame velocity, flame width, etc., in Coulbert's equation.

Alger assumes an exponential growth based on burning rate doubling times of 2 min and 4 min, which give exponential constants of 2.89 and 5.77, respectively. The equations that give area heat release are;

$$\dot{Q} = 2e^{t/2.89}\ (2\text{ min})$$
$$\dot{Q} = 2e^{t/5.77}\ (4\text{ min})$$

Friedman's model also utilizes burning rate doubling time as the exponential constant:

$$\dot{Q} = \dot{Q}_o e^{\alpha\theta}$$

where:

$\dot{Q}_o$ = initial heat-release rate
θ = 0.693
α = fire growth parameter characteristics of the material and the scenario. The doubling time of the fire is $0.693/\alpha$.

Friedman anlyzed a number of large-scale fire tests (up to 100 000 kW) conducted at Factory Mutual Research Corporation and fitted them to the exponential growth law. This provided the "α" value (in seconds) for each burning material and the particular scenario.

Figure 7 shows the variations in growth rate obtained by plotting the three model relationships. In the nonlinear area of the graphs, the difference in induction for an accelerated fire growth phase is about 20 min for the most diverse model relationship. However, once the functional slopes approach linear growth rates, they become roughly parallel. A preliminary analysis of mass-loss rates for large-scale wood-burns at LLL yielded a fair correlation with the linear portion of these models. The nonlinear portions can be viewed as bounding conditions that represent the intensity of the original ignition sources and the ignitability of adjacent fuels. Coulbert's A and B curves would represent a very rapid and intense ignition source, which would cause very rapid fire growth. On the other hand, as the slopes become less steep out to Alger's 4-min doubling time, the size or duration of the ignition experience would be low. Currently, we are studying these curves to define a range of possible fire scenarios in the 2XIIB facility. As we obtain more information, however, we may find a curve somewhere in between the two extremes that describes median fire growth in the main bay.

Fire size and flame height

To estimate the damage caused by the thermal effects of a fire in the 2XIIB facility, it would be desirable to obtain a rough indication of the size of the fire as it grows with time. Presently, we are studying the work of Thomas (Fire Research Station at Borehamwood) and others to obtain an approximate temporal and spatial picture of the fire.

Smoke generation

Optical and electronic components used in inertial and magnetic confinement fusion experiments are very sensitive, and therefore potentially vulnerable to the effects of combustion products. Consequently, it is necessary to perform both a quantitative and qualitative analysis of the combustion products generated by the fire as it grows. This is not a trivial task. At present we are doing experimental work to determine the elements and compounds that are generated by fuels found in the 2XIIB facility, *e.g.*, PVC, neoprene, etc. In addition, we are calculating the quantity of combustion products that are generated by the fuels as a function of fire growth rate.

In general, aerosol production is proportional to the mass-loss rate ($\dot{M}$) of the burning fuel. The assumption is almost totally dependent on input from experimental data. Our preliminary calculations of large-scale wood fires in the LLL fire-test cell yield an average combustion product volume of 7 m^3/kg of wood burned. Stoichiometric calculations yield 16.7 m^3/kg. Other calculations in the literature yield around 4 m^3/kg [6]. Data on particulate mass, size, and concentration are available from LLL and other fire test centers. All these factors are a function of the fire growth curves in Fig. 7.

Response of the automatic fire detection/ protection system

We found that damage to the experimental facility is not only a function of the severity of the fire but also a function of the response of the automatic fire protection system. Figure 8 (this Figure was taken from W. N. Herschfield, "Safehaven concepts applied to hi-rise design", *Specifying Eng.*, 39 (6) (1978) 93) shows the significance of early fire detection. Note that early detection by a smoke detector means the fire can be counteracted in its incipient stage. This allows for quick control and, hence, minimal resultant damage. Without smoke detectors we must rely on sprinkler head activation, which cannot occur until the fire has progressed to a significant level of severity. At this stage the fire is much more difficult to control (extended control time) and can cause sizable damage. Early fire detection and control has been the case for the 2XIIB main bay; according to Fig. 8 it would not be desirable to wait for sprinkler actuation.

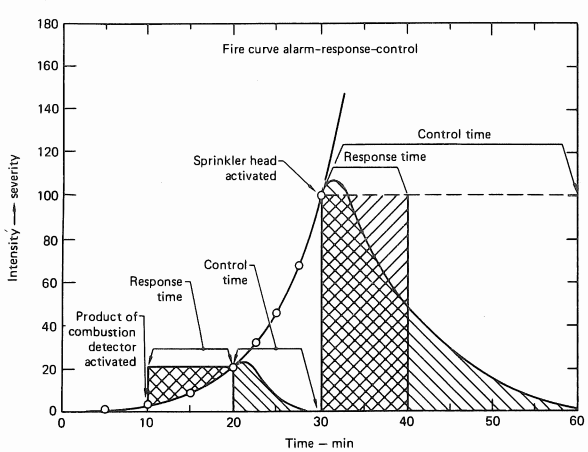


Fig. 8. Advantage of early fire detection.

To monitor the status of the automatic fire protection system at the 2XIIB facility, it is necessary to describe the fire, in temporal and spatial terms that correspond to the triggering mechanisms of the detectors and sprinklers. Governing mechanisms, then, are the rate and amount of smoke generation for the ionization detectors and time–temperature relationship at the ceiling for the sprinklers.

Sprinkler actuation

We used Alpert's calculations [7] for ceiling-mounted automatic suppression systems to determine the response time of sprinklers that are actuated by the turbulent plume or ceiling-jet. An extensive study of large fires (in which flame height was comparable to ceiling height) at the West Glocester Test Center has confirmed the validity of this flow description. The results have been used to calculate the response time of sprinklers or detectors by heat-release rate, ceiling height, and sprinkler or detector location.

Two parameters of considerable importance in any discussion of fire-induced convection near a ceiling are the heat-release rate of the burning fuel and the ceiling height above the fuel. Experimental data indicate that these two parameters, properly defined, generally determine the major characteristics of the fire-induced flow. The ceiling height, H, henceforth refers to the distance between the uppermost burning fuel surface and the ceiling, while the heat-release rate, $\dot{Q}$, is consistently taken to be the product of the fuel weight-loss and the maximum theoretical heating value per unit mass of fuel. In reality, only a portion of the maximum combustion energy is transferred directly to the flow, but this portion may be about the same for most ordinary combustibles.

Experiments cited in separate reports involved fires with heat-release rates ranging from 668 kW (38 000 BtU/min) to nearly 105 435 kW (6 × 10^6 BtU/min). Ceiling heights ranged from 4.6 m (15 ft) to 15.5 m (51 ft). It has been found that outside the fire plume, the maximum gas temperature, T_{max}, occurs a few inches from the ceiling and that temperatures decrease to near room temperature value, T_{rm}, a few feet below the ceiling. The exact locations below the ceiling, where $T = T_{max}$ and where T approaches T_{rm}, are primarily a function of ceiling height and radial position. The maximum gas temperature, T_{max}, at a given radial position near the ceiling, can be correlated by the equations:

$$T_{max} - T_{rm} = 4.74 \frac{\left(\frac{\dot{Q}}{r}\right)^{2/3}}{H}, \text{ for } r > 0.18H \text{ and}$$

$$T_{max} - T_{rm} = 14.9 \frac{\dot{Q}^{2/3}}{H^{5/3}}, \text{ for } r \leq 0.18H,$$

where

T = temperature, $\dot{Q}$ = heat-release rate, H = height, and r = radial position.

Figure 9 shows a series of curves plotted from Alpert's relationships for the 2XIIB main bay. The assumed height, H, is 10.7 m (35 ft) from the second floor machine area to the ceiling. The $r \leqslant 0.18H$ represents a sprinkler in or close to the fire plume: r = 2.4 m (7.8 ft), (curve B) represents the 3.7 m × 3.1 m (12 ft × 10 ft) sprinkler grid that actually exists in the 2XIIB main bay. The other curves show the effect of increasing the grid in 1.2 m (4 ft) increments. The sprinklers have 74 °C (165 °F) fusible links. Because we lacked better information at the time this paper was prepared, we chose a gas temperature of 95 °C (200 °F) for threshold sprinkler actuation. This factor will have to be developed further.

The line at 75 °C (Fig. 9) takes into account an ambient air temperature of 20 °C (68 °F).

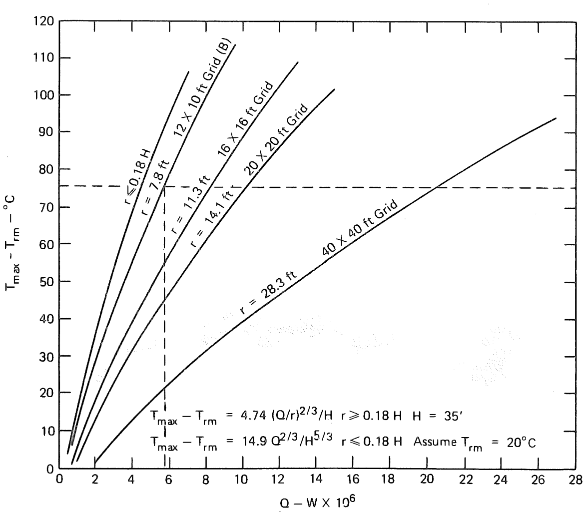


Fig. 9. Temperature rise at ceiling.

This activation line intersects curve B at a heat-release rate of about 6 MW on the abcissa. If we refer to Fig. 10, which shows the fire growth curves on an expanded scale, we can estimate sprinkler response times. The range of curves produce a range of response times from 7.5 to 30 min. The actual time would probably fall at a median time within this range.

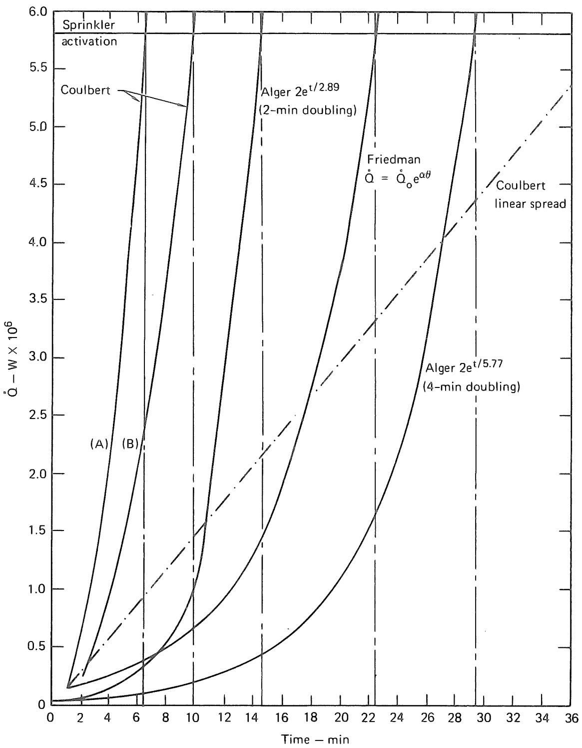


Fig. 10. Heat release rate for sprinkler activation.

Response of smoke detectors

Because we have not yet completed detailed calculations for this phase of the analysis, we can only present an outline of the analytical approach.

Alpert [7] states that the transfer of combustion products, such as smoke, to detectors in the near-ceiling flow is a mass transfer process, similar in many respects to the transfer of heat. For example, the rate at which mass is transferred to an object is generally expressed as the product of a mass transfer coefficient and the difference between the mass concentration (kg/m^3) in the flow and the mass concentration close to the object. Theoretical analysis has shown that the mass concentration of a given constituent in near-ceiling combustion products should be proportional to the excess of gas temperature over room temperature.

We are currently finalizing an analysis of relationships developed by Alpert [7] and studying work performed by Lee and Mulholland [8] to relate predicted particulate smoke densities to detector activation.

FAULT-TREE ANALYSIS OF THE 2XIIB FIRE PROTECTION SYSTEM

The LLL Fire Science Group performed a reliability analysis of the 2XIIB fire protection system with the aid of the Econ, Inc. We will present excerpts from the firm's final report here.

To evaluate the fire risk associated with a particular fire protection system, we must consider the probability of the system's successful operation. By successful operation we mean both reliable fire detection and reliable fire extinguishment. One approach to evaluating the successful operation of a fire protection system is to examine all possible failure modes and their probability of occurrence. We used fault-tree analysis to determine the failure probability of the system in quantitative terms. The results from this analysis should be useful to fire protection engineers and project managers interested in improving fire protection systems in experimental fusion energy facilities.

System fault-trees represent the undesirable events from which a corresponding probability can be calculated using secondary events or causes. In this study, failure of the modified preaction fire protection system to perform within a certain time period after initiation of a fire represents one undesired event; the other undesired event is the inadvertent activation of the modified preaction fire protection system. The relationship of both these events to fusion experiment schedule delay and hardware damage provides the motivation for our analysis.

A fault-tree is structured so that the undesired event appears at the top of the tree. The sequence of events that leads to an undesirable system failure is shown below the top event. These events are logically linked to the undesirable event by branches, which are, in turn, linked to standard "OR" and "AND" gates. The gates specify a Boolean logic algorithm for combining the contributing events. The top event (a relatively higher order event), then, is related to more basic, lower order events. These lower order events can be developed until the sequence of events leads to the primary causes for which failure rate data are available. Obviously, the last contributing events in a failure-oriented sequence represent the resolution of the analysis.

The advantage of using the fault-tree technique is that we locate the system elements that contribute to the occurrence of the undesired top event. Inductively finding these elements, or component states (by a bottom-to-top evaluation), can be quite a tedious and almost unworkable task because of the number of component states that must be considered. This is particularly true for complex systems or very detailed evaluations of relatively simple systems.

When a fault-tree is complete, both qualitative and quantitative evaluations are possible. Of primary importance is the qualitative analysis of the minimal component sets. These sets are known as the critical failure paths, and when they fail, they cause system failure. In the reliability community, these sets are designated as "min cut sets." They are important because they designate unique modes by which the top event can occur and represent in an objective and communicative manner the causes of system failure (H. E. Lambert, Systems safety analysis and fault-tree analysis, *Lawrence Livermore Laboratory, Rept. UCID-16238, 1973).*

The effectiveness of a fire suppression response depends on attendant response, automatic sprinkler response, and the fire department's response. The attendant response involves building personnel; they recognize a fire and react with hand-held fire-extinguishing equipment. In such instances, the fire is usually small and easily contained. The automatic sprinkler response is the ability of the fire protection system to perform a "sense and extinguish" mission. Finally, the fire department's response is to dispatch fire-fighting personnel to the building.

This troika describes the total fire protection system and attempts to address the three components of the system in a coordinated way. In this study, the attendant response, fire department response, and the automatic sprinkler system response were developed by qualitative fault-trees; however, the automatic sprinkler response was also developed by quantitative fault-trees because we considered the quantitative aspects of the sprinkler system: sprinkler coverage, system capacity, and system reliability.

System reliability of the automatic sprinkler system in Building 435 is the central concern of this study. On a simple level, system reliability encompasses component hardware, operator error, maintenance error, environmental system degradation, and system design (where appropriate).

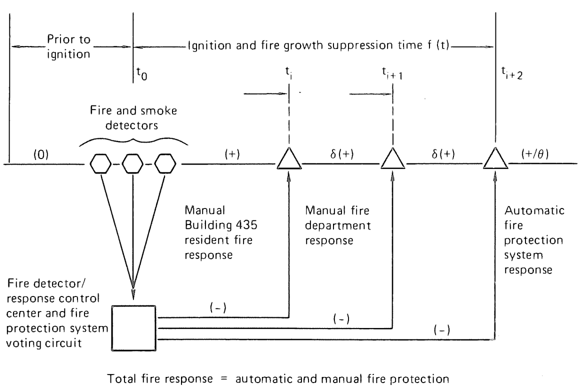


Fig. 11. Negative feed-forward loop model for 2XIIB fire protection system.

Automatic fire protection system

The fire protection system in building 435 is a modified preaction system (this system is unique to building 435). Fire detection and suppression subsystems form a negative, feed-forward fire control loop (Fig. 11). The system senses the fire and reacts. It has both an automatic and a manual response to fires. The automatic response is the automatic application of water to the fire. The manual response is the response of building occupants or the arrival of the Laboratory fire department. Primarily, the fire department handles small fires that are first detected by the fire protection system. The automatic suppression system will only be activated in the event of a catastrophic ignition or an intense localized fire that keys a detector and fuses a sprinkler head.

The history of fires in building 435 indicates a low probability for the occurrence of large fires. However, such fires are more likely to cause extensive damage. Thus, in this analysis we emphasize the reliability characteristics of the automatic response. Because the analysis of the entire fire protection system requires a reliability estimation of both the automatic and manual response, we will assume that the manual response never fails.

Figure 12 is a schematic of the fire protection system in building 435. A dispatcher-

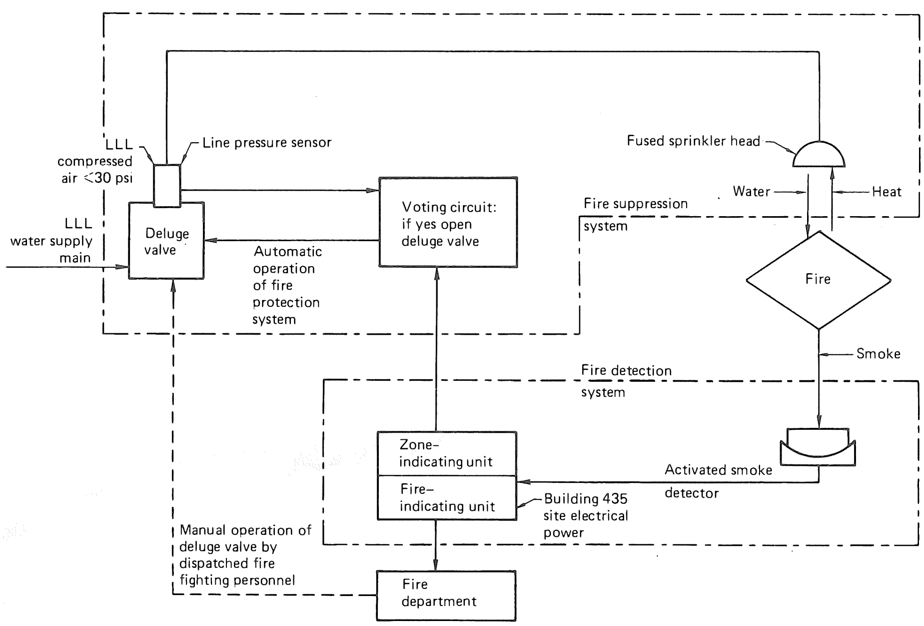


Fig. 12. Schematic of 2XIIB fire protection system.

manned control console monitors all fire emergency circuits such as smoke detectors, telephones, tamper-proof switches, etc. Any signal from a smoke detector is also sent to a voting circuit of the automatic sprinkler system. The automatic segment of the fire suppression system is the preaction sprinkler system. The preaction sprinkler system has a preaction valve that is activated by both a signal from the detection system and a drop in air pressure in the drypipe arrangement, which is caused by a fused sprinkler head. The other key component of the suppression system is the Laboratory's full-time fire department.

The fire detection system is part of a general protective signaling system that has a hard-wired circuit with detection devices at one end and the emergency control console at the other. Smoke detectors are located throughout the building, including the basement/tunnel area and the cable bridge. Ceiling-mounted, ionization type smoke detectors are located on all levels of the 2XIIB facility.

The leads from the zoned smoke detectors are connected to the dispatcher's console by a fire-indicating/zone-indicating unit (FIU/ZIU) that serves to power the detector and to indicate the zone alarm. The smoke detectors in a zone are wired in parallel. If a detector in any zone sets off an alarm, the dispatcher receives a signal from the FIU. The signal received at the firehouse is either supervisory or alarm, with no description of zone. Zone designation is provided at the building by either the FIU/ZIU or an annunciator panel located near the main entrance(s).

All other protective signals pass through the fire-indicating unit. These include tamper switch signals, pull-box alarm signals, and loss of air pressure signals from the sprinkler system. If there is an incomplete circuit to the fire house or a tamper switch signal, a supervisory signal (yellow light) is sent. For a smoke detector signal or a loss of air pressure signal, an alarm signal is sent (red light on the panel).

In the event of catastrophic fire, the dispatcher can request aid from the surrounding community and can alert the Livermore Fire Department, the LLL Hazards Control personnel security, etc. Besides the in-station alarm to notify the fire department, the dispatcher has a dial-a-page system, a telephone system, and various two-way radios pretuned to frequencies used by on-site personnel and the Livermore Fire Department.

Analysis of the automatic fire protection system

We used a simplified model of the automatic fire protection system for the analysis so that we could extend it to a full-scale representation of the system in building 435 (Fig. 13). It consisted of four sprinklers and two detectors and incorporated the majority of the detailed inputs that would be required in a full-scale system evaluation. Hence, the methods of reliability evaluation could be applied to larger problems. A small model was also chosen for the sake of clarity.

We constructed the system's fault trees for "no extinguishment" and "inadvertant activation" and then assembled reliability/failure data obtained from the National Fire Protection Association, the LLL maintenance crew,

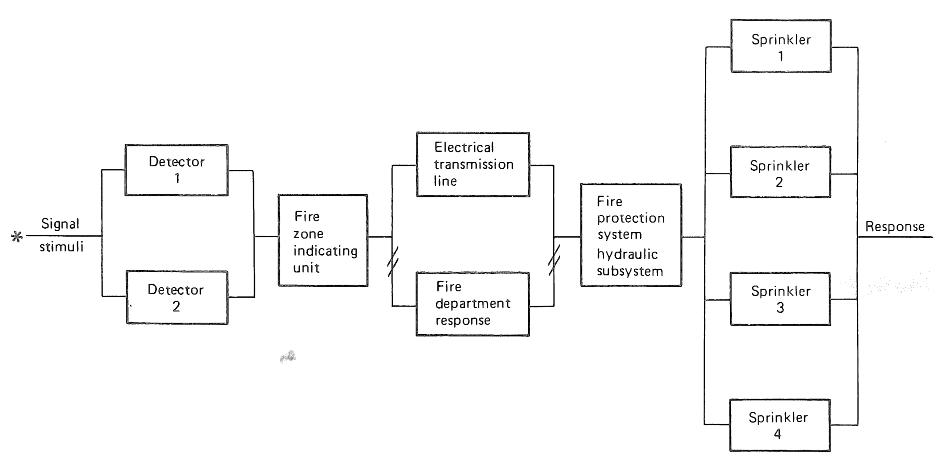


Fig. 13. Simplified logic diagram of fire protection system in 2XIIB.

the LLL Fire Department, the LLL Plant Engineering Department, Factory Mutual Research Corporation (Norwood, Mass.), and the United Kingdom Atomic Energy Agency. We also obtained data from IEEE Std. 500, the WASH-1400 Reactor Safety Study, and basic engineering judgment.

We carried out both a qualitative and quantitative fault-tree analysis of the system. The qualitative analysis, which was supported by the FTAP computer code, (R. Willie, FTAP: Computer-aided fault-tree analysis, *ORC 78-14*, University of California, Berkeley, California) requires no numerical or probabilistic data input. Results of this analysis provide insight into the logical structure, design, and maintenance of the fire protection system in relation to scenarios for system failure. The quantitative analysis, which was supported by the computer code IMPORTANCE, (H. L. Lambert, IMPORTANCE: The IMPORTANCE computer code, *Lawrence Livermore Laboratory, Rept. UCRL-79269*, 1977) estimates system failure probability (vulnerability) by quantifying and ranking possible system failure modes. This is accomplished by the logical manipulation of component failure rates.

Fire protection system fault trees

The "no extinguishment applied" tree

The undesired event in the "no extinguishment applied" tree was defined as "no extinguishment applied to a fire in zone X within T minutes." To achieve this event, the fire department, an occupant of the building, and the sprinkler system would have to fail to apply extinguishment during the critical period after ignition. If one of the three does apply extinguishment, then the specifications of the undesired event are not met. Thus, an "AND" gate is placed between the undesired event and the three "no extinguishment applied" events because all are necessary to cause the undesired event. The fault-tree was developed along these three principle branches.

The fault-tree analysis was performed to ascertain the reliability (one minus the probability of failure) of the system, not its performance. Instead, the analysis determines the probability that the system does not work at all. In later work we may redefine the undesired event to address the system's effectiveness.

Of the three main branches of the tree, the one of major interest is the installed automatic sprinkler and detection system. Figures 14 - 16 show this fault tree, in which the undesired event is defined as "four out of four sprinkler heads fail to emit water when a fire exists in the 2XIIB area". This tree represents our second evaluation for the system. We found that our initial study was too coarse and did not treat the FIU/ZIU circuitry, the primary signaling and power source in the system, with enough detail. Hence, we restructured the tree and reanalyzed the events.

The fault-tree (Fig. 14) immediately separates into four branches that correspond to the four sprinkler heads assumed to be in proximity to the fire. The next level of branches indicates the events that could cause the individual sprinkler heads to fail; for example, supply materials or structures could block or retard air heat transfer to the sprinkler. Hence, there would be insufficient heat to set the sprinkler off. As we advance further down the tree, we find events for components in the FIU/ZIU and detector circuit. The final branches are events for the supervisory circuit, the piping and valving, and the emergency power supply.

In this analysis, we assumed the following:

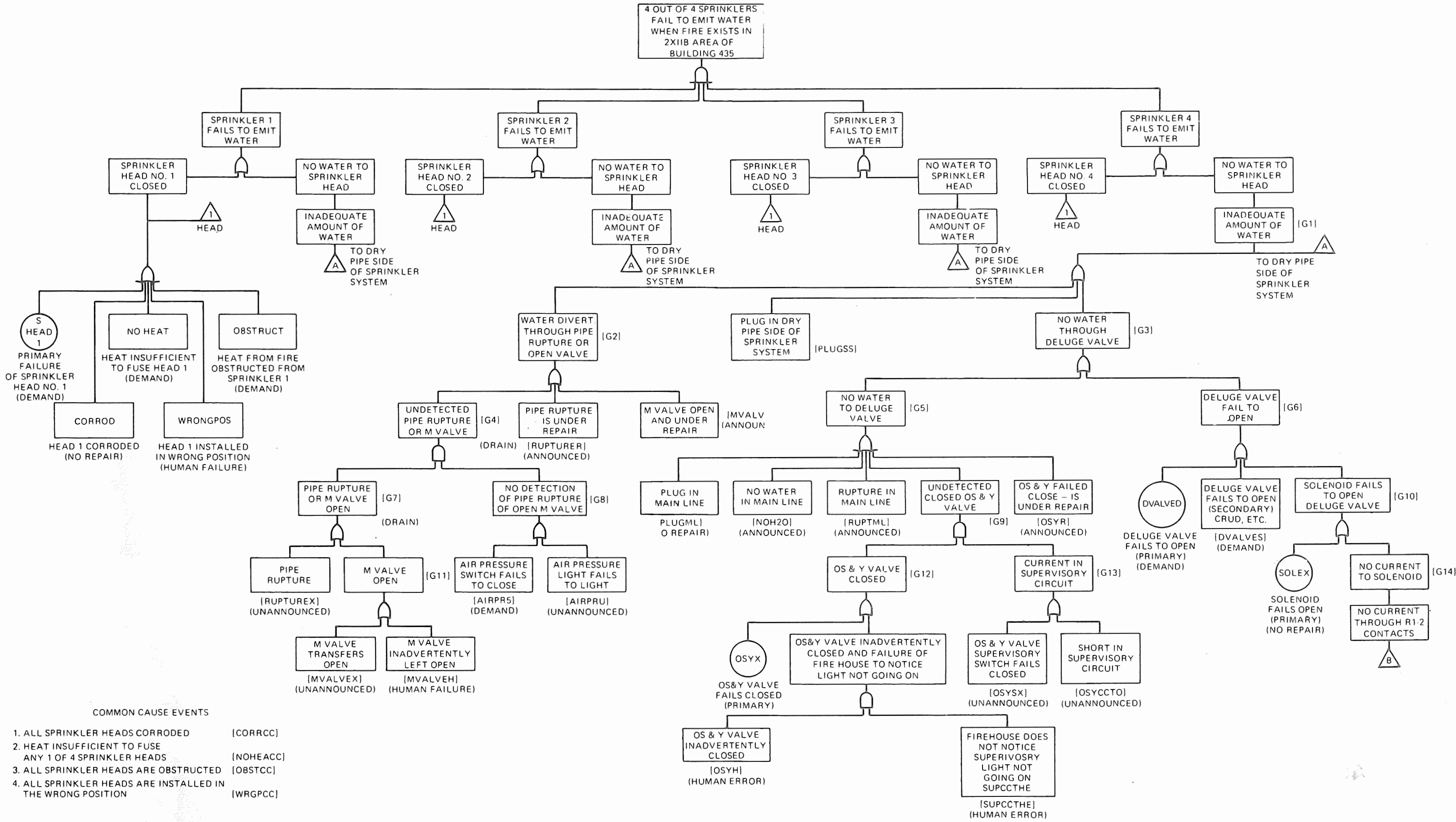
- Components, subsystems, and similar items can have only two conditional modes; they can either operate successfully or they can fail. No operation is partially successful.
- Basic failures are independent of each other.
- A component in the fire protection system can fail in four ways when there is a demand.

(1) It can fail to change state, for example, relay contacts fuse closed.

(2) It can fail and failure can go undetected (no repair), for example, a plug in the drypipe line. (Failure probability, P, = cyclic failure rate. $P = 1 - e^{\lambda t}$, where λ = failure rate.)

(3) It can fail and failure can be detected; *i.e.*, the component is under repair (announced failure). For example, a seal leak in the drypipe is detected by the air pressure switch. ($P = \lambda\tau$, where τ = repair time and λ = failure rate.)

(4) It can fail and failure can be detected at the end of scheduled inspection; *i.e.*, the component is under repair (unannounced failure). For example, there is a rupture in the preaction system and the air pressure switch fails. Two failures are detected at the next inspection. ($P = \theta/2$, where θ = the inspection interval.)



COMMON CAUSE EVENTS

1. ALL SPRINKLER HEADS CORRODED [CORRCC]
2. HEAT INSUFFICIENT TO FUSE ANY 1 OF 4 SPRINKLER HEADS [NOHEACC]
3. ALL SPRINKLER HEADS ARE OBSTRUCTED [OBSTCC]
4. ALL SPRINKLER HEADS ARE INSTALLED IN THE WRONG POSITION [WRGPCC]

Fig. 14. Automatic fire protection system fault-tree.

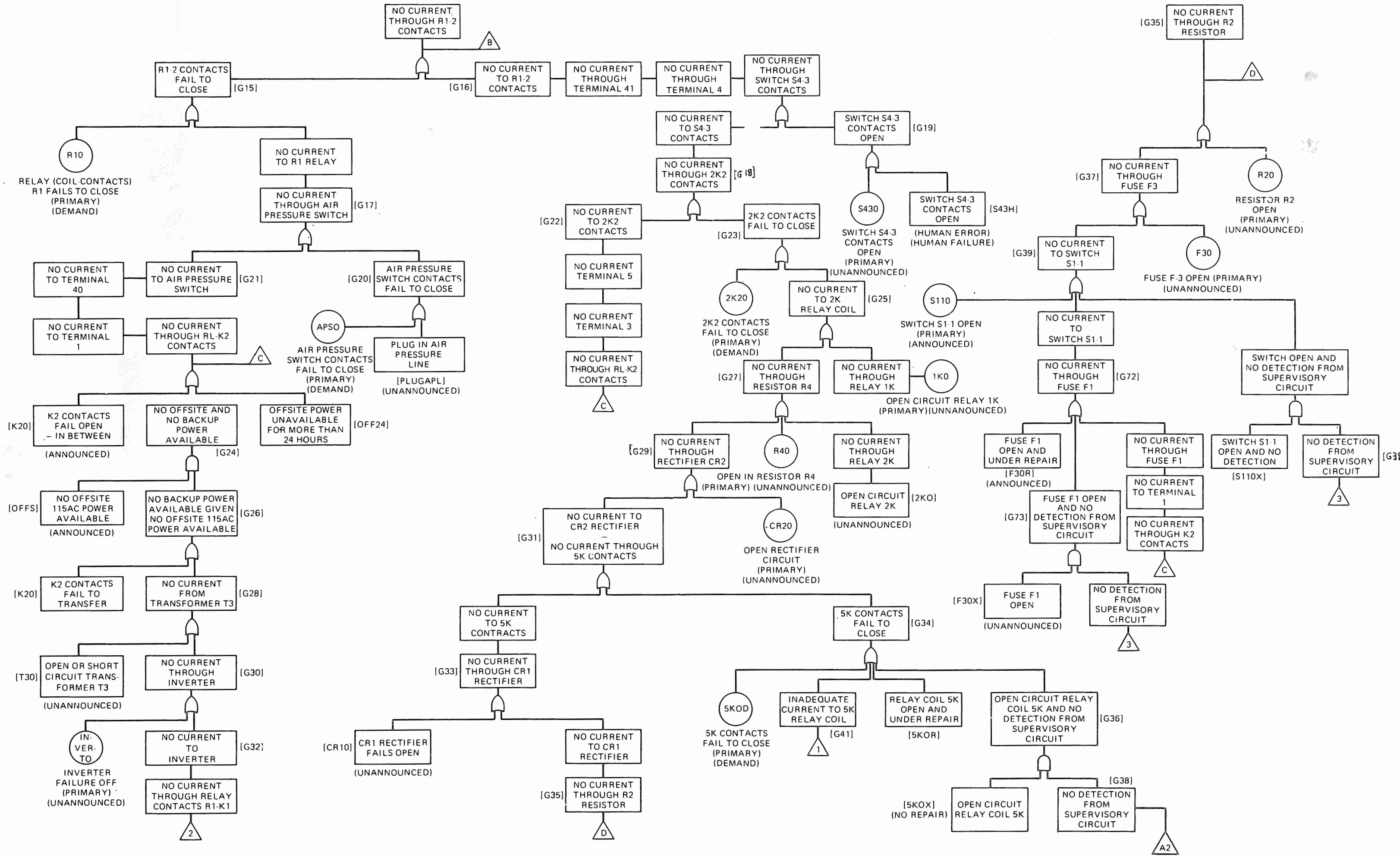


Fig. 15. Automatic fire protection system fault-tree.

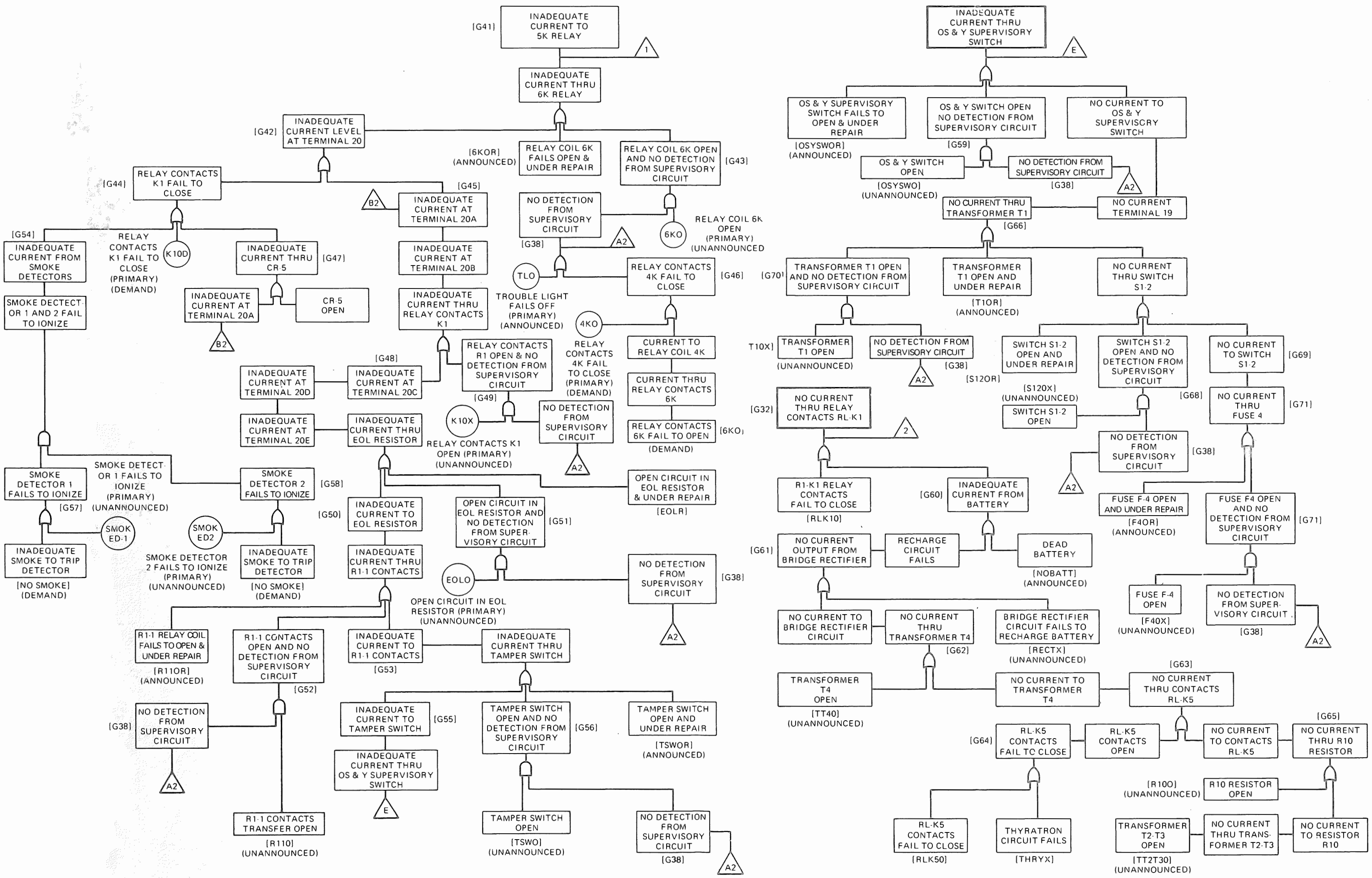


Fig. 16. Automatic fire protection system fault-tree.

• If we assume that a fire exists, the failure of the automatic fire protection system model will require the failure of four out of four sprinkler heads, *or* two out of two smoke detectors, *or* the piping and valving system, *or* the FIU/ZIU supervisory circuit. These points are readily apparent in Fig. 13.

Success in predicting the probability of a specific occurrence depends on how accurately the system is represented in a fault-tree, how detailed the tree is, and how valid one's mathematical expression and probabilities are.

The "four out of four sprinkler heads fail" tree

The undesired event in the "four out of four sprinkler heads fail" tree is defined as "four out of four sprinkler heads fail to emit water when a fire exists in the 2XIIB area." This tree is composed of 109 basic events. The FTAP run produced some 713 min cutsets (failure scenarios). The range of these min cutsets was from a minimum of one event to a maximum of four events. Figure 17 illustrates the breakdown of these qualitative results. They indicate

• Single-event or single-point failures predominate in the FIU/ZIU circuit. This means that there is insufficient circuit redundancy from the smoke detectors to the solenoid actuator on the system deluge valve.

• The success of the entire system is keyed to a significant number of components in the FIU/ZIU circuit.

• Random failures of relays, rectifiers, and resistors may compromise the system. Because these are typically unannounced failures, they are only correctable through competent inspection and service.

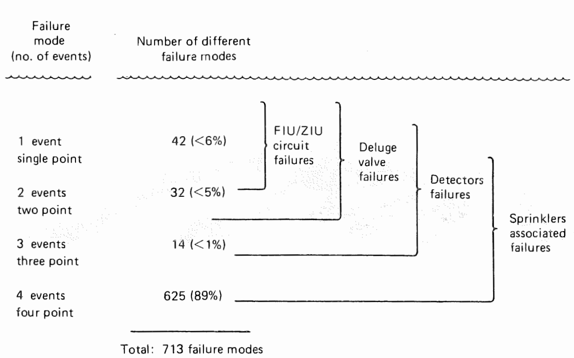


Fig. 17. Distribution of min cutset results.

• The series design of the FIU/ZIU circuit precludes its operation during repair. Announced failures (single point) can be more readily controlled by timely, short repair schedules.

• The majority of failure modes are four-point failures relating to the individual sprinkler heads in the model. The sprinkler heads fail in five modes:

(1) They can fail under normal conditions (primary failure).

(2) They can corrode.

(3) They can fail to fuse because of insufficient heat.

(4) They can be obstructed and fail to receive sufficient heat.

(5) They can be installed in the wrong position.

The analysis also indicated common cause failures for the last four failure modes.

The quantitative analysis, aided by the computer code IMPORTANCE, calculated a top event probability of 1.8×10^{-1}, or 18/100 per demand, for system failure. This results in a system reliability of 82%. The computer code ranked the elements of the fault-tree in respect of their individual contributions to the undesired event in addition to ranking the importance of the various cutsets. Important contributors to system failure were the single-point failures associated with the smoke detector circuit, *i.e.*, the reliability of the individual relays in the FIU/ZIU circuit.

Insufficient smoke to fire detectors and obstructed sprinkler heads were also important contributors to system failure. Other single-point failures were associated with the sprinkler system valve and the piping network. The primary factors were the deluge valve and the process air. Again, the success of the entire system is keyed to the reliability of components, their maintenance, and their repair.

Other causes of failure were debris from scale, pipe ruptures, and an open master drain valve. Thus, the most important aspect of the piping network is the duration of repair and service periods.

The "water inadvertently applied to fusion experiment" tree

A major concern of personnel conducting the 2XIIB experiment is the accidental release of water on highly sensitive equipment. An accidental release of water occurs when the automatic fire protection system inadvertantly releases water; *i.e.*, it activates when it should not.

The "inadvertant release" fault tree, which is smaller than the "failure to emit water" fault tree, was composed of 26 basic events and generated 42 cutsets of two events. Based upon the general logic structure of the fault tree, min cutsets of four events are possible yet were not considered. The calculated probability of an inadvertant release occurring in the fire protection system was 5.7×10^{-8}/day, or 2.0×10^{-5}/year.

First order events in this fault tree included improper sprinkler head testing and installing, random breakage of the sprinkler system by machinery and the movement of large pieces of equipment, and inadvertant smoke detector activation from cigarette smoking or welding. Presently, fire detection systems only sense fires and smoke and heat from other sources. A way of solving this problem is to increase the detection thresholds. However, this solution would cause an undesirable delay in warning time.

The low probability of accidental release correlates with the system's 82% reliability figure. Designing against an inadvertant release makes it more difficult for the system to activate when there is an actual fire.

CONCLUSIONS

The fire safety analysis of the main bay of the 2XIIB fusion facility has allowed us to make the following preliminary conclusions:

(1) The primary fire threat will be a preflashover fire that has enough oxygen and that is fueled primarily by wood and cable-insultating materials. Fire growth curves show that a wood-fueled fire will take up to 20 min to accelerate to the maximum steady state growth rate, depending on the ignition and fire spread scenarios. Calculations for available ventilation, excluding mechanical air, indicate that a large quantity of combustibles will burn without hindrance.

(2) The fire will grow to a heat-release rate of approximately 6 MW before sprinkler intervention occurs. This corresponds to a range of response times from 8 to 30 min, which are reflected in the growth curves.

(3) Based on experimental and analytical work conducted at the National Bureau of Standards, it appears possible to predict smoke detector response by modeling the mass concentration of combustion products and the temperature rise at the detector as functions of the mass-loss rate of the specific fuel. Full-scale fire tests in high-bay structures have shown that detector response will occur much before sprinkler activation. However, response times will be greatly modified because of transient air movement, inversion layers, and mechanical ventilation.

(4) Both the quantity and the quality of combustion products are significant. If the corrosive effects of smoke can be determined, then smoke damage can be estimated. The volume and mass concentration can be determined from the mass-loss rate of the burning fuel. This portion of the study is extremely important. Damage to optical and electronic components may occur before automatic or manual suppression is applied to the fire. In extreme cases, this damage may occur before detection.

(5) The fault-tree analysis of the automatic fire protection system shows that the chances of system failure are 18% per demand. The results indicate that the most significant contributors to system failure were insufficient smoke to detectors and obstructed sprinkler heads. Single-point failures associated with the smoke detector circuit, *i.e.*, the reliability of individual relays in the FIU/ZIU circuit were also important contributors to system failure. Finally, the deluge valve and process air played a role in system failure.

So far we have only addressed the question of system reliability; to do a complete fire safety analysis, we will have to evaluate system effectiveness.

The ultimate goal of this study is to provide the U.S. Department of Energy with a fire risk analysis of its fusion energy research facilities. As such, we will have to determine costs for tangible and intangible items. By tangible we mean experimental hardware, personnel, etc.; by intangible items we mean experimental time and loss of key personnel. The fire growth model will produce fire threat and damage levels for each facility. The response time, reliability, and effectiveness of the fire protection system will modify the damage level.

The findings from this study will eventually enable the U.S. Department of Energy to set up guidelines for rational fire protection strategies and determine cost-effective plans for new systems and cost-effective improvements for existing systems. Fire protection engineers at research centers will also benefit from these findings. For example, they will know what kind of equipment to choose for their respective systems. They will also be able to plan repair and maintenance schedules to avoid potential system failures.

Ideally, if and when fusion becomes an economically reasonable way of producing energy, we will have rational criteria for designing and operating fire-safe fusion energy plants.

NOTICE

REFERENCES

1 R. Pape and T. E. Waterman, Pre-flashover compartment fires (Rough Draft), IIT Research Institute, 1979.
2 R. Friedman, *Quantification of Threat from a Rapidly Growing Fire, in Terms of Relative Material Properties,* Factory Mutual Res. Corp., Norwood, Mass. (1977).
3 R. S. Alger and S. J. Wiersma, Update times and logic for the DTNSRDC firespread model for FFG-7, *DTNSRDC Code 1740.2,* Stanford Res. Inst. Menlo Park, Calif., 1977.
4 C. D. Coulbert, Energy release criteria for fire hazard analysis — Part I, *Fire Technol.,* 13 (No 3) (1977) 173.
5 C. D. Coulbert, Energy release criteria for fire hazard analysis — Part II, *Fire Technol.,* 13 (No 4) (1977) 173.
6 M. Ya. Roytman, *Principles of Fire Safety Standards for Building Construction,* Arnerind Publishing Co. PVT. Ltd., New Delhi, 1975.
7 R. L. Alpert, *Response Time for Ceiling-Mounted Fire Detectors,* Factory Mutual Res., Norwood, Mass., FMRC Serial No. 19722-3 (1972).
8 T. G. K. Lee and G. W. Mulholland, Physical Properties of Smokes pertinent to Smoke Detector Technology, *NBSIR 77-1312,* Nat. Bur. Std., Washington, DC, 1977.
9 J. R. Perrine, G. P. Naanep, and J. P. Skratt, A preliminary analysis of the reliability of fire suppression systems protecting fusion experiments at Lawrence Livermore Laboratory (final draft report), Econ, Inc., San Jose, Calif., 1978.