NUCLEAR CRITICALITY SAFETY GUIDE
FOR FIRE PROTECTION PROFESSIONALS
IN DOE NUCLEAR FACILITIES

Prepared for the U.S. Department of Energy
Defense Programs
Environmental Management

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1.0 SCOPE OF DOCUMENT

This guide is intended to provide information for use by fire protection professionals in the application of reasonable methods of fire protection in those facilities where there is a potential for nuclear criticality. This guide may also be used by nuclear criticality specialists, risk analysts, and other safety professionals with interest in selecting alternate means of fire protection to balance the risks associated with facility fire and with nuclear criticality.

It is intended that this guide be applied to facilities which process, handle, or store fissile materials. Such facilities and operations may include, for example, reactor fuel operations, uranium enrichment operations, plutonium or uranium solvent extraction operations, Pu or HE recovery operations, and other similar operations. Fissile isotopes included in the scope of this guide are limited to ^{233}U, ^{235}U, and ^{239}Pu as addressed by ANSI/ANS 8.1.

Operations involving intentional creation of chain reactions such as critical experiments or reactor operations are considered to be beyond the scope of this guide. However, other parts of these facilities are covered and some of the concepts included in this guide may be applicable, directly or indirectly, to such operations. Fissionable isotopes, such as neptunium, americium, curium, and other plutonium isotopes, are also beyond the scope of this guide.

2.0 INTRODUCTION

Misunderstandings and miscommunications have often led to situations in which fire protection systems and activities have been viewed as reducing criticality safety. Similarly, the need to prevent criticality incidents has, in some cases, had an adverse impact on fire safety. This Guide will review and analyze historical data to show that:

1. Fire is a significant threat to DOE facilities

2. Fire protection systems, in particular sprinkler systems and standpipe systems, are needed to minimize the fire exposure.

3. The need to limit sprinkler protection usually results from failure to achieve criticality safety by preferred means.

4. Lack of sprinkler and standpipe systems results in larger fires requiring manual firefighting activities that discharge considerably more water in a more damaging form than sprinklers.

3.0 DEFINITIONS

critical - fulfilling the condition that a medium capable of sustaining a nuclear fission chain reaction has an effective multiplication factor, k_{eff}, equal to unity. (DOE STD-XXXX-93, Draft B, Nuclear Criticality Safety Guide for DOE Nonreactor Nuclear Facilities)

criticality - the condition of being critical. (DOE STD-XXXX-93, Draft B. Nuclear Criticality Safety Guide for DOE Nonreactor Nuclear Facilities)

criticality accident - The release of energy as the result of accidentally producing a self-sustaining or divergent neutron chain reaction. (ANSI/ANS 8.1)

double-contingency principle - a precept that requires designs to incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a critically accident is possible. Protection is provided by either:

1. the control of two independent process parameters (which is the preferred approach, if practical) or

2. a system of multiple (at least two) controls on a single parameter.

In all cases, a single failure will not result in the potential for a criticality accident.

effective multiplication factor (k_{eff}) - The ratio of the total number of neutrons produced during a time interval (excluding neutrons produced by sources whose strengths are not a function of fission rate) to the total number of neutrons lost by absorption and leakage during the same interval. (ANSI/ANS 8.1)

fissile isotope - a nuclide capable of undergoing fission by interaction with slow neutrons.

fissionable isotope - any nuclide capable of undergoing fission by any process.

fission - the division of a heavy nucleus into two or more parts with masses of equal order of magnitude, usually accompanied by emission of neutrons, gamma radiations and, rarely, small charged nuclear fragments. (DOE STD-XXXX-93, Draft B, Nuclear Criticality Safety Guide for DOE Nonreactor Nuclear Facilities)

risk - the quantitative or qualitative expression of possible loss that considers both the probability the hazard will cause harm and the consequences of that event. (DOE STD-XXXX-93. Draft B. Nuclear Criticality Safety Guide for DOE Nonreactor Nuclear Facilities)

4.0 FIRE AND CRITICALITY RISKS

Striving to achieve an optimum level of overall safety, the safety professional in any safety discipline must reach a balance among what may appear, at times, to be conflicting safety goals. The safety professional must consider the relative risk of various hazards and the alternatives in arriving at a reasonably safe solution.

