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Fire Protection System Operating Experience Review for Fusion Applications

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ABSTRACT

This report presents a review of fire protection system operating experiences from particle accelerator, fusion experiment, and other applications. Safety relevant operating experiences and accident information are discussed. Quantitative order-of-magnitude estimates of fire protection system component failure rates and fire accident initiating event frequencies are presented for use in risk assessment, reliability, and availability studies. Safety concerns with these systems are discussed, including spurious operation. This information should be useful to fusion system designers and safety analysts, such as the team working on the Engineering Design Activities for the International Thermonuclear Experimental Reactor.

SUMMARY

This report is an overview of fire protection system operating experiences from selected fusion experiments, particle accelerators, and other related facilities. This report is not a chronicle of all fire protection system problems, but rather a guide to the persistent problems that are discussed in the literature. While fire protection systems are much more beneficial than harmful, they are important to study since the input energy requirements in magnetic fusion are growing and with that growth the possibility of fire also grows. More regulatory review of safety systems, including fire protection systems, is expected as fusion systems grow more robust and routinely use tritium fuel. This report, and others like it, will help to either prove that meaningful data can be generated for magnetic fusion safety work, or to generate enough controversy over these values so that equipment vendors and existing experiment operators are motivated to collect data and develop more accurate data sets.

Safety concerns with fire suppression systems (i.e. spurious actuations), are briefly discussed. Fire protection system component failure rate estimates are made for a variety of components. The data are not firm, these are illustrative failure rates to support order-of-magnitude estimates. The failure rate values presented here apply to fusion experiments, either because (a) the data originated from equipment used on existing fusion experiments, (b) the data from non-fusion experiments have been corrected to account for the effects of the more severe fusion environment, or (c) the data for the component in question from non-fusion operating experience sources directly applies because there is no difference in operating environment because of application in a fusion facility.

The report concludes with some estimates of fire and explosion initiating event frequencies. These frequencies can be used as scoping values on future generation machines, such as the International Thermonuclear Experimental Reactor (ITER), because the frequency values are from either the Next European Torus (a machine nearly as large as ITER) or the values were generated for ITER itself. Values presented here are order-of-magnitude judgment only.

This report is the fourth in a series of reports to harvest existing data for support of reliability in design, reliability/availability analysis, and risk assessment for fusion experiments. The previous reports dealt with magnets, cryogenic, and vacuum systems. Future reports will dwell on safety and safety-related systems to support ITER safety analyses.

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CONTENTS

NOMENCLATURE

AFFF	Aqueous film forming foam
BNL	Brookhaven National Laboratory
CERN	Center for European Research Nucleaire in Geneva, Switzerland
cm	centimeter
d	demand
DBF	Design basis fire
DOE	Department of Energy
EDA	Engineering Design Activities for ITER
ft^2	square foot
FNAL	Fermi National Accelerator Laboratory
FRNC	Fiber reinforced nylon copolymer cable insulation
FTO	fail to operate
gpm	gallons per minute
h	hour
IE	initiating event
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
JT-60	Japan Torus, 60 m^3 volume
kPa	kiloPascal
kV	kiloVolt
m	meter
m^2	square meter
m^3	cubic meter
min	minute
mm	millimeter
MPF	Maximum possible fire
MW	megaWatt
NFPA	National Fire Protection Association
ONS	Office of Nuclear Safety in the US DOE
ORPS	Occurrence Reporting and Processing System
Pa	Pascal
PBX-M	Princeton Beta Experiment, Modified
PPPL	Princeton Plasma Physics Laboratory
PRA	probabilistic risk assessment
psig	pounds per square inch, gauge pressure
PVC	Polyvinyl chloride cable insulation
rpm	revolutions per minute
s	second
SLAC	Stanford Linear Accelerator Center
TFTR	Tokamak Fusion Test Reactor

FIRE PROTECTION SYSTEM OPERATING EXPERIENCE REVIEW FOR FUSION APPLICATIONS

1. INTRODUCTION

This report contains a limited review of fire protection system operating experiences for use by fusion system designers and safety analysts. Representative types of events found in published operating histories, safety concerns for fire suppression systems, failure rates for fire protection components, and system failure frequencies are discussed. Fire protection systems are necessary for both inertial confinement and magnetic confinement approaches to fusion due to the hazards undertaken and the costs of equipment involved. Therefore, this report should be of interest to a wide group of designers and safety personnel.

Fire protection for fusion research was previously required by US Department of Energy (DOE) direction in Order 5480.7A ("Fire Protection", February 17, 1993), and still is for many DOE facilities. However, this order has been superseded by DOE Orders 420 (Facility Safety, October 1995) and 440 (Worker Protection Management for DOE Federal and Contractor Employees, September 1995), but facilities that have already contracted with the DOE must still meet the older regulation. Most US fusion experiments are protected by automatic water sprinkler systems and Halon gas systems. The prevailing attitude in Europe favors good alarm systems and fire brigade response instead of sprinkler systems. However, the International Atomic Energy Agency publication on fire protection for nuclear fission power plants favors automatic sprinklers for new construction.[1-1]

Safety concerns with fires in fusion experiments are numerous. There are many electrical power supply systems and large numbers of cables and electrical distribution switchgear whose faults could start a fire. There are usually many equipment items requiring lubrication (pump and valve motors, fans, compressors, etc.) that could possibly suffer a fault (mechanical or electrical) and start a fire. There can be combustible solvents in use for maintenance cleaning or decontamination, and solvent vapors could catch fire. Demineralizer resins from water cleanup systems might be combustible. The many control systems also pose a fire threat if a "hot" short circuit developed in the system. Fusion facilities also handle hydrogen, which is a combustible gas, and perhaps lithium metal, which, when molten, is extremely reactive with air and water.[1-2] Then there are the more typical industrial fire problems of welding or brazing activities, careless cigarette disposal, poor housekeeping, lightning strikes, vehicle fires (forklift, truck, etc.), spontaneous combustion of cleaning rags or other materials, and other causes. All of these fire hazards can be properly managed with attention to fire protection in design and with good operating practices.

This report is not intended to be a complete discussion on fire risk assessment or fire hazards analysis, nor is it a chronicle of all significant fire events or all fire equipment failure rates. Resources are too limited for such a complete treatment. This work does give a representative view of fire protection system experiences from a safety viewpoint; it cites items to be conscious of during design and gives best estimates for frequencies of failures that designers and safety analysts may use for the new International Thermonuclear Experimental Reactor (ITER) fusion design or other fusion reactor designs. Providing representative fire hazards analysis approaches should help safety personnel select initiating events for safety and risk work. Estimates of the frequencies of these events are suggested, based on values in the literature.

Some definitions are important for this report. The first is 'fire protection system'. Fire protection systems include fire barriers and their penetrations, fire detection alarms, and fire suppression systems. For this report, fire departments or brigades are not included; they are outside the scope of the equipment reliability discussion (however, a brief section on manual firefighting is given in Chapter 3). Fire protection systems can also include administrative practices to reduce fire frequency, such as good housekeeping, established fire watch for hot work, inspection and maintenance of plant equipment, etc., but since administrative practices or procedures are difficult to assess in a generic fashion the initial, equipment-oriented definition given above shall be used in this report. The next definition is design basis fire (DBF). This is a fire event that is planned for in the design of the facility. It is the most severe fire for a given fire area (a room bounded by 2 hour or greater fire barriers), therefore a DBF is referred to as a bounding, or severe, fire that challenges the integrity of fire barriers, requires suppression system operation, and challenges the detection and alarm system operation. However, automatic and manual suppression efforts are assumed to have failed, and only equipment items specifically designed to survive such a hot, intense, long-lived fire are assumed to remain functional. Each fire area of a facility will have a DBF, and these are analyzed for their impacts to both on-site and off-site personnel although the off-site effects are often minimal (note that fire plumes can disperse hazardous chemicals or radioactive substances; fire fighting personnel can be injured during suppression activities; and other factors). The DBFs help to establish appropriate fire protection design parameters (perhaps beyond code requirements) so that equipment vital to facility safety can be relied upon to function even during a fire situation. This definition of DBF is also found in Appendix R of 10CFR50 ("Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979," 1995 edition). The maximum possible fire (MPF) is the worst case fire at a facility - the suppression systems are overwhelmed or fail to function, the fire barriers fail; perhaps the entire structure burns. The maximum possible fire loss is the MPF fire loss amount - the dollar cost of restoring the facility to operation, the cost of lost production or program continuity, any fire equipment damaged in the suppression effort, and all property loss amounts summed together. The maximum credible fire loss is the monetary amount of damage in a fire where the fire protection systems all functioned as designed. Such losses include direct damage from the fire, smoke damage, collateral water damage, facility lost time, etc.[1-3]

A fire probabilistic risk assessment (PRA) does not focus on the fire area.[1-3] In a fire PRA, vital equipment positions and vital areas inside the facility are identified, then fire initiating events are postulated and analyzed in event trees for those vital areas. Then the success or failure of fire detection systems, fire suppression systems, manual firefighting, and fire containment barriers are challenged. The fire PRA should find that the DBFs have been modeled in the lowest branches of the event trees. In some fire PRA work, it is possible that the worst damage, such as losing control wiring or vital power cables, occurs before the suppression systems even actuate. Therefore, the fire does not have to be a "raging inferno" to cause facility off-normal responses and/or possible radioactive releases. The suppression system might extinguish the fire, but the facility might still be in an off-normal event situation as a result of fire damage. Fire PRAs address these situations. Typically, fire PRAs do not address personnel life safety (evacuation) considerations, dollar costs of losses due to the initiating events, or firefighter risks, as addressed in fire hazards analyses. While a fire hazards analysis and a fire PRA do overlap, there are significant differences.

This report is structured to first discuss fire protection system operating experiences from selected magnetic fusion experiments, particle accelerators, and other US DOE operations. These experiences are used to give insight to fire events and fire equipment responses to testing and to fire events. Then component failure rate estimates are presented. These rates can be used in either scoping fire hazards analyses or in fire PRAs, and finally, a chapter on postulated initiating events and their frequency estimates is presented. This report is the fourth in a series of reports to harvest existing data for support of reliability in design, reliability/availability analysis, and risk assessment for fusion experiments. The previous reports dealt with magnets, cryogenic, and vacuum systems.[1-4,1-5,1-6] Future reports will dwell on safety and safety-related systems to support ITER safety analyses.

Chapter 1 References

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2. FIRE PROTECTION SYSTEM OPERATING EXPERIENCES

2.1 Introduction

This chapter discusses fire protection system experience for selected fusion facilities, particle accelerators, and other facilities that employ high technology systems (vacuum, cryogenics, laser, and high power electrical systems, etc., that are larger than laboratory bench top scale equipment). These experiences have all been found mainly from the published literature and in a few cases from interviews with experts. Each of the facilities is characterized as well as possible for their given level of published information and resources available for report preparation. Citing these parameters should help determine the similarity of these experiences to future fusion facilities.

Before describing the equipment in use at fusion experiments, it is instructive to define some terms, and also define some types of systems. The most typical water-based fire suppression system is a wet pipe automatic sprinkler system. This system consists of piping and sprinklers near the ceiling, filled with water. The water is stagnant, usually pressurized to between 446 kPa and 1.14 MPa (50 and 150 psig). The sprinkler heads, or flow nozzles, have openings that are generally 12.7 mm (0.5 inch) in diameter. These openings are capped and the caps are held in place by either a frangible glass bulb or a fusible metal element. These bulbs or elements are heat activated. When the bulb or metal reaches 74 °C (165 °F, a typical value), the element fails, the cap is pushed out of the sprinkler head opening by water pressure, and the water flows. Activation temperatures for the heat activated elements can range from 57 to 288 °C (135 to 550 °F). A deflector plate on a frame causes the water to be distributed in a desired pattern, typically a circular pattern. As a rough rule of thumb, there is usually one sprinkler head for each 9.3 m^2 (100 ft^2) of floor area. Water can be supplied from the municipal water system, specialized plant water systems, gravity feed tanks, lakes, pressure tanks, or pumped from wells. In DOE facilities, two sources of water of adequate capacity are recommended for fire water supply, but high risk facilities require two sources of water and two types of pump drivers (such as diesel and electric motors) to have acceptable diversity in the water supply system. There is a local water flow alarm, called a water motor gong (a "paddlewheel" which causes a clapper to strike a gong when the water flows), and usually a second alarm (electrical signal, not audible signal) to a remote station. For this reason, wet pipe sprinklers are also considered to be fire alarm systems as well as fire suppression systems. More information about wet pipe systems is given in Hoover[2-1] and in NFPA 13, the standard on sprinkler design.[2-2]

Dry pipe water-based fire suppression systems are similar to wet pipe systems, except that the sprinkler pipes are filled with air or nitrogen at low pressure (perhaps 274 kPa [25 psig] or higher), and there is a differential operating valve that keeps the fire water from entering the piping until the gas pressure is released. When a fire fuses a sprinkler head, the air or nitrogen flows out, depressurizing the line. After enough gas has been released, the dry pipe valve opens, and water flows into the piping. The water fills the sprinkler piping and flows out of the opened sprinkler head or heads. The gas pressure is monitored, with supervisory signals if the gas pressure decreases below a predetermined value. This system is used in situations where having water in the lines presents an engineering problem, such as in a cold storage warehouse, or poorly heated buildings. The response time of this system can be up to a minute longer than a wet pipe system, so there is a design requirement to increase the design area of application by 30%.

Another type of fire suppression system is the preaction system. This system has the piping filled with air, and has a supervisory air pressure of perhaps 108 to 216 kPa (1 to 2 psig) when the system protects floor areas over 186 m^2 (2000 ft^2). The valve controlling water flow is a deluge valve. The deluge valve only opened by receiving a signal from an alarm system, not by a flow of water or loss of air pressure. The gas pressure in the lines is monitored. Fire detectors mounted in the protected area, either photoelectric or ionization smoke detectors, infrared heat detectors, flame detectors, or others, send a signal to the fire alarm control panel which must send a signal to open the deluge valve. For water to flow onto a fire, the detectors must signal to open the valve, the valve must open, and the sprinkler head must fuse (open). The preaction system is used in locations where water damage must be kept to a minimum, and the water will be quickly applied in the event of a fire (such as a computer room).

The deluge system is the final water system to be described here. In this system, the sprinkler heads are always open, and the piping is filled only with atmospheric air. A deluge valve controls water flow to the heads. The deluge valve is controlled by signals from fire detectors. These detectors might be ultraviolet flame, infrared flame, or smoke detectors. When the deluge valve opens, water flows from all sprinkler heads. These systems are used when flooding with water is required to stop fast-developing fires, such as for cooling towers, or perhaps for liquid fuel locations (aircraft hangars, diesel engine driven electrical generators, etc.). Hoover has descriptions of these systems.[2-1] Some deluge systems may have a synthetic foam concentrate added to the water, making a low expansion aqueous film forming foam (AFFF). AFFF systems are often used for protecting large quantities of hydrocarbon fuels, such as gasoline. There are several types of aqueous film forming foam (AFFF) systems. The AFFF method of fire suppression uses 97% water to mix with a synthetic chemical concentrate (a fluorochemical and hydrocarbon surfactant mix) to produce a foam that coats surfaces and excludes oxygen from the burning surface. The foam solution also has a cooling effect as the water from the foam evaporates. These foams are often used for aircraft fire safety and for combustible liquid fire protection, such as for above ground fuel tanks.[2-3]

Non-water systems include dry chemical and gas suppression systems (carbon dioxide and halogenated agents such as Halon 1301). Bryan[2-3] gives good general descriptions of these systems. Among the most widely used of these systems was the gas suppression (Halon) system, and the dry chemical (typically, the Purple K or Super K potassium compounds) system is still in use. Computer equipment has been protected with Halon systems because the Halon acts quickly to extinguish a fire and there is little collateral damage. Since Halon is being phased out, carbon dioxide systems are being used, as well as the environmentally friendly Halon substitutes. In DOE computer facilities, water sprinkler system protection is required, and Halon is considered to be a supplemental protection measure.[2-4] Sometimes, electrical panels or cabinets are protected with local application gas systems instead of room-flooding gas systems. Dry chemical extinguishment can be provided locally for large outdoor electrical transformers, or as a indoor flooding system for electrical cable tray fires.

Carbon dioxide systems work to reduce the oxygen concentration in the protected area from the normal 21% oxygen in air down to below 15% so that combustion is extinguished by oxygen starvation. The gas does not leave any solid or liquid residues, and it is electrically non-conducting, so it is a good choice to use for electrical equipment protection. Carbon dioxide should not be used for reactive metals like lithium since the metal can reduce the carbon dioxide, thus providing oxygen to continue combustion. High pressure cylinders store liquid carbon dioxide at perhaps 102 kPa (850 psig) and these discharge through nozzles to flood an area. Similar to the water systems described above, fire detectors send a signal to a fire alarm control panel, which opens the valves that allow carbon dioxide to flow out of the nozzles and into the room. These systems can be oversized for expected leakage, and they can be sized for "two-shot" or two CO_2 deployment operations without replenishing the agent. Some of the difficulties with these systems are the possibility of freezing up the discharge piping if it is not well designed, the white fog created by condensation of atmospheric humidity when the CO_2 is released, the noise of gas deployment, the possible thermal shock damage to hot equipment when the gas smothers it, and the fact that reducing oxygen content can be harmful, or even fatal, to personnel. Hoover,[2-1] Bryan, and Coon[2-3] describe these systems.

Halon systems were the most frequently used non-water systems, and many are still in use today, so these systems will be briefly described here. Halon 1301 is bromotrifluoromethane (CF_3Br) gas. This gas acts to break the chemical chain reactions that form the combustion process. Generally, a 5% Halon flooding concentration in a room will extinguish a fire, but usually there is some design conservatism built in so that the system is designed for 5 to 7% Halon. This conservatism is added to flooding systems to account for possible dilution by non-isolated ventilation systems, ventilation fan coast-down, or leakage out of the room due to propped-open doors, windows, unsealed penetrations, open doors for evacuating personnel, etc. The gas is stored in cylindrical or spherical containers and is deployed through exhaust nozzles into the room or onto a localized area. Detectors, such as photoelectric or ionization smoke detectors, actuate the halon gas release.

Unfortunately, Halon 1301 is now believed to damage the ozone layer in the upper atmosphere, so it is being replaced as a fire suppression gas in the US.[2-5,2-6] Some of the possible replacements are carbon dioxide, difluorobromomethane (halon 2401), and 1,1,1,2,3,3,3 heptafluoropropane (CF_3CHFCF_3). Halons and their substitutes are usually stored at high pressures (these substances usually have low boiling points, so liquefying saves space without any loss of deployment performance) and have nitrogen cover gas pressurized to guarantee that exhaust velocity will be constant throughout a discharge. Typical storage pressures are 2477 to 4128 kPa (360 to 600 psig) at 21 °C and the globe containers might weigh 90 kg or more. Halon gas is discharged through the nozzles as a liquid, which rapidly vaporizes. Halon is heavier than air, so only discharge pressure, nozzle design, and nozzle placement can insure mixing of the Halon with room air to gain proper diffusion and consequent extinguishment. Since Halon is very quickly deployed, it is possible for loose objects in a room (pieces of paper, computer printouts, etc.) to be swept up. This debris can make room evacuation more difficult. The Halon gas suppression systems can also be very loud when deploying their gases, which precludes voice instructions and can greatly heighten tension of evacuating personnel.

Explosion suppression systems are used to control gas, dust, or other explosions. These systems are described by Bryan.[2-3] The basic system is fast acting (on the order of 50 milliseconds or less), using detectors (pressure, pressure rate-of-rise, or ultraviolet) that trigger explosive valves (or fast acting valves) that open canisters of high pressure gas (Halon or nitrogen) to flood the room. The gas will cause turbulence that can hamper progression of a deflagration or detonation wave, and the gas will alter the oxygen to material ratio. Halon is very effective in this application by preventing combustion. These systems can be very sensitive, since they are required to function in such small time frames.

Fire detection systems also serve a valuable fire protection function. These systems alert personnel to take action, either to manually fight fires (e.g., fire brigade), or to evacuate for life safety. These systems can also actuate equipment, such as ventilation dampers, electromechanical door closers, or suppression systems. Bryan[2-3] and others[2-7] give descriptions of various fire detection sensors. There are several kinds of sensors: thermal sensors (fixed temperature alarm setpoint and rate-of-rise temperature detectors), ionization or photoelectric smoke detectors, pressure sensors for explosions, infrared and ultraviolet flame detectors, combustible gas sensors, and combustion product sensors. Some types of detectors are more appropriate for certain rooms or fire safety areas than others. In this report, the type of detector will be identified whenever possible. These detectors are wired to a fire alarm control panel, which controls various equipment (audible alarms, ventilation dampers, door closers, remote notification of Fire Department, etc.).

Besides suppression and detection systems, fire barriers also are a part of fire protection systems. A "standard" fire wall (set by many building codes) has at least a 4-hour rating for fire resistance, and there should be no penetrations in this wall.[2-1] A "non-standard" fire wall has penetrations, and generally has a shorter fire resistance time rating than 4 hours. Fire walls are described in NFPA 221.[2-8] Fire walls must withstand impact of objects that could be propelled in a fire or explosion, withstand collapse of other building constituents (i.e., roof), and resist the effect of thermal expansion of building structural steel and expansion effects of the wall material itself. Fire walls can undergo severe expansion and distortion from one-sided heating;[2-1] this can lead to failure. Fire doors have similar fire-resistance time ratings to walls. Another area of fire resistant construction is the fire rated penetration. There can be literally thousands of wall penetrations required to bring power and services to a tokamak experiment. The penetrations must stop the spread of fire from burning along an electrical cable (or other item) into another area and stop the movement of smoke and heat from area to area. These penetrations can be sealed with solid materials such as gypsum or with foam plastic materials.

2.2 Fusion Facilities

Magnetic fusion facility experiences are discussed first, since they are most similar to the proposed International Thermonuclear Experimental Reactor (ITER) and other next generation experiments. There is not much published information about fire protection systems, fire events, or fire protection responses in fusion experiments. The fire protection systems and the fire events for magnetic fusion facilities are discussed when the information is available.

Tokamak Fusion Test Reactor (TFTR). The TFTR experiment at the Princeton Plasma Physics Laboratory (PPPL) in New Jersey began operation in December 1982.[2-9] This experiment has operated for over 12 years. The TFTR machine in the test cell is protected by a preaction automatic sprinkler system. "Preaction" is described above. These sprinklers are designed to give 6.9 liter/min-m^2 (0.17 gpm/ft^2) water flow per sprinkler head over a 279 m^2 (3000 ft^2) area, which corresponds to a rating of Ordinary Hazard Group 2 using the National Fire Protection Association Standard 13[2-2] for sprinkler design. That standard is specified in DOE Order 5480.7A[2-10] for use at existing DOE facilities (although this order has recently been superseded by new DOE Orders, most fusion experiments still comply with 5480.7A under their original contract). The preaction deluge valve is activated by thermal rate-of-rise detectors on the test cell ceiling. The hot cell is similarly sprinklered, except that the fire detection system uses both ionization smoke and thermal rate-of-rise detectors. The tritium areas at TFTR are protected by a wet pipe sprinkler system, a three-hour-fire-rated room, ionization smoke detector systems, alarmed water flow on the sprinklers, and tritium dampers on the ventilation system. The sprinkler heads in the tritium area are rated at 74 °C (165 °F). The TFTR control room and computer rooms are protected by a Halon 1301 system and with ionization smoke detectors, and rate-of-rise/fixed temperature thermal detectors. This system is designed to flood the control room with a 5% halon concentration within 10 seconds. The motor generator building is protected with a wet pipe sprinkler system, and the motor generator pits are protected by automatic carbon dioxide systems.[2-11]

The TFTR machine has had tests of its fire stops to demonstrate their effectiveness. There are over 3,000 fire stop penetrations for the machine in the test cell walls and floor. There are 90 types of penetrations, ranging from several square inches ($\sim 10^{-3}$ m^2) in area to 100 square feet (9.3 m^2). Combinations of room temperature vulcanizing silicone rubber and alumina-silica ceramic form boards were used as seals for these penetrations.[2-12]

Princeton has had several fire events. The first event noted in the literature was an electrical fire on September 12, 1970, long before TFTR was built. A fire developed at a 138 kV to 4 kV transformer and seriously damaged a bank of 4 kV panels and other equipment in the motor generator building. Fire fighting was manual, first with the employees nearby using dry powder fire extinguishers, then the PPPL fire brigade with truck-mounted equipment, then the Plainsboro Fire Department.[2-13] This fire was thought to be the largest fire in the first thirty years of laboratory operation.

Other fires have occurred at PPPL, although these have not been large or very costly. On September 25, 1989, another electrical fire occurred on the Princeton Beta Experiment-Modified (PBX-M). A safety disconnect switch in the toroidal field coil circuit overheated due to a mechanical failure. The ensuing fire involved three switches. Personnel responded with hand-held carbon dioxide fire extinguishers and wheeled carbon dioxide extinguishers. The personnel hit the halon abort button (a 60 second timer button to delay halon release in case the fire can be controlled without the expense of deploying halon). The fire was too vigorous to control by personnel with the carbon dioxide extinguishers, but the halon did not release after the timer ran out. The halon system was reviewed and repaired.[2-14] The fire brigade responded and used dry chemical extinguishers. The Plainsboro Fire Department was also called, but the fire was extinguished when they arrived.

On February 25, 1992, a fire occurred in the 138 kV switchyard of the PBX-M experiment. A capacitor in the switchyard had failed and spilled less than a quart of mineral oil onto the concrete. The fire brigade extinguished the fire using a portable halon extinguisher.[2-15]

Some other fire system-related events at PPPL have occurred as well. Spurious halon dumps have occurred. One event occurred in the radiofrequency building due to cooling water leakage shorting a fire detector, and one event occurred during a test of the halon system.[2-16,2-17] On August 14, 1992, another spurious halon discharge occurred at PPPL due to a faulty detector.[2-18] These inadvertent halon dumps have also occurred in other facilities of the Department of Energy, which will be discussed later in this chapter.

Alcator C-MOD. This experiment is located at the Massachusetts Institute of Technology. The original Alcator experiment began in the early 1970's, and the upgrade to Alcator C-MOD was completed in the early 1990's. The building that houses the Alcator was originally a Nabisco food production plant; it was altered with thick concrete radiation shielding walls, etc., to accommodate the fusion experiment. The Alcator is sprinkler protected. The offices and control room are NFPA light hazard category; the labs and electronic shops are NFPA ordinary hazard group 1; the machine shops, diagnostic rooms, radiofrequency and power rooms are NFPA ordinary hazard group 2. The experiment room housing the tokamak is ordinary hazard group 2. The sprinkler heads are typically spaced at 4.3 m (14 feet) by 2.8 m (9 feet), delivering a design density of 6.1 liter/min-m^2 (0.15 gpm/ft^2) over the hydraulically most remote 279 m^2 (3000 ft^2) in the laboratories and the control room, 8.5 liter/min-m^2 (0.21 gpm/ft^2) over the most remote 139 m^2 (1500 ft^2) in the diagnostic labs and power room, and 7.7 liter/min-m^2 (0.19 gpm/ft^2) over the most remote 139 m^2 (1500 ft^2) in the offices and shop areas. Most of the sprinkler heads are rated for 74 °C (165 °F), except the diagnostic room heads, which are rated at 100 °C (212 °F). The alternator building is served by a preaction sprinkler system. The sprinklers are tested quarterly and are serviced once a year. Smoke detectors are used in the diagnostic labs, the experiment cell, and the power room. These detectors are connected to the MIT Proprietary Fire Alarm System operated by MIT Physical Plant personnel. These personnel will call the city fire department after verifying that the alarm is signaling an actual fire event.[2-19]

The water source for the sprinklers is the city water supply from the Cambridge, Massachusetts municipal system. A 1982 hydrant flow test to measure the water supply gave values of 459.9 kPa (52 psig) static pressure and 432.3 kPa (48 psig) residual pressure at a flow rate of 4052 liters/min (1072 gpm). This hydrant test was the basis for the hydraulic calculations of the sprinkler system installation.[2-19] The sprinkler systems are tested quarterly and are serviced once a year. The smoke detectors are inspected semi-annually. No fire events have been found in the occurrence report data banks for the Alcator C Mod facility.

Joint European Torus (JET). The JET experiment near Culham Laboratory in the United Kingdom initially operated in June 1983. Information on the fire protection systems at JET was not found in the literature review performed for this report. Reviews of JET operating experience showed that there are fire detection systems (smoke detectors), and that these systems are sensitive and they are connected to central alarm systems.

JET has had several fires and many false fire alarms.[2-20 to 2-29] In the time period between 1985 and 1987 (the time documented and available for review), there were 34 unwanted alarms in 1986 (and two real alarms for fires), and 20 unwanted alarms in 1987 (and one real alarm for a fire). By unwanted alarm, we mean that the fire detectors gave an alarm for a non-fire condition; either by failure or by ingress of a fire smoke-like substance. In Europe, the published average ratio of unwanted alarms to valid alarms is 11 to 1, and while there are no established guidelines about unwanted alarm frequency, 65 unwanted alarms per 1000 detector heads per year is considered reasonable.[2-30] Reasons for the high number of unwanted alarms at JET were the sensitivity of the detectors. Personnel smoking tobacco in areas nearby the detectors were a leading reason for the high number of alarms, as well as dust from ventilation ducts being mistaken for smoke by the duct detectors; and in one case, oil vapor from a vacuum pump with a leaky seal was the cause of recurring unwanted smoke alarms. The average downtime to investigate these alarms was perhaps 10 to 15 minutes, and fire fighting could take on the order of an hour, to several hours or more. The three fire events were electrical equipment fires, in power supplies for the neutral beams and poloidal field coils.

Japan Torus-60 (JT-60). JT-60, at the Naka Fusion Research Establishment in Japan, began operation in April 1985. No published information on fire protection systems or on fire events at JT-60 was found for this report. The operating experience published to date[2-31,2-32] does not mention fires, so either none have occurred, or these events were outside the normal equipment-related problems being reported.

Russian superconducting tokamak experiment (T-15). The T-15 experiment is located at the Kurchatov Institute of Atomic Energy, near Moscow. T-15 initially operated with low power pulses in December 1988.[2-33] No published information on fires or fire protection provisions at T-15 was found for this report.

DIII-D. This experiment at General Atomics in La Jolla, California began operation in February 1986.[2-34] As is typical of US DOE facilities, the DIII-D buildings have sprinkler systems. Even the mobile shielding roof over the DIII-D experiment has sprinkler protection, with a special fitting to allow the piping to be disconnected when the shielding roof is moved away from over the top of the machine. DIII-D has had only a few fire events. The most important one was an electrical arc with an explosive electrical arc and fire in the toroidal field coil bus. The incident was caused by a foreign object shorting out the bus. Other problems have included the large, outdoor capacitors being grounded out by a mixture of dust and rain.[2-35,2-36]

Other fusion experiment experiences. Experiences from several other fusion experiments were reviewed to find what types of possible events can occur. One event of particular interest occurred at the Tore Supra experiment in Cadarache, France, which began operation in April 1988. Tore Supra suffered a "severe electrical breakdown" in a transformer. A short circuit in a 63 kV transformer in the poloidal field system occurred in the first year of Tore Supra operation.[2-37] The event caused an explosive energy release. Large transformer faults are not uncommon in industry.[2-38] This event, and others given above, serve to illustrate that electrical equipment can fail and lead to fires, especially when dealing with the power requirements for fusion. Future machines, such as ITER, would have superconducting poloidal field coils of lower energy consumption, but there is still a great possibility of electrical fires over the life of the facility.

2.3 Accelerator Facilities

Several of the large accelerators around the world, including the facilities at Fermi National Accelerator Laboratory (FNAL) in Batavia, Illinois, and the Stanford Linear Accelerator Center (SLAC) publish some of their operating experiences. Since accelerators typically use equipment similar to fusion experiments (superconducting magnets, vacuum systems, cryoplants, high power electrical systems, etc.) these operating experiences can be quite relevant to fusion. Unfortunately, no fire or fire protection experiences from the Center for European Research Nucleaire (CERN) were found in the literature review for this report.

FNAL. The FermiLab main ring, the Tevatron, and other experiments at FNAL are generally protected from fire damage by water-based suppression systems, and in some locations by Halon gas suppression systems. The sprinkler systems are designed for the ordinary hazard class from NFPA Standard 13.[2-2] The Halon systems are designed to deploy for a 5% concentration within 10 seconds. Some design deficiencies have been noted, such as proper plugging of floor and wall penetrations, some areas of inadequate sprinkler coverage, and the use of cooking utensils (microwave oven, coffee, etc.) in Halon areas -- such activities could generate smoke from cooking and receive a Halon release in response to the cooking smoke.[2-39]

Other operating experiences at FermiLab have not been found in the literature, but there is one famous fire event that cost on the order of $1 million in repairs. This is the Wide Band Laboratory fire in October 1987. A worker had been hooking up instrument leads for the wide band photon experiments. One of the leads was mismatched, so that some connectors were left uninsulated. When the equipment was energized, the unconnected pins grounded and eventually started a fire underneath the experiment. The fire damaged equipment directly, and the smoke damage in the laboratory hall was also considerable.[2-40]

SLAC. The Stanford Linear Accelerator Center (SLAC) has also had some fire events. These electrical fires were concentrated in the resistive magnet power supplies. These events are documented in reports on DOE operating experiences.[2-41 to 2-44]

BNL. In a preliminary safety analysis report,[2-45] Brookhaven National Laboratory (BNL) researchers described the fire protection systems for the 200 MeV linear accelerator. The accelerator building has a wet pipe sprinkler system, smoke detectors, and the BNL fire department monitors the alarm circuit. The building itself is non-combustible construction, but it contains many electrical cables for electrical power, instrumentation, and control signals. BNL researchers judged the cable fire risk probability to be 'occasional'. This probability is assumed to mean that one or more cable fires will occur over the life of the facility, so the frequency of occurrence is in the 0.1 to 0.01 per year range.

2.4. US Department of Energy Operations

The US Department of Energy (DOE) operates many facilities, and some of these are of interest to fusion. DOE facilities of interest include hot cells, tritium handling labs, computer facilities, and also fission reactors (for control systems, heat transport systems, etc.). Some of the fire protection experiences are discussed here for the reader to understand what types of events have occurred in these varying operations.

There are several reports that discuss fire events in the US DOE. These are the summary reports on incidents[2-41 to 2-44] and a report on fire protection systems.[2-46] There are also some site specific reports, such as the Savannah River report.[2-47,2-48] One DOE bulletin stated that over 100 fires occurred at DOE facilities in 1990, and many of these small fires were welding-related.[2-49] Most DOE fires have three main causes - construction or maintenance (welding, grinding, "hot work", etc.), electrical fault, and "other". The "other" category can include careless disposal of smoking materials, spontaneous combustion of rags, lightning, chemical reactions, gas or vapor ignition, and others.

Table 2-1 gives a summary of some of the more recent fire protection-related events in DOE facilities. These are not a complete list of any event possible, but simply a list of the types of events that have occurred over the past few years at US DOE facilities. Many of these events could occur in magnetic fusion experiment facilities. Most of the events are human errors relating to fire protection systems (i.e., it is not a system fault that inspections were not carried out on schedule), but these are the sort of problems that are routinely experienced. The dollar costs for these events were not given in the reference materials; these events are reported from a safety perspective rather than a facility operations perspective. The weekly summaries can be accessed from the internet at uniform resource locator address gopher://146.138.63.106/11%5cdir%5cnfs%5coeweekly.

Table 2-1. Summary of selected events involving fire protection systems in DOE facilities

Title/Brief description	Date	Reference citation[a]
Contamination causes mercury check to fail. Personnel were performing a semi-annual test on a deluge sprinkler system. The mercury check, which dampens the air signal from the heat-actuated device to the mechanical trip for the deluge valve, was erratic. The deluge system was not operable. The mercury check was replaced and the failed unit was analyzed. Metallic contamination from wearing parts was found. Procedures were revised to examine the mercury check more closely.	08/15/95	ONS 95-45
Revised surveillance test procedure identifies fire system deficiencies. Personnel performing a quarterly surveillance test activated a sprinkler water flow alarm. They found that the alarm shut down the wrong air-handling units and dehumidifiers. The revised test procedure indicated which units should shut down for smoke control. Investigators believe that the originally installed wiring was wrong, and it was discovered during the test when the proper units for shut down had been identified. The system was changed to shut down correct units.	11/01/95	ONS 95-45
Steam causes halon discharge. A fire alarm in a lab room actuated from steam generated by drying towels in a temporary drying oven. Personnel evacuated the building. The halon system actuated, releasing 516 lb (235 kg) of halon 1301 gas. This was the first time that the drying oven had been used. The report stated that there had been a similar, non-fire halon release the previous year.	08/09/95	ONS-95-44
Failure of notification system hampers building evacuation. Technicians smelled a strong odor of natural gas. They pulled a manual fire alarm to evacuate the building. Nothing happened. They pulled other manual alarms, and again nothing happened. They tried to use the public address system, but it was inoperable since the	10/10/95	ONS 95-43

Title/Brief description	Date	Reference citation[a]
ONS 95-43, continued access codes had been changed without informing appropriate personnel. Verbal directions were given to personnel to evacuate. The personnel called 911 for the fire department. Arriving fire fighters found a leaking gas shut off valve. Later inspection revealed that audible appliances were bypassed during smoke detector replacement operations.		
Fire system flow alarm incorrectly assumed to be false.	05/30/95	ONS 95-23
Risk-based decision analysis used for glovebox fire operating event. Cleaning rags in a glovebox caught fire. An employee actuated the fire alarm.	11/22/94	ONS 95-19
Fire suppression system not installed as described by Operational Safety Requirements. A fire suppression system was required and was never installed. Facility personnel thought that it was not needed in the low combustible area. A study was initiated to determine if a fire suppression system was needed.	04/26/95	ONS 95-17
Failure to perform fire protection system testing.	04/04/95	ONS 95-16
Older smoke detectors pose contamination hazards. Older detectors using Americium 241 leaked when they were replaced in a system upgrade.	03/23/95	ONS 95-12
Failure to comply with fire protection system surveillance requirements. Testing frequencies were less than specified in NFPA standards adopted by DOE Order 5480.7A.	02/04/95	ONS 95-06
Wrong fuse leads to fire alarm malfunction. A 2-ampere fuse was mistakenly installed in a fire alarm panel where a 12-ampere fuse was needed. The panel initiated an alarm in 5 clustered buildings. There was concern that simultaneous work affecting the fire water pressure had caused the alarm.	02/01/95	ONS 95-06

Title/Brief description	Date	Reference citation
Fire in glovebox. A metallographic sample fell onto a terry towel and caught the towel on fire. An employee extinguished the fire before heat detectors in the glovebox actuated alarms or the glovebox suppression system.	01/25/95	ONS 95-05
Water intrusion causes spurious fire alarm. Snow melt caused water intrusion and the water shorted out a manual pull station.	12/25/94	ONS 94-52
Fire watch not in place during sprinkler outage. As valve replacement in a sprinkler system was under way, no fire watch was initiated for over 7 hours.	12/19/94	ONS 94-51
Inadequate freeze protection affected safety-related equipment. Several incidents of frozen sprinkler piping at several DOE facilities.	11/29/94	ONS 94-48
Leaking lube oil starts fire. A commercial nuclear power plant had a containment building fire when pump lube oil leaked from a cracked fitting and the oil started to burn. Oil-soaked insulation around the pump burned. Maintenance men responding to the pump problems called the fire brigade and had the plant shut down. Fire brigade personnel responded and put the fire out with dry chemical extinguishers.	10/21/94	ONS 94-43
Fire and contamination at a DOE nuclear reactor. A faulty electrical connection in an experiment ion source caused a fire in combustible insulating materials.	03/31/94	ONS 94-40
Fires occur on roofs of vacant reactor building and nuclear fuel-forming facility. In one event, welding ignited a flammable solvent. The fire was quickly extinguished manually. In the second event, grinding sparks ignited gasoline that had been poured to kill a nest of ants. That fire was also quickly extinguished by personnel at the location.	09/09/94	ONS 94-39

Title/Brief description	Date	Reference citation
Valve found closed in fire protection system. The water valve had been closed in January 1994 to isolate the parts of the system damaged in freezing conditions. A fire patrol was initiated then, but it was terminated in March 1994 without any restoration of the system. From March to September, the fire risk was high. Fortunately, no fire occurred during the time that the system was isolated.	09/20/94	ONS 94-39
Study reveals deficiencies in lightning protection.	09/10/94	ONS 94-37
Isolated fire hydrants found during fire alarm response. A fire alarm sounded when smoke from a burned up compressor motor was detected. Responding fire fighters found the hydrant valve closed. The water was not needed to control the compressor smoke. The hydrant valves around this building were all opened after the event.	08/16/94	ONS 94-34
Alert technician prevents radioactive release in bag house fire. A hot ember caused a fire in the fabric bags of a filtration bag house. The operator had the fans shut down so that the air flow did not fan the flames.	06/09/94	ONS 94-25
Fire in waste handling line glovebox. A cleaning rag in the glovebox caught fire. The fire was not large enough to actuate the Halon suppression system. Personnel manually actuated the suppression system.	04/15/94	ONS 94-16
Effects of fire protection system actuation on safety related equipment. The six most significant items in this study (NUREG-1472) were relays that could actuate Halon after seismic events, smoke detectors that could alarm from seismic event-induced dusts, some equipment protected by deluge systems could have water damage, fire suppressant availability during a seismic event, switchgear fires might experience water damage, and electro-mechanical components in cable spreading rooms could be water damaged.	02/09/94	ONS 94-13

Title/Brief description	Date	Reference citation
Frozen sprinkler head causes water leak from contaminated building. About 1,800 gallons of water leaked from an unoccupied building. Fire fighters responded to the water flow alarm and isolated the leak.	03/13/94	ONS 94-06
Plant water surge degrades fire sprinkler. A breach in the fire water line caused depressurization. A fire pump started to boost pressure, but the pressure *surge* caused pipes to fail. The system was over 30 years old and had not been well maintained.	12/03/93	ONS 94-03
Freeze protection. Several events are cited regarding freezing sprinkler piping in buildings.	01/17/94	ONS 94-03
Plant equipment affected by lightning. Operators discovered charred and burned wiring to a fan when they tried to start it.	07/29/93	ONS 93-31
Loss of fire protection water supply. Maintenance crews inadvertently valved out both overhead water supply tanks for the fire protection system. The mistake was found and service was returned within 10 minutes.	07/17/93	ONS 93-29
Halon system degraded. During an inspection, fire protection engineers determined that 5 of 6 halon cylinders each weighed about 4.5 kg less than the required weight. The loss was either the cumulative effect from many tests, or there was a leaky fitting(s) in the halon lines.	07/08/93	ONS 93-28
Loss of alarm capability. A total loss of offsite power and partial loss of battery-backup power meant the loss of seven smoke detector zones and the loss of valve tamper alarms, as well as intrusion, computer power and other alarms. Other alarms lost on a second panel were pull stations, sprinkler flow, and security alarms. These were restored in about 40 minutes.	06/29/93	ONS 93-26

Title/Brief description	Date	Reference citation
Loss of fire alarm capability. A loss of offsite power caused alarms to switch over to battery power. The battery power depleted in 90 minutes, rather than the 24 hours they should have provided. Pull stations were de-energized. Partial alarms were restored in 6 hours, the full capability was restored within 12 hours.	04/08/93	ONS 93-15
Procedure violation by fire watcher. A shift advisor discovered a fire watcher reading a magazine; the man's fire watch log sheets were filled out in advance of any watch patrol action. The watchman was relieved of duty.	03/05/93	ONS 93-10
Lithium fire in waste handling facility. About 0.7 kg of lithium ribbon was being prepared for packing. Placing the lithium in methanol in a plastic container, the lithium ignited the methanol and the plastic container; there was some water in the methanol. Employees used an incorrect dry chemical fire extinguisher on the lithium, but did use water on the collateral fires ignited by the burning lithium. The fire department arrived and extinguished the lithium fire. The NFPA Fire Protection Handbook section 5-21 "Combustible Metal Extinguishing Agents and Application Techniques" is a good reference for correct attack of lithium fires.	12/14/92	ONS 92-36
Halon malfunction causes evacuation of control room. Operators evacuated as given in procedures when the halon system actuated. The faulty discharge was possible due to two reasons, either degradation of the fusible links by excessive time in service (over 26 yrs) or due to fusible link vibration that degraded the links over time.	12/18/92	ONS 92-36
Makeshift welding connection causes electrical fire. Welders needed to lengthen the reach of arc welding leads. They attached a taped connection to the tungsten inert gas welding lead. The connection overheated and caught insulation on fire. The flames were stamped out by a worker as the fire watchman was responding with a fire extinguisher.	12/10/92	ONS 92-34

Title/Brief description	Date	Reference citation
Fire in hot cell. Cutting welds were being performed in a hot cell. Sparks or hot particles landed on a hydraulic hose on the cell floor and ignited the rubber hose. The fire was too small to trigger the halon system, so the system was manually actuated to extinguish the fire.	12/08/92	ONS 92-33
Experience with fire main valve failures. A leak occurred in an underground 152.4 mm (6 inch) diameter fire main. The pipe was aged and could not withstand the pressure test personnel tried to perform. Underground leaks have been occurring frequently because many fire system post indicator valves have been corroding. The nickel plated valve disks are experiencing galvanic corrosion and must be replaced in as little as 6 years of service. The manufacturer is investigating the corrosion to develop better protection.	11/17/92	ONS 92-31
Inadvertent halon discharge. A personnel error caused an incorrect signal to a halon system, and the system actuated during a test. This is the sixth such event at DOE facilities in 1992.	11/05/92	ONS 92-29

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a. The reference citation is the US Department of Energy <u>Operating Experience Weekly Summary</u>, published by the Office of Nuclear Safety (ONS). The first two digits signify the calendar year, and the second set of digits signify the number of the week of the year (for example, summary 93-12 is March 19 to March 25, 1993). These ONS summaries supplement the DOE Occurrence Reporting and Processing System (ORPS), a computerized system of fault events stored at the Idaho National Engineering Laboratory. ONS urges analysts to review the entire occurrence report for complete understanding of the events cited in the weekly summaries.

2.5 Selected Fire Events

Some other fire events in the US are rather famous for the damage ensuing from fire. Several of these events are discussed here. A fire in a telephone switching center in Hindsdale, a suburb of Chicago, Illinois, caused a wide area telephone outage in 1988.[2-50] Over 35,000 customers were without telephone service for up to a month. Without a requirement to install a fire suppression system, the telephone company management chose to do without a system. Water-based fire suppression systems were not installed due to the concern over damage arising from spurious actuation. The expensive Halon systems costing up to several hundred thousand dollars were not installed since many of the cables were overhead, and Halon is heavier than air. Halon quickly settles if not well distributed, so the telephone company management believed it would be a poor choice for mitigating overhead cable tray fires. They also did not have a central station fire alarm, only a remote station alarm to an office of the telephone company, not to an alarm company. This arrangement was based on the idea that the fire department, responding to false alarms, would damage doors while forcing entry and perhaps damage equipment as well. On the afternoon of May 8, 1988, an electrical short circuit occurred and a cable fire started. When the fire alarm to the remote telephone office annunciated, the watchman called his local foreman, instead of following procedure and calling the fire department. Perhaps the watchman did not want to send the fire department to the Hindsdale building and have them force entry. The watchman's foreman called the Hindsdale foreman, who determined that the fire alarm was real; he tried to call the fire department. By that time, the fire had damaged the telephone switches and cables enough that the telephones were inoperable. The Hindsdale foreman flagged down a motorist, who in turn found a policeman. The policeman radioed a fire call in to the fire department. Fire fighters arrived 42 minutes after the fire had started. In that 42 minutes, the fire damaged the fiber optic communications hub quite severely. This event is regarded as the worst fire in the history of US telephony, with hundreds of millions of dollars of lost business in the month of repair time for the Hindsdale switching center.

The most famous nuclear power plant fire is the Brown's Ferry fire in 1975.[2-51] In that event, a worker was leak checking cable tray penetrations to the containment building during plant operation. Typical leak checking practice in industry at the time was to use a candle flame, since the flame readily responds to even slight air flows. When the worker used the candle, the flame was drawn into the polyurethane insulation stuffed around the cable tray. The worker tried to beat out the flames with his flashlight, then he tried to smother the fire with rags, and then he used two CO_2 fire extinguishers on the fire - but the suppressant carried through into the containment building instead of staying at the base of the insulation fire. The worker then used two dry chemical fire extinguishers, but with the same results as the carbon dioxide. The fire spread into cable insulation, and into the reactor containment building. Therefore, there was fire in both the cable-spreading room and the reactor building. There were delays in actuating the CO_2 room flooding system in the cable spreading room; precautions for life safety and to prevent inadvertent actuation had to be met and defeated, respectively. The fire slowed to 2 to 3 cm/min burn rates with the CO_2 in the room, and the cable spreading room portion of the fire was declared extinguished in 4 hours from fire ignition. Several workers with dry chemical and carbon dioxide extinguishers immediately attacked the fire in the reactor building, but the hot cables would rekindle. The building soon became smoke filled, decreasing visibility and necessitating use of breathing apparatus. Power to the building lights was lost about one hour into the fire fighting operations. Fire fighting was not well coordinated, and there were competing demands for breathing apparatus, since operators needed to use the same air packs to enter the reactor building for valve position changes to align the plant for shutdown cooling mode. Emergency core cooling control was lost due to cable damage. The reactor was scrammed at about 30 minutes into the fire event, when operators realized the severity of the fire. Water was finally used on the fire about 6.5 hours into the event, after concerns about electrical shorting were reduced (the plant was now properly aligned for shutdown cooling) and personnel were evacuated to preclude any electrical shock hazard. After water hoses were applied in the cable trays, the fire was extinguished within 40 minutes. It took another roughly 8 hours after fire extinguishment to fully establish shutdown cooling flow in a normal plant configuration. Fire damage was 117 conduits, 26 cable trays, and 1611 cables. Of the 1611 cables, 628 of them were safety-related. The direct fire damage cost about $10 million to repair, and replacement power cost much more than that amount. The main lessons learned were that placing some safety-related cables in conduits was not adequate protection, since the conduits heated up and failed the cable insulation inside the conduit. Another lesson was that if the fire is not quickly extinguished with gas or dry chemicals, then use water, since it will very likely be less damaging than allowing the fire to burn and damage more equipment in the plant.

An explosion event of concern to fusion is the off-gas building explosion at the Cooper Power Plant.[2-52] On January 7, 1976, operators noted an alarm indicating reduced flow out the 325 foot-tall (99.4 m) off-gas stack at the Cooper boiling water reactor. The off-gas system purges radiolytic decomposition gases (hydrogen and oxygen) from the cooling water. It appeared that the stack fan was running poorly, so the operators switched fans. The second fan did not give a normal flow rate, so two operators were sent out to investigate the fans in the off-gas building. The operators noted that the air pressure in the building was not low (normally low like the reactor building) and that radiation readings were high. They noticed an unusual odor, and they evacuated the building. Probably a spark from some machine in the off-gas building detonated the hydrogen from the off-gas system shortly after the two men reached a safe location. The building was demolished. Investigation revealed that the stack had plugged shut with ice, and the fans were not designed to deal with such a situation. The building was re-built, and heaters were added to the off-gas stack to prevent ice plugging.

An issue of debate is how fire protection systems will respond in earthquake events.[2-53] There are concerns that gas suppression systems will be triggered by the dust clouds rising in earthquakes or by vibrations, so that when they might be needed after the earthquake, they are expended. There are concerns that fire sprinkler piping might not survive an earthquake, and would flow water that would spread radioactive contamination and add water damage to the earthquake damage. The operating experiences thus far show that, in power plants and other non-residential buildings, fires following an earthquake are rare,[2-54,2-55] although this experience has not been favorable in large earthquake events. Certainly, keeping the fire suppression and fire barrier systems intact are important for safety following an earthquake. The NFPA 13 sprinkler design standard[2-2] directs piping hanger design for seismic regions in the US. There is also some additional guidance published on this topic for water-based systems,[2-56] and there is National Fire Protection Association (NFPA) design guidance for other systems (NFPA 12 - Carbon Dioxide systems, NFPA 12A - Halon 1301 systems, NFPA 17 - Dry Chemical systems, etc.).

These events reveal some weaknesses that should not be repeated. For example, focus points or 'hubs' should be protected from damage, so that fires or other common cause events do not stop communications or control signals. We also note that people do not always respond the way procedures dictate they should. Training and information as to why procedures require certain actions are needed, so that personnel are more likely to follow the procedures. The Browns Ferry fire showed many things - the non-combustibility required of sealing and cable insulation materials, the need for physical separation (not just a conduit barrier) between cable trains, the need for coordinated fire fighting efforts, the need for operators to shut the plant down quickly if a fire is not brought under control within a short time, and that water can be safely used as a fire suppressant around electrical equipment.

The hydrogen explosion event showed that monitoring is important, and that rooms handling combustible gases should be monitored for gas leakage. Eliminating ignition sources whenever possible is also good advice. Prudent design calls for being able to withstand a hydrogen explosion if one occurs as part of off-normal circumstances, while in normal operation, efforts are made to preclude explosive concentrations and remove any ignition sources.[2-57]

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3. FIRE PROTECTION SYSTEM COMPONENT FAILURE RATES

3.1 Introduction

This chapter contains discussions on the failure rates of various fire protection system components. Suppression system components and typical system failure rates, detectors, and fire barriers are included here. These data have been obtained from actual operating experiences whenever possible. While there is no well developed data bank on fire systems and data is very limited,[3-1,3-2] this chapter is a presentation of published descriptions of actual operating experiences.

3.2 Water-based Fire Suppression Systems

There are two facets of the reliability issue to address: the system effectiveness and the system availability. The former topic means the ability of the sprinkler system to control or extinguish a fire given that the system operates. The latter topic is the likelihood of the system operating when there is a valid fire demand. A third concern addressed here is non-fire water damage from a leaking sprinkler system, since this is a real-world mode of failure of these systems.

Sprinkler effectiveness. There have been several published studies of fire sprinkler system reliability and effectiveness.[3-3,3-4] These studies indicate that sprinkler systems are very effective; in Australia many fires (over 60%) are controlled or extinguished by only one sprinkler head operating, and over 90% of fires being controlled or extinguished by six heads operating.[3-3] In the US, these numbers are lower, about 35% of the fires being extinguished or controlled by one sprinkler head. Marryatt[3-3] suggests that this is due to the higher pressure (125 to 200 psig, compared to the US at usually under 125 psig) at which the Australian systems operate, so one sprinkler puts down more volume of water per minute than a typical US sprinkler. It could also be due to the fact that Marryatt also defines controlled as less than 20% damage to the total value involved (building and contents).[3-3] This 20% estimate can be argued as being a rather liberal definition of "controlled fire"; more Australian fires end up in Marryatt's controlled category than in other countries. Nonetheless, if the rated delivery of the system is shown to be within the area/density curves given in NFPA 13[3-5] for the occupancy hazard class of the facility, and the water supply delivers up to rated capacity, then it appears to be a reasonable assumption that the suppression system will be 100% effective. For more detailed analysis, Levinson and Yeater[3-6] have developed an analysis technique to estimate the sprinkler system effectiveness.

The idea of overwhelming the sprinkler system by the combustible materials present (paints or other wall coverings, floor coverings, insulation, and other materials), the presence of combustible liquids (hydraulic oils, process chemicals, or other volatile liquids), or shielding from the water (fire under a table or desk, in a stack of wooden pallets, etc.) must be considered. For fires of very high intensity, the sprinkler system might have degraded effectiveness, perhaps down to zero effectiveness. Unfortunately, the analyst is faced with a decision about how effective the sprinklers might be in such instances. Conservatism suggests the analyst assume zero effectiveness in those cases,[3-7] but this would often be overly conservative. If the fire grows larger, then more sprinkler heads will open and the volume of water should eventually, in most cases, halt fire progression. In other cases, the water supply is overtaxed. The cases where the water supply is adequate still leaves the questions of fire spread past the heads (above them, or into concealed spaces) and the possibility of the fire generating enough structural damage to collapse the roof - which would render the sprinkler system completely ineffective. For the remainder of this chapter, we shall assume that these suppression systems are effective in controlling or extinguishing the fires.

System availability. The Handbook of the Society of Fire Protection Engineers[3-7] gives a discussion of fire system reliability and fire risk analysis. The unfortunate issue with availability calculation is not in the mathematical methods used to calculate the availability - these have been proven on many types of systems, from nuclear power, aerospace, chemical process and industrial plants - but with having adequate component failure rate data to use in the models. As stated above, such data are sparse for fire suppression systems. Some suggested data points are presented in this chapter. Many of these data are point estimates that are given as judgment values; consequently they have no calculated or even estimated error bounds. In those cases, it is often the engineering judgment practice to assume a liberal error factor (error factor is the 95% upper bound failure rate divided by the average failure rate) of 10, or even 30 in extreme cases of skepticism over the point estimate. In statistics, an error factor of two or three is considered to be a sign of a very accurate, coherent data set that has the analyst's confidence. Larger error factors indicate a wider spread in the data, hence less confidence in the average value.

There has been some published work on fire system fault tree modeling, as discussed later. After presenting these component failure rate data, estimates from the literature about reasonable probability values for system "demand" failure rates (the probability of system failure given a fire of high enough temperature to melt one or more fusible elements) will be presented to serve as a comparison to any results readers might have after using these point estimate data on their own fire suppression systems. Table 3-1 presents the compilation of failure rate data for sprinkler system and other components.

One important issue raised in several literature sources is that of run-off water from the fire protection system. Many facilities have not been designed to accommodate the possibly high volume of water that could be delivered in the event of a large fire (a few hundred gallons per minute, or a cubic meter per minute). In an International Atomic Energy Agency (IAEA) safety guide [Fire Protection in Nuclear Power Plants, safety series 50-SG-D2, 1992], the issue of run-off and the issue of drains protected against the spread

Table 3-1. Sprinkler System Component Failure Rates

Component description	Failure rate	Error factor	Ref.
heat detector, FTO	0.09/d	assume 11	3-2
smoke detector, FTO	0.13/d	assume 7.7	3-2
flame detector, FTO	0.24/d	assume 4.2	3-2
dry pipe valve			
fail to open	0.007/d	assume 10	3-2
deluge or pre-action valve			
fail to open	0.006/d	assume 10	3-2
water shut-off valve to sprinkler heads or to hose stations is closed	0.012/d	unknown	3-2
pneumatic deluge valve			
fail to open	0.01/d	5	3-8
large internal leak	1.4E-06/h	2.7	3-8
small internal leak	2.4E-06/h	2	3-8
external leak	1.2E-06/h	2	3-8
heat detector			
fail to operate	1.2E-06/h	3.25	3-8
erratic output	5E-06/h	1.8	3-8
flame detector			
fail to operate	3.5E-06/h	1.5	3-8
erratic output	4E-07/h	3.5	3-8
contaminated	8.7E-07/h	2.75	3-8
smoke detector			
zero or max output	5.4E-07/h	2.4	3-8
erratic output	2.4E-07/h	1.75	3-8
contaminated	5.5E-07/h	2.2	3-8
rate-of-rise heat detector			
zero or max output	1.5E-07/h	4.8	3-8
erratic output	1.5E-07/h	4.8	3-8

Table 3-1. Sprinkler System Component Failure Rates (continued)

Component description	Failure rate	Error factor	Ref.
test, calibration and monitoring panel			
fail to operate given valid input signal	5.7E-06/h	2.3	3-8
spurious operation	1.6E-05/h	2	3-8
faulty indication	1.8E-05/h	1.9	3-8
fail to operate	3.6E-05/h	2.25	3-8
sprinkler steel piping			
external leak	3E-09/h-foot	3	3-9
pipe rupture (from material flaws)	1E-10/h-foot	3	3-9
sprinkler head			
glass bulb fails to open on demand	9E-03/d	unknown	3-10
pressure test leakage	3E-02/d	unknown	3-10
fusible element fails to open on demand	1E-06/d	unknown	3-11
normal pressure leak	1E-07/y	unknown	3-12
alarm motor & gong FTO	0.016/y	unknown	3-10
accelerator fails to operate	0.008/y	unknown	3-10
sprinkler stop valve fails closed	0.002/y	unknown	3-10
alarm valve fails closed	4E-05/y	unknown	3-10

Table 3-1. Sprinkler System Component Failure Rates (continued)

Component description	Failure rate	Error factor	Ref.
centrifugal fire pump, electric motor driven			
fails to start	3E-03/d	2	3-8
fails while running	3.6E-05/h	2	3-8
spurious trip	3.8E-05/h	4.5	3-8
external leakage	3.9E-05/h	4.7	3-8
low output	3.9E-05/h	4.7	3-8
centrifugal fire pump, diesel engine driven			
fails to start	2.3E-02/d	1.2	3-8
fails while running	3.1E-05/h	1.5	3-8
spurious trip	1E-05/h	1.8	3-8
external leakage	1.2E-05/h	1.7	3-8
low output	1.35E-06/h	4.5	3-8
steel piping, < 3 inch (76.2 mm) diameter			
leakage	1E-09/h-foot	30	3-9
rupture	1E-10/h-foot	30	3-9
plugging	1E-10/h-foot	30	3-9
steel piping, > 3 inch (76.2 mm) diameter			
leakage	1E-10/h-foot	30	3-9
rupture	1E-11/h-foot	30	3-9
plugging (3 to 8 in)	1E-11/h-foot	30	3-9

Most fire system piping in the US is schedule 40, so the nuclear piping is very similar to fire system piping. Also, plugging of piping greater than 8 inch (203 mm) diameter is not considered possible by scale or fouling. If large foreign objects (pieces of wood, metal debris, etc.) can enter the system, then this assumption must be re-evaluated.

(no failure rate data on copper or other piping materials beside steel were found in the literature search)

Component description	Failure rate	Error factor	Ref.
steel piping tees			
all modes	2E-05/h	113	3-9

Table 3-1. Sprinkler System Component Failure Rates (continued)

Component description	Failure rate	Error factor	Ref.
steel piping elbows			
all modes	1.9E-05/h	100	3-9
	(no data on cast iron fittings were found)		
steel tank (unpressurized)			
leakage	1E-07/h	3	3-9
rupture	2E-08/h	3	3-9
Aqueous film forming foam (AFFF) mechanical system			
proportioner FTO	2E-03/h	ub	3-13
foam maker FTO	2E-03/h	ub	3-13
foam maker plugged	2E-03/h	ub	3-13
(avg. repair times are about 2 hours each)			

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nomenclature:
/d stands for per fire demand
/h stands for per calendar hour; 8760 hours in a year
/y stand for per calendar year
FTO is an acronym for fail to operate
Notes:

Analysts are strongly urged to trace these data back to the source documents to verify that these data are appropriate for the usage application. If the usage is a different environment, then these data should be amended accordingly. Some of these data came from offshore oil platform fire systems, which may be a more harsh environment than typical land-based systems. See Moss and Strutt, "Data Sources for Reliability Design Analysis," Proceedings of the Institution of Mechanical Engineers, 207, E1, 1993, pages 13-19, for a discussion of multiplicative factors to adjust failure rates for different environments.

On leakage and rupture: the leakage failure rate is often thought to conservatively be a factor of ten higher than rupture, the 4% to 10% values are discussed by H. M. Thomas, "Piping and Pressure Vessel Failure Probability," Reliability Engineering, 2, 1981, pages 83-124.

Some failure rates are given as hourly values. For unavailabilities during a fire, use the formula: unavailability = (failure rate)(time interval between tests)/2. This formula is described in the PRA Procedures Guide, NUREG/CR-2300, January 1983, page 5-5.

Water supply system data (piping, valves, pumps) can be used to analyze an entire AFFF system. AFFF startup is assumed to be the demand failure rate of a deluge valve.

of fire are addressed. The gravity drains in a room must be protected against the spread of fire just like any other room penetration, especially protected against combustible liquids. Many fission plants will cap the drains to halt the spread of activated gaseous products and radioactive contamination; while this is an adequate solution for normal operations, it does not help to capture run-off fire water in an off-normal event.

The data values given in Table 3-1 are the best data found during a literature search on fire suppression system reliability. Many of these data were used directly in a recent fire hazards analysis of a DOE radioactive waste storage facility,[3-14] even though the data were gathered on offshore oil platform equipment. An additional literature search identified some already solved fault trees for general systems, and also some expert opinions that will provide a check of numerical values from a specific system's fault tree. These reported values from already solved fault trees can also help the analyst select a correct order of magnitude to assign to a fire protection system during conceptual design stages of a project.

There are several published estimates of fire system reliability and response to fire events. Alber et al.[3-15] gives two fire protection system values, 2E-03/demand for a supervised fire sprinkler system, and 5E-02/demand for an unsupervised sprinkler system. Both values refer to response in a design basis fire. No error bounds were given for these values. Miller[3-16] states that fire protection systems for crucial applications (such as a nuclear power plant control room) should have a reliability of perhaps 1E-04/demand, while for lesser consequence fires, the protective system reliability could be on the order of 1E-03/demand (such as a hazardous chemical plant). As the potential loss amount decreases, so does the required reliability for the fire protection system. At about $10,000 loss (in 1974 dollars) the reliability value estimated by Miller is 1E-02/demand.

Alvares and Hasegawa[3-17,3-18] performed fault tree analysis on dry pipe and then on wet pipe systems for fusion experiments at Lawrence Livermore National Laboratory (LLNL) and for some other fusion experiments. They found that the dry pipe system at LLNL had a 0.18/demand failure rate (or 82% reliability to operate in a fire situation) and the wet pipe system at a Sandia facility had a 0.02/demand failure rate (or 98% reliability). They commented that the preaction dry pipe system, with the design provisions to preclude inadvertent water leakage, also reduced the ability of the system to deliver water when needed. They gave an inadvertent leakage failure rate of 2E-05/year for the dry pipe system and a slightly lower value for the wet pipe system. Their results for the other DOE fusion experiment preaction fire suppression systems rated between 82 to 85% reliability, and wet pipe systems rated about 95%. These are reasonable estimates to use on fusion experiment facilities that use similar preaction systems. A bounding failure rate of 0.2/demand for preaction systems appears reasonable for conceptual studies.

Others have also provided guidance and opinions for sprinkler system reliability. Taking the overall data from Marryatt[3-3] gives ~5E-03/demand (99.46% reliable) for sprinkler system reliability. Finucane[3-19] suggests that a well maintained sprinkler system with a fire detection system will have a 1E-02/demand failure rate. Graber[3-20] suggests that a properly maintained system will have a 1E-02/demand failure rate. This is the same value that Moelling et al.[3-11] found in their analysis. US DOE experience[3-4] gives one wet pipe system failure (closed valve) for 91 fire events over 28 years of operations, this is roughly 0.011/demand. Some fire risk assessment work for US fission power plants has used 0.025/demand failure rate for wet pipe systems.[3-21] Siu and Apostolakis[3-22] used a detailed reliability analysis procedure to combine fission power plant and NFPA suppression system data, and found an average failure rate value of about 0.1/demand. They did point out that there could be an oversampling of failure events with a resulting overestimate of the failure rate since the smaller, quickly controlled fires are not uniformly reported to the NFPA. Under reporting of smaller fires has been a great concern for the fire protection industry. Considering this wide, international set of opinions that water-based fire protection systems operate in the range of 1E-02/demand, this value seems to be a reasonable one to adopt for conceptual analyses and to use as a comparison for individual fault tree analysis results. Overall, it seems that dry pipe systems perform less reliably than wet pipe systems. Issues with the dry pipe valve - leakage and possible freezing, corrosion and possible valve plugging, leakage into the riser accumulating a column of water that keeps the valve closed - seem to plague this type of system. While the individual sprinkler heads are usually quite reliable, the availability and adequacy of the water supply is a great concern for system functionality in a fire event. Another issue is the quality of the water, so that plugging from sediment, gravel, stones, or other debris does not stop flow in the fire system piping. Fire water supply systems must generally have two water sources. There is literature describing the reliability of water distribution systems. For example, Kansal et al.[3-23] give a small distribution system reliability of greater than 98%. In some older work by Damelin et al.,[3-24] even higher values of above 99.9% were calculated (but these did not incorporate effects of pipe breaks, etc.). While a municipal system might supply water at such high reliabilities, issues of city valve closures to isolate piping for maintenance or piping additions, power outages that de-energize the pumps, partially closed valves that degrade flow, and other problems might still prohibit adequate water from being supplied to the fire suppression system. Several authors[3-25, 3-26, 3-27] suggest some ways to keep water supplies adequate and on-line.

Sprinkler leakage/Water damage. An issue to consider in water damage events is the reliability of the sprinkler fusible elements. The English and Australian systems usually employ a glass bulb unit rather than the American "wood's metal" (Bi-Pb-Sn-Cd alloy) melting element. The frangible glass bulb heats up, the liquid (usually alcohol based) inside the bulb pressurizes and breaks the glass bulb, then the plug is pushed out by system pressure and the water flows from the sprinkler head. Marryatt[3-3] stated that the glass bulb was designed to prevent the 'cold flow' phenomenon of deterioration of the metallic fusible element. Cold flow refers to the head leaking or deterioration that allows the head to deliver water without melting the element. However, Nash and Young[3-10] stated that there are failure modes associated with the glass bulbs. The bulb can leak, so that the remaining alcohol or other fluid does not expand to break the glass. The glass might not totally break, leaving enough present to hold the sprinkler head shut. The head might leak or 'weep' water down onto the glass bulb and keep it cool enough to not break in the fire heat. Or, there can be corrosion or other fouling that plugs the orifice, so that water pressure does not open the head. Some of these failure mechanisms are unique to the glass bulb. When the proper precautions are taken (from NFPA 13[3-5]: replace heads that have been near those that actually fused in a fire, use high temperature fusible elements in areas that might have repeated high temperatures such as skylights, atriums, attics, etc.), the metallic fusible elements appear to be quite reliable. Some of the problems with the metallic fusible element are corrosive atmospheres can build up deposits on the element so that it does not fuse at the proper temperature, or these corrosives can chemically attack the metal so that it becomes hard and infusible. The glass bulb is less susceptible to chemical attack. Freezing (that does not breach the piping) can cause reduced link tension, which can slow down the sprinkler operation in a fire. Any sort of coating on the sprinkler element (paint, heavy dust, or other 'loading') can slow down its response time. Overall, while the glass bulb has some advantages over the metal element (no cold flow, low susceptibility to chemicals), the metal element also has some different advantages over the glass bulb (no alcohol leakage, no problem with clearing the head when melted). NFPA 13[3-5] does not specify which sort of element must be used in a sprinkler head. Therefore, the designer can choose the type of fusible element most suitable for the building and application.

From reference 3-28, we see that most sprinkler piping leakage is from the pipe and fittings, not the sprinkler heads, and we see that the water damage from leaking sprinklers is much less than the damage from fires. Maybee[3-4] discusses the water damage losses associated with fire protection systems. He points out that the fire suppression system water leaks were few in number and small in volume. The frequency of leakage events and the damage costs per event were both roughly half that of the other water system leaks sustained by Department of Energy buildings over the time period of his study. Maybee even pointed out that with the system water flow alarm sounding, the sprinklers were a "freezing alert" system as well as fire fighting system.

Another aspect of sprinkler leakage/water damage problem is an inadvertent operation of the system. The NFPA gives a 1E-07 per year chance of a head opening due to a random fault of a fusible element (see Table 3-1). Maybee[3-4] suggests that system damage leading to water leakage from wet pipe automatic sprinkler systems has a frequency of 1 fault per 800 system-years, or 1.25E-03/year (piping leaks, heads that have some fault (steam on the head, impact, freezing, etc.), and other causes). Schroeder and Eide[3-29] reviewed DOE and commercial nuclear power plant data, and they suggest that the inadvertent actuation of water-based systems is 5E-03/year, error factor of 5, for wet pipe systems, an inadvertent actuation frequency of 3E-02/year, error factor of 5, for dry pipe systems, and an inadvertent actuation frequency of 1E-04/year, error factor of 10 for preaction systems. These numbers seem reasonable. The values are low enough to be unlikely, which agrees with Maybee's data,[3-4] but the frequency is still high enough that an event could conceivably occur in the lifetime of a given building (perhaps 40 or 50 years). The order of magnitude value 1E-03/year is a reasonable bound for sprinkler leakage event planning in conceptual design analyses.

3.3 Non Water-based Fire Protection Systems

The previous section treated most of the fire protection systems that are in use in industry and research. This section deals with gas suppression (carbon dioxide, nitrogen, and halogenated agents) and dry chemical suppression systems (the Super K and Purple K potassium bicarbonate compounds). These systems were briefly described in Chapter 2. The effectiveness of these systems can be assumed as 100%; that is, when these systems are deployed as room flooding, the agents are excellent for extinguishing the combustion process. The only problems would be with unisolated ventilation, leaks in the flooded room, or some other reason that the gas or chemical would not be contained in the room (or could not reach the seat of the fire). Such faults that allow dilution or restrict the agent from the seat of the flames are very difficult to recognize for facilities that have not yet been constructed. For preliminary safety work, verification that the room is designed to be sealed is adequate to support the assumption that the agent is 100% effective.

Less is written on the reliability of these systems than for water-based systems. Some estimates of the reliability of these systems do exist, and these are given in Table 3-2. The systems described in this table are total flooding systems, but for scoping studies, these values should apply to local application systems as well. One excellent paper[3-30] gives a fault tree analysis of a Halon protection system for a computer room. This Halon system had demand failure rates of 0.05 (error factor 1.6) for electrical fires, 0.13 (error factor 1.8) for a paper trash fire, and 0.08 (error factor 1.6) for an exposure fire burning into the computer room from outside the room. These values agree reasonably well with the general value given in Table 3-2. When the hourly Halon system failure rate given in Table 3-2 is converted to an unavailability on demand, it does not agree with these other estimates. OREDA authors[3-8] did report that this hourly failure rate value was from a small sample over a short time, and therefore it might not be very accurate. A pessimistic Halon system failure on demand of 0.2 was used in one fire risk assessment, but it was argued that a more proper value was 5.4E-02 to 6.0E-02 per system demand.[3-31] The values given in Table 3-2 and in reference 3-30 are reasonable compared to this cited range.

The dry chemical system has varying reported values. The difference is almost two orders of magnitude. One reason for this discrepancy would be that historically, dry chemical systems have had reliability problems, such as powder compaction during storage and pipework plugging upon discharge, that degraded their performance (see IAEA safety series 50-SG-D2, 1992). If the dry chemical suppression system is well designed and appears free of such difficulties, then the lower failure rate value is probably acceptable to use until a detailed analysis is possible.

Table 3-2. Non Water-based Fire Suppression System Component Failure Rates

Component description	Failure rate	Error factor	Ref.
Halon distribution nozzle fail to function (functional test 1/year)	2.7E-07/h	1.5	3-8
Halon, total system FTO	0.06/d	unknown	3-2
Halon, total system FTO (functional test, 1/year)	8.7E-05/h	1.4	3-8
CO_2, total system FTO	0.04/d	unknown	3-2
CO_2, total system FTO (functional test, 4/year)	8E-06/h	2.6	3-8
Dry chemical system FTO (purple K, assume one functional test/year)	1.4E-06/h	3.9	3-32
Dry chemical system FTO (purple K, assume one functional test/year)	8.7E-05/h	unknown	3-14

/h stands for per calendar hour, /d stands for per fire challenge or demand to operate
Some failure rates are given as hourly values. For unavailabilities during a fire, use the formula: unavailability = (failure rate)(time interval between tests)/2. This formula is described in the PRA Procedures Guide, NUREG/CR-2300, January 1983, page 5-5.

Inadvertent actuation is also a concern for these suppression systems. As we have seen in Chapter 2, there have been spurious Halon dumps and testing-fault Halon dumps at DOE facilities. Also, at the Idaho National Engineering Laboratory, the Advanced Test Reactor had a spurious actuation of a carbon dioxide suppression system in the reactor control room. The reactor operators had to evacuate the reactor control room for life safety reasons, while the reactor was operating. The fire suppression system was converted to Halon, based on the engineering analysis following that July 6, 1974 event. The change was made because Halon 1301 does not pose the asphyxiation hazard of CO_2. Schroeder and Eide[3-29] suggested a value of 5E-03/year (error factor of 5) for both Halon and carbon dioxide spurious actuation rates, based on industrial and nuclear power plant experiences.

Dry chemical systems probably have the same rates, since they use many of the same fire detectors for actuation and usually have the same test intervals as Halon and carbon dioxide suppression systems. A similar assumption between dry chemical and carbon dioxide systems was made in the analysis of reference 3-14.

3.4 Fire Protection Alarm Systems

The detector and control panel failure rates were given in Table 3-1, for a variety of detector types. Another important issue with detectors is radiation damage that could affect detector performance. Capaul et al.[3-33] have determined acceptable radiation exposure limits for several kinds of fire detectors (smoke, flame, heat, and temperature) based on power plant experience with fire detectors. The ionization smoke detector examined began to reach the upper nuisance alarm threshold after 4 roentgens/hour for about 1000 hours. This detector was the one most susceptible to radiation damage. Some other experience guides about the use of fire detectors are given by Murray and O'Neill.[3-34] They discuss the propensity of ultraviolet detectors to pick up signals from intense light (i.e., light from arc welding) reflected from shiny coatings on nearby equipment and other possible problems with detectors. The placement of detectors is also important for timely notification of fire events. Placing detectors where they are most sensitive to smoke and heat is an important design issue. For example, placing the detectors near ventilation ducts that will allow fresh air over the detector, which will negate detector effectiveness for room fires. Placing the detectors so that there are obstructions (piping runs, many cable trays, ventilation ducts) to rising heat or smoke will also retard detector response.

Power systems for detectors can be treated using any of the standard data collections for electrical power units. Moss and Strutt (cited in Table 3-1) give several sources of failure rate data for electrical equipment. The IAEA TECDOC 478[3-9] is an example of these data sources. When modeling failure rates for the electrical power support systems, the analyst is cautioned to recall that power is supervised (continuously monitored and off-normal events are annunciated) for fire alarm systems.

The alarms can have several functions - these can actuate many different pieces of equipment. Elevators may be sent to fire service positions. Ventilation fans may be shut down or may be set to smoke control. Fire dampers in some ventilation systems may be closed. Electromechanical fire door closers may be actuated. Smoke control roof ventilation panels may be opened. Usually, audible (and visual) alarms will sound, and perhaps a central station alarm will be sent. Power systems may be shifted over to emergency power supplies and emergency ac power sources may be aligned. Bukowski and O'Laughlin describe all these features.[3-35] Obviously, having unwanted, or false, alarms can be quite disruptive to facility operations if the alarms control all of these functions. Even the time lost to investigate an unwanted alarm can be very valuable, but it is a good operations practice to take a fire alarm seriously until it is proven to be spurious.

3.5 Reliability of Fire Resistive Construction

The reliability of fire barriers, fire walls and other fire resistive construction items is apparently not often discussed in the literature. Perhaps this is due to the problem of people using door stops [among US fire protection engineers, a wooden door stop is referred to as a " 'four or eight' hour fusible link", and a metal door stop is a "ten hour fusible link"] and other objects to block open fire doors, or the problem of retrofit construction activities (such as stringing new computer hookups or instrument wiring, for example) defeating a fire wall by improper sealing of new penetrations. These issues are under the purview of building managers, to assure that people are not defeating safety systems through improper operations or add-on construction activities. Another issue is that the fire barrier time rating is based on a given fire intensity and duration. If the room fire loading (weight of combustibles per unit floor area, i.e., kg/m^2) exceeds the amount dictated by the time rating of the barrier, then the barrier is expected to fail prematurely and allow heat, smoke, and fire spread. Barrier failure can be from penetration failure that allows smoke and heat spread, or it can fail by differential thermal expansion (warping) that leads to cracking and then possible collapse. The penetrations are not always listed as having the same fire resistance time rating as the wall, since combustibles are not usually found in close proximity to the penetrations they are not challenged like the larger expanse of the wall itself. Also, if a small penetration does fail and allow fire spread, then fire suppression forces can react to control a small fire on the far side of the wall.

Since fire walls with high time ratings (such as 3 or 4 hours) for fire resistance are very expensive, and are often very thick to withstand the temperature gradient effects. Usually, fire walls of lesser time ratings are used in many buildings. NFPA 221 describes fire walls.[3-36]

Some suggested values for fire barrier reliability are given below in Table 3-3. These values are given with the consideration that the fire is not greater than the intensity that the barriers were rated to withstand. Another work cited in the literature discusses fire barrier reliability, assuming a normal distribution where the mean value is the rated time for enduring a fire of a given intensity. The actual intensity of a fire will then give a value of reliability for the barrier.[3-37] That method can be used when the barrier dimensions, rating, and fire intensity are known. Analysts are urged to obtain that report as comparison to the values reported here, when the level of design detail permits such comparisons.

3.6 Manual Fire Suppression

In many buildings, employees are the first people to respond to fires. Perhaps they are in the immediate vicinity of a fire, or perhaps they are performing some operation that actually causes the fire, such as welding operations. In either case, often personnel will try to extinguish a fire in its early growth stages. This practice can be of benefit since the

Table 3-3. Reliability of Fire Resistive Construction

Component description	Failure rate	Error factor	Ref.
Fire door, fails to contain fire	0.074/d	3?	3-2
Fire curtain, fails to contain fire	0.074/d	3?	3-2
Fire damper, fails to operate	0.003/d	3?	3-2
Fire wall, fails to contain fire	0.001/d	3?	3-2
Fire penetration seal, fails to contain fire	0.001/d	3?	3-2

/d stands for per fire challenge or demand to operate in a fire situation
The small error factors were assumed, since the source estimates were based on nuclear power plant operating experiences.

automatic suppression systems will not be actuated, causing less collateral damage from the fire suppressant, less cost in recharging the suppression system, less environment damage (if the suppressant is potentially harmful), and less fire damage since the fire is extinguished before it can grow or spread very far. When personnel are directly at the scene, the probability of extinguishing the fire is very high unless the fire is very vigorous.

Since a fire can grow at a very fast pace (a fire started with ample combustibles and air flow present can double in size in perhaps 30 seconds), manual fire fighting can have two phases. The first phase is usage of one or more portable fire extinguishers, or perhaps using a hose from a hose station, by personnel responding to the fire scene (either workers, fire watch, or fire brigade). The second phase is fire fighting operations by professionally-trained fire fighters. When personnel are not in proximity to the fire when it is initiated, fire detection systems are relied upon. These systems are usually sensitive enough to send an alarm in the first minute of a fire, certainly in the first two minutes of a fire unless they are faulty. If they are faulty, the fire would continue to grow until other detectors alarm or people notice the smoke smell from the ventilation system. Plant personnel responding to an alarm should be able to arrive on the scene of the fire in perhaps 3 to 5 minutes, depending on the size of the facility. Usually, the probability of success for people on the scene to extinguish a growing fire is given as 20% in the first two minutes after they find the fire.[3-38,3-39] Since a wet-pipe sprinkler system would actuate in time frames of 2 to 5 minutes (depending on the ceiling height, the fire intensity, ventilation, and other factors), manual efforts might often be secondary to automatic sprinklers. If there are no sprinklers, and personnel are unable to extinguish the fire in a few minutes, then the personnel generally choose to evacuate and let the fire be dealt with by professionally-trained fire fighters who have personal protective equipment (self contained breathing apparatus, etc.). As these fire fighters take over (from an alarm, they can generally arrive within perhaps 10 minutes unless the facility is remotely sited), the situation changes. They are equipped to stay in the fire area longer, direct large hose streams at the base of the flames, and the probability of extinguishing the fire increases (the probability of extinguishment approaches 1 at 90 minutes from fire detection). The LaSalle nuclear power plant fire risk analysis[3-40] is a good example of manual fire suppression analysis.

3.7 Explosion Suppression Systems

This section addresses reliability of systems designed to mitigate the effects of explosions. These systems include blow-out panels, pressure rate-of-rise detection systems, and fast acting gas suppression.

Blow out panels. These panels have been used in various industries that deal with explosive gases, dusts, liquids, or solids. The panels have various names, such as flaps, pop-out panels, rupture panels, hinged panels, hinged louvers, rupture discs, tethered panels, explosion vents, etc. The design idea is that these panels will open at a preset pressure so that explosion pressure in a room is relieved without distressing the building walls or sensitive equipment in the room, whichever is most susceptible to overpressure. There is much literature devoted to calculating the maximum overpressure that can be realized and appropriately sizing the vent area.

There are two causes for concern with these panels. The first is that they open at the required pressure; that is, they open on demand. If they open too late, then the room overpressurizes to some extent, and this could lead to radioactive materials being vented out of room wall penetrations (piping, cable, drain, and other penetrations) instead of being contained or properly routed to a cleanup system. The second concern is the panels leaking room air. Each of these concerns is discussed below.

Panel failure rates for opening on demand have not been found in the literature. One paper by Rajagopalan and Camacho[3-41] discussed the use of these panels to mitigate potential steam pipe breaks in Canadian fission reactors. They did not have reliability data on the panels, but gave the panels between 1E-03 to 1E-04/demand failure rate (higher for large steam line breaks, lower for loss of coolant accidents). They indicated that the panels in use all passed rupture tests, so there is high confidence in these failure rates. Many panels of this type are reusable, so they can be tested. We shall assume the high value of

1E-03/demand as the upper bound failure rate for these panels, since this is conservative for the present time. Overall, the Canadian panels are roughly 161 cm by 54 cm, and are composed of two stainless steel thin sheets sandwiching a polymeric sealing membrane. An important design consideration from the literature is that the panels do not reclose when they reach the end of their travel (and rebound). Many hinged panels have hooks or clasps to catch and hold the panels open after the panel moves. This design precaution was not mentioned in the paper, so we assume it was not a problem for the particular panel design to be used in Canada.

In an effort to verify the upper bound 1E-03/demand panel failure rate, the literature on rupture panels was reviewed both electronically and manually. No other failure rates were found in that search. Review of literature on the design of panels shows that design guidance is to provide the exact panel size needed to relieve the pressure; there is <u>no</u> suggested design margin built in (such as an extra 20% area or et cetera) to account for faulty panels.[3-42,3-43] This strict design to match the panel area with the calculated explosion vent area without any added design conservatism suggests that the panels historically have been reliable, and panel failure rates in the 1E-03 to 1E-04 per demand range seem more reasonable. Other literature citations showed that the panels are (qualitatively) reputed to work well.[3-44,3-45,3-46] The panels are said to typically respond within 50 milliseconds[3-44] of the beginning of an overpressure condition - the panels are specified to have low mass per unit area (an upper limit of 12.2 kg/m^2 in reference 3-43) to decrease inertia so the time to open is kept short. The panels also generally open at lower pressures while in service than the pressures used in static panel tests,[3-46] presumably due to the impact pressure loading of deflagrations. The static test pressure variance was on the order of ±10%, but the 53 deflagration tests performed on panels in Canada[3-46] showed that the panels uniformly opened at somewhat lower pressures than the design opening pressure, which is safety conservative for this equipment. The panels under test were designed to open at 3.4 kPa (0.5 psig) differential pressure. The NFPA[3-43] gives guidance that the panels must be able to withstand the effects of wind pressure loading (if exterior panels), or the effects of wind suction pressure when the panels are mounted inside a stack. Lees[3-47] cautions that explosion pressures can only be vented via short ducts, or else the room pressure will not be dissipated and will still damage equipment.

Panel leakage failure rates are assumed to be similar to gasket leakage failure rates, since gaskets or similar types of seals will be used on these panels. A flange gasket leakage failure rate is 1E-07/hour, and rupture (large leakage) is 1E-09/hour, both with an error factor of 10.[3-48] For the present time, these failure rates will be applied to panel small leakage and large leakage. If this possible failure becomes a larger concern, then this assumption should be reviewed.

A concern for vent panel operation is that it might be protecting a room that normally has an elevated temperature. Fission power plant containment building air temperatures have been seen to vary between 27 °C (80 °F) to 87 °C (190 °F), with averages of about 38 °C (100 °F).[3-49] The panels must be chosen for their durability in slightly elevated temperatures, since normal ventilation in these rooms might be minimized for reasons of economy, or for radiation protection.

Pressure-rate-of-rise detectors. These detectors are similar to those discussed above. These units are described by Bryan.[3-50] They are usually a diaphragm detector, and they are sensitive so that they can respond quickly to an explosion event. Some applications use ultraviolet flame detectors. These detectors have rigorous standards to meet, so that inadvertent actuations are avoided. The detector upper bound failure rates are assumed to be on the order of 0.01/demand, since no values were found in the literature. If more accurate values are needed, perhaps manufacturers can provide information. No literature describing spurious actuations was found. Perhaps these events are very rare.

Explosion suppression system. The first item to examine is the explosive valve. These valves operate in milliseconds. Explosive valves are also sometimes used in fission reactors for flooding the reactor core. There is some published failure rate information on these valves in nuclear applications, and the application is similar enough to apply these failure rates to fire protection. For a valve failing to operate on demand, a failure rate of 3E-03/demand, with an error factor of 10 can be used. For a valve plugging, a failure rate of 4E-05/demand with an error factor of 3 can be used (assuming monthly test/inspection).[3-9]

The Halon 1301 system for explosion suppression is very similar to Halon flooding systems, except that this system is under higher pressure, perhaps 6 MPa (870 psig).[3-45] Failure rate values for the components can be used from Table 3-2. Overall, this system is highly dependent upon the sensors for accurate signals, so that normal or abnormal (but not explosive) pressure excursions do not cause nuisance activations. The sensors must be of very high quality, and must tolerate shock, vibration, and temperature fluctuations without suffering from instrument drift. The upper bound value of 0.01/demand for these sensors seems reasonable. The sensors probably dominate the system reliability. With a three-month maintenance interval,[3-51] this demand probability corresponds to a 1E-05/hour failure rate. If the failure rate is lower than 1E-05/hour, then the demand probability is reduced accordingly.

Explosion suppression, with proper sensors, and combined with explosion vents, can decrease the probability of a damaging explosion by at least a factor of 10,[3-52] or a factor of 25 or more.[3-53] While these estimates were based on grain dust explosions, the order of magnitude should apply equally well to gas explosions. Bryan[3-50] stated that these systems have worked well in industry, and have functioned reliably. The failure on demand is probably less than 1E-02/demand. For the present time, we shall assume that these systems operate at an upper bound of 1E-02/demand failure rate. The inadvertent actuation of such a system should be on the same order of magnitude as a preaction water-based system, since they both rely on sensors to signal a valve to open. Until further information is found, then a value of 1E-04/year, with a wide error factor of 10, will be assumed for an explosion protection system.

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4. FIRE INITIATING EVENTS

4.1 Introduction

Fires in experimental fusion facilities are usually rare, but as discussed in Chapter 2, small fires have occurred in most of the major fusion experiments. Since there will be changes in the technology for future experiments - notably the move to superconducting magnets that require much smaller electrical energy requirements, but also higher electrical demands for plasma heating - using only past fusion experiment facility experiences may not give an accurate representation of the frequency of fire events. While operating experience data is useful in helping to identify possible fire scenarios, fire frequency data from several sources will be examined to give general guidance on the frequencies of fires in fusion experiments. These sources are mainly from power plants and research laboratories. The research laboratory is considered here since particle accelerators have been approached in this way for fire safety,[4-1] and the standards for ITER housekeeping should be very high (much higher than typical industrial plants), like they are in research laboratories.

There are many different types of fires. Electrical fires might indeed be the most frequent for a fusion experiment plant, including cable fires, electrical panel fires, transformer fires, or motor insulation fires. There could also be combustible lubricant fires (as in frictional overheat causing lubricating grease or oil to catch fire) in mechanical equipment. There could be combustible products or vapors in waste streams, ignited by spontaneous heating or by static electricity. Employees might not handle heat sources with proper care. As an extremely remote possibility, there could potentially be arson.

For fire hazards analysis, it is important to know the amount of combustible materials present, and their heat output. This information helps to determine the worst heat that can be generated. Information on typical materials can be found in reports, such as by Lee.[4-2] Fire modeling also requires knowledge of fire science. Tuve[4-3] gives basic, introductory information on fire science. Often, tests of fire behavior are performed to learn about fire responses in actual building conditions.

In fire testing of cable insulation fires at a decommissioned power plant,[4-4] several information items important to fire modeling were observed. First, the fire temperature was in the range of 1000 °C for a 4 MW fire of 350 kg of polyvinyl chloride (PVC) cable insulation. This temperature is about the same as fire temperatures in most residential building fires, which are usually slightly below the melting point of copper (1082 °C).[4-5] Another finding was that the temperature of the hot fire gases dropped significantly when the fire plume mixed with the room temperature air adjacent to the fire. Smoke obscured visibility very badly within 15 minutes of fire initiation, so that even very experienced plant personnel would have had to feel their way along plant corridors. Other tests showed that flame spread along cables was up to values of 6 m/minute for fiber reinforced nylon copolymer (FRNC) cable insulation.

4.2 Initiating Event Frequencies

Literature surveys for fire initiating event (IE) frequencies were performed to develop a basis for generic frequencies. An overall frequency was given as 3E-02/year for a power plant, with an error factor of 3.[4-6] In general, the values found were in the 1E-02 to 1E-03/year range for various rooms or fire areas in nuclear power plants. Some representative data are:[4-7,4-8]

auxiliary building	5E-02/year	error factor 2.7
switchgear room	5E-03/year	
pump room	3E-02/year	error factor 5
control room	5E-03/year	error factor 3
electrical panel fire	2E-04/panel-year	
battery bank room	3E-03/year	
cable spreading room	7E-03/year	error factor 3.3
diesel generator room	2E-02/year	
reactor building	2E-02/year	
turbine building	2E-02/year	error factor 4.4

These estimates are based on nuclear power plant sizes and amounts of equipment, so some scaling may be necessary to apply to fusion occupancies. The important thing to note here is that almost all of the fire frequencies reside within the 1E-02 to 1E-04/year frequency category, the unlikely events category. In general, perhaps using a 1E-02/year frequency for a room or fire area with several ignition sources and using 1E-03/year for a room or fire area with few ignition sources is appropriate for scoping work. Regarding laboratory fire frequencies, a chemical plant risk assessment quoted a fire frequency of 1E-04/year, for a chemical storage facility which is similar to chemical storage in research labs.[4-9] Another laboratory fire IE frequency, for a plutonium handling lab, was given as 1E-03/year.[4-10] This frequency is significant since the facility is a glovebox facility. Data analysis of tritium operations (without any fires or explosions) yielded a value of 3E-03/glovebox-year for fires or explosions at the Tritium Systems Test Assembly.[4-11] This value can be considered as an upper bound, since the point estimate will be lower now that they have accumulated several dozen more glovebox-years of additional operating experience without any fires or explosions. Some fire frequencies per 1,500 m^2 building in European industries have been calculated as:[4-12]

chemical and allied industries	0.12/year-building
metal manufacture	0.14/year-building
electrical industry	0.04/year-building
instrument industry	0.03/year-building
paper industry	0.07/year-building

Perhaps the electrical and instrument industries are closest in function to research lab settings when one considers cleanliness needed for the processes and the inherent hazards (solvents, combustible nature of the materials, etc.) of the processes. These two frequencies compare reasonably well to the nuclear power plant frequencies given above, but are much larger than those 1E-03 and 1E-04 per year frequencies cited above for laboratories.

Equipment entering a facility can also be a cause of fire. Trucks that enter the facility to deliver various supplies or equipment could potentially experience engine or other fires (hot exhaust line, etc.). Fork lift trucks for moving equipment inside the plant might also catch fire. A vehicle fire frequency is on the order of perhaps 1E-03/year (well maintained vehicles with clean engines should have lower fire frequencies). An electric-driven forklift fire frequency is on the order of 3E-05/year.[4-13] Diesel driven forklifts are perhaps an order of magnitude higher frequency than electric forklifts. Propane driven forklifts are considered to be on the order of diesel driven forklifts unless other, more definite information is found. Vehicle fires can be greatly reduced by keeping the engine clean and inspecting the fueling systems for leaks. The building fire suppression systems must be sized to deal with such a large transient combustible presence if the trucks stay parked inside the facility for any length of time (i.e., for hours at a time, or overnight). Forklift battery charging stations or other refueling/parking stations must be adequately protected. Another factor to consider is preventing a diesel engine from ingesting any combustible gases. In one case some years ago, a diesel engine that accidentally ingested combustible hydrocarbon gases oversped and destroyed itself by igniting incoming gas. The diesel started a large fire and two men were killed.[4-14]

Some other assumptions made along with these fire frequencies are that "hot" short circuits probably occur in a conservatively large value of 10% of fires in control wiring, meaning that only one in ten fires will cause spurious control signals to be sent to equipment. This assumption is made since most electrical systems are well grounded against short circuiting. Another assumption is that suppression efforts in control wiring can only limit damage; some control functions will be lost in the few minutes before the suppression system can control or extinguish a fire. These lost or spurious control functions are usually taken to be those in cabling situated at the base of the fire, and more control cabling directly in the hot gas plume rising up from the fire can be lost as well.

Some other general rules are that most electrical equipment fails in 'loss of function' failure modes; such equipment rarely causes a fire. As a coarse rule, using 1% of the failure rate for loss of function should give a fire frequency for that piece of equipment. Consider the failure rate for fire or explosion for 63 kV and larger circuit breakers as 5.9E-04/year.[4-15] Comparing this to the overall failure rate of 0.054/year, we see a factor of almost 100 difference. The author has also found that this 1% factor correlates reasonably well with fire frequencies in nuclear power plant rooms, considering pump motors, fan motors, compressors, and other motive equipment. Using 1% in the absence of any known fire or explosion failure mode data is a reasonable approximation.

Fire modeling, that is, tracking the progression of a fire by the heat and smoke and damage it produces, has been performed for cables[4-16,4-17] and sophisticated computer codes exist for this task.[4-18] As a part of a risk assessment, such a code can be indispensable, but as part of a fire hazards analysis, the code is limited since it can treat only so many finite combinations of ignition scenarios and combustible material sources.

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