According to H. C. Paxton in Critical Control in Operations will Fissile Materials, "Safety is an acceptable balance of risk against benefit; it is meaningless as a concept isolated from other goals." In his text, Nuclear Criticality Safety: Theory and Practice, Ronald Knief further elaborates, "Nuclear safety in fuel cycle facilities encompasses both criticality safety and radiation protection activities. General industrial safety and fire protection are also important adjuncts to overall facility safety. Each safety discipline tends to focus initially on the plant operations themselves, but then must interact effectively with the other safety activities."

The goal of this guide is to provide information to allow effective interaction between the fire protection and nuclear criticality safety disciplines. With effective interaction, an acceptable balance of the fire and nuclear critically risks may be achieved. To provide some perspective on the relative risks of nuclear criticality and fires, the following sections discuss some of the hazards and risks associated with these perils.

4.1 Discussion of Nuclear Criticality

4.1.1 Definition and description of criticality peril

In order to effectively assess the relative safety risks of nuclear criticality and fire, it is important that the fire protection professional have a sound, basic understanding of nuclear criticality. The fire protection professional must clearly understand what a nuclear criticality is and what it is not.

A nuclear fission takes place when a heavy nucleus captures a neutron, becomes unstable, and splits or fissions into two or more smaller nuclei. The fission results in multiple "daughter" isotopes, release of energy in the form of gamma radiation, and the release of high energy neutrons. The average number of neutrons emitted per fission is energy dependent. Fissions occur naturally and somewhat regularly in many fissionable materials.

The key difference between naturally occurring, non-critical fissions and critical fission incidents is the rate of neutron/nucleus interactions. In non-critical situations, the rate of leakage of neutrons is sufficiently high to preclude interaction of neutrons and fissile nuclei in a self-sustaining chain reaction. In a critical situation, the number of neutron/nucleus fission interactions is of sufficient numbers to sustain the fission process.

Thermal fission of ^{235}U, for example, produces an average of 2.43 neutrons per fission. If more than 1.43 neutrons are lost from the system due to neutron leakage, or non-fission interactions with other nuclei, less than one neutron will be available to sustain the fission chain reaction. In such a situation, the system will remain sub-critical.

For fission to take place in fissile material, not only must there be a sufficient number of neutrons available for interaction with fissile nuclei, the neutrons must be at low enough energy or speed to interact with the nuclei. The neutrons must be slowed or thermalized to a low enough energy to interact with the fissile nuclei to result in fission.

A material which slows neutrons is known as a neutron moderator. Hydrogen is a very effective neutron moderator. Water, with its high hydrogen content, is a good moderator of neutrons.

Leakage of neutrons from a fissile material helps to prevent the continuation of the fission process within the material. Reflection of neutrons leaking from fissile materials back into the system will promote the fission process. Water molecules, which also "bounce" neutrons, tend to reflect escaping neutrons back into the system.

One index of criticality is given by the **neutron multiplication factor, k**. The neutron multiplication factor is defined as the ratio of the number of neutrons in one generation (i.e., period of time) to the number of neutrons in the just-previous generation.

$$k = \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in the just-previous generation}}$$

Since not all neutrons produced are available to interact within the system due to leakage of neutrons from the system, it is useful to have a measure of the neutrons which are available for fission in the system. This measure is known as the **effective neutron multiplication factor, k_{eff}**. The effective neutron multiplication factor is defined as the ratio of the neutron production rate to the neutron loss rate.

$$k_{eff} = \frac{\textit{neutron production rate}}{\textit{neutron loss rate}}$$

When the neutron production rate and the loss rate exactly balance, k_{eff} equals one, the fission is self-sustaining, and the system is critical. If neutron production rate is less than the neutron loss rate in the previous generation, k_{eff} is less than one, and the system is subcritical. If the neutron production rate is greater than the leakage rate, k_{eff} is greater than one, and the system is supercritical.

$k_{eff} < 1$ subcritical

$k_{eff} = 1$ critical

$k_{eff} > 1$ supercritical

A nuclear criticality generally initiates as a rapid, short duration event. Typically, there is a "blue flash", a rapid release of neutrons and gamma rays, and release of fission products. Following a sharp spike of energy release during the initial excursion, accidental nuclear criticalities tend to be self-limiting and immediately shutdown the reaction. In aqueous solutions this is due to localized heating of the liquid which reduces the density of the moderator and the production of hydrogen and oxygen bubbles which produce voids which further reduces the moderator density. In some cases, a transient condition may be created, in which subsequent criticality events continue periodically over a period of time. The subsequent criticalities, following the initial spike, tend to be lesser magnitude than the initial spike.

In order for there to be a danger of a criticality to occur, there must be a fissile material present. For the purposes of this guide, this includes specific isotopes of uranium and plutonium. (^{233}U, ^{235}U, ^{239}Pu) There must be sufficient mass of of the fissile material present. In addition, the material must be in density sufficient for its volume to optimize the leakage of neutrons. Material shape is important in determining neutron leakage rate. Spherical shapes optimize the volume to surface areas thus minimizing neutron leakage. As mentioned previously, a water moderator and reflector of neutrons enhances the fission process. Factors influencing the potential for criticality are illustrated in Figure No. 1.

FACTORS IN WATER MODERATED CRITICALITY

- ISOTOPE AND ENRICHMENT
- MASS PRESENT
- DENSITY OF ISOTOPE
- SHAPE, VOLUME OF ISOTOPE
- CONCENTRATION OF ISOTOPE
- SPACING OF MATERIAL
- NEUTRON ABSORBERS, POISONS
- MODERATOR PRESENCE
- MODERATOR DENSITY

Figure 1

In his report, Criticality Control in Operations with Fissile Material, Paxton illustrates this concept:

> "...Let us illustrate the various influences on criticality by limiting our attention to two common materials, enriched uranium and water. To start, we consider a critical sphere of U(93) metal at normal density. The diameter of this sphere is about 6.9 in., corresponding to a volume of 2.8 liters and a total mass of about 52 kg. If the same quantity of material is formed into a slab or an elongated cylinder, distances through which neutrons must scatter to reach a surface are decreased (the surface-to-volume ratio increases), so the chance that a neutron may escape from the material is increased. In other words, leakage is increased at the expense of fission and capture, so that the new shapes are subcritical. Returning to the sphere, if the size is maintained but the density of U(93) is decreased, neutrons pass through less matter on their way to the surface, the chance of leakage is increased, and the new sphere is subcritical. Likewise, a decrease in ^{235}U enrichment at constant size and density decreases the chance of fission relative to leakage and capture, so that the sphere is again subcritical.

Now, several different influences of water on our U(93) sphere will become apparent. If the sphere is immersed in water, some neutrons that would otherwise escape from the surface are scattered back into the fissile material, leakage is reduced, and the sphere is supercritical. Actually, the critical diameter of the uranium sphere drops to 5.3 in. (corresponding to 1.3 liters or ~ 24.5 kg of uranium). Of course, this neutron-return effect is by no means limited to water. Any material that surrounds fissile sphere will act similarly as a neutron "reflector."..."

It is important that the fire protection professional understand that, although the accidental criticality includes a rapid release of energy, it is not a nuclear explosion in the same sense as a nuclear weapon detonation. None of the criticality accidents which have occurred in process operations has resulted in any significant property damage and few resulted in any significant contamination. The limited consequences of criticality accidents is further discussed in Section 4.1.4 of this guide.

4.1.2 History - Examples of Past Criticality Accidents

According to Statton and Smith[1], since the beginning of the nuclear industry, there have been only eight reported criticality events in process operations in the free world. Others have occurred in reactors and critical assemblies. A discussion of the process operations criticality incidents is included in this guide to provide background on those events to provide insight into the causes and consequences of some criticality incidents.

These eight accidents are summarized in Table No. 1 and are further discussed in Appendix.

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[1] Stratton, W.R., and Smith, D.R., A Review of Criticality Accidents, DOE/NCT-04, Lawrence Livermore National Laboratory, March, 1989.

CRITICALITY ACCIDENTS IN PROCESS OPERATIONS							
DATE	LOCATION	MATERIAL	GEOMETRY	CAUSE	FISSIONS	DAMAGE	MAXIMUM PERSON DOSE OR EXPOSURE
June 16,1958	Y-12 Plant Oak Ridge, TN	2.5 kg^{235}U nitrate	55-gal. drum	Water added to uranyl nitrate solution	1 x 10^{18}	none	461 rem
December 30, 1958	LASL Los Alamos, NM	3.27 kg Pu in two-phase system	250 gal. cylindrical tank	stirring change geometry	1.5 x 10^{17}	none	12,000 rem
October 16, 1959	ICPP Idaho	34.5 kg ^{235}U in 800 l. water	5000 gal. cylindrical tank	solution inadvertently siphoned	4 x 10^{19}	none	50 R
January 25, 1961	ICPP Idaho	8 kg ^{235}U in 40 l. water	2 ft diameter cylinder	solution moved to unsafe geometry	6 x 10^{17}	none	< 100 mr
April 7, 1962	Recuplex Plant Hanford, WA	1.55 kg Pu	18 inch cylinder	solution transfer to large tank	8 x 10^{17}	none	110 rem
July 24, 1964	United Nuclear Corp. Wough River Junction, RI	2.64 kg ^{235}U	18 inch cylinder	solution poured into unsafe tank	1.3 x 10^{17}	none	10,000 R
August 24, 1970	BNFL Pu Plant Windscale, England	2.15 kg Pu	cylinder	Pu in trapped solvent	1 x 10^{15}	none	2 rads
October 17, 1978	ICPP Idaho	10.5 Kg U(89) 9.3 kg ^{235}U	cylindrical scrub column	^{235}U stripped from solvent	3 x 10^{18}	none	none

TABLE NO. 1

4.1.3 Frequency of Criticality Accidents

In the fifty year history of the nuclear industry in the free world there have been only eight criticality accidents reported in processing operations. (See Figure No. 2) During the period from June, 1958 through July, 1964, the average frequency of criticality accidents was approximately one accident every 12 months. Since 1964, there have been only two reported criticality accidents and there have been none since 1978. While there is little statistical significance due to the small number of incidents, there has been an average frequency of criticality accidents of 0.16 criticality accidents per year (one accident every 6.25 years) for all fissile material processing operations over the fifty year history.

4.1.4 Consequences

The consequences of a criticality are a function of several factors. Some of those factors include whether the operation is hands-on or in a shielded facility, the magnitude of the excursion, the position of personnel at the time of the excursion, and emergency action which are taken in response to the incident.

There are some common characteristics of the consequences of the criticality accidents which have occurred. None of the incidents have resulted in any significant damage to process equipment or facilities. At most, the damage has been limited to clean-up of solutions in facilities designed for decontamination.

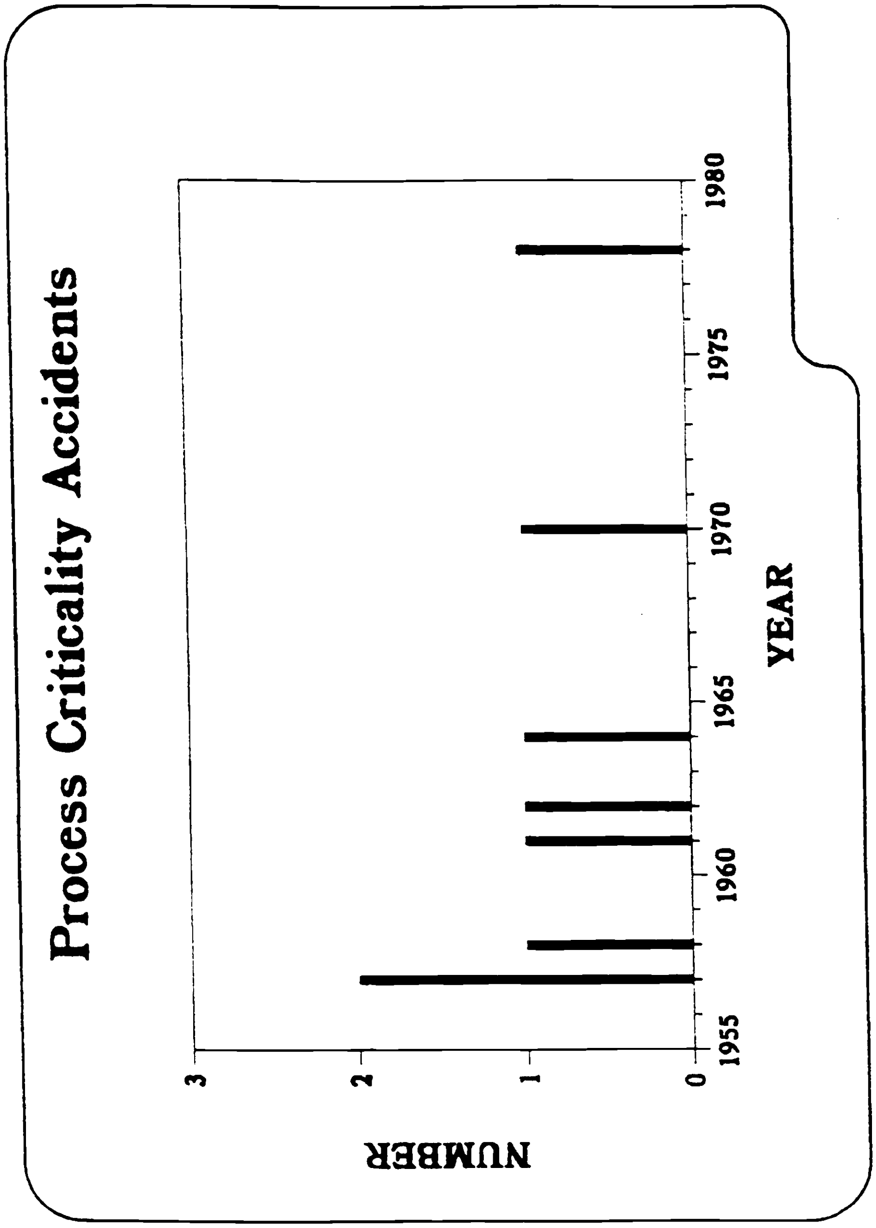

Process Criticality Accidents
NUMBER
0
1
2
3
YEAR
1955
1960
1965
1970
1975
1980

Figure No. 2

A result of criticalities is the release of fission products and fission product radioactivity. In each of the cases the property damage consequences of fission product release has been negligible. There has been no significant contamination of facilities due to fission product release and environmental releases have been minimal. The magnitude of nuclear contamination due to dispersal and loss of confinement of special nuclear material has far exceeded the contamination due to fission products of the criticality.

Any accidental loss of human life is tragic. Every reasonable means must be taken to avoid accidental loss of life. Considering the number of fissile processes which have been conducted over the past fifty years, the fact that only two lives have been lost due to accidental nuclear criticalities in process operations is a testament to the care exercised in protecting nuclear facilities against accidents.

Beyond the two fatalities, the health and safety impact of criticality accidents on personnel has been very low. Due to distance, shielding, or the duration of the exposure, the non-lethal radiation dose received by other personnel present at the time of criticality accidents have had no lasting effect on their health.

4.2 Discussion of Fire Peril

4.2.1 Discussion of Industrial/Commercial Fire Problem

Fire has a major impact on the U. S. economy and the safety of citizens. According to National Fire Protection Association statistics, there were 4,730 non-fire fighter deaths and 28,700 non-fire fighter injuries due to fires in the U.S. in 1992. Property damage due to fires in the U. S. in 1992 were estimated to amount to $8.295 billion. Over 20% of the property damage by fires in the U. S. in 1992 was sustained in industrial, commercial, and special use properties. In 1992, ten catastrophic multi-death fires in non-residential structures (including industrial, commercial, and assembly occupancies) claimed 52 lives. DOE-owned, contractor-operated facilities include a wide variety of types of occupancies. For the most part, occupancies which would be covered by this guide could be generally classified as industrial/commercial properties.

Fortunately, DOE has enjoyed a much more favorable fire history than other industrial/commercial groupings both in frequency and severity due to the "improved risk" level of fire protection provided at most DOE facilities. However, the DOE is not exempt from experiencing significant fires.

Some examples follow.

4.2.2 DOE History - Examples of Some Past Events

Rocky Flats Fire, Bldg. No. 776-777
May 11, 1969

The most notable event, from a fire damage, potential personnel hazard, and potential nuclear criticality hazard, was the Rocky Flats fire of 1969. This fire is believed to have initiated in a lidless can containing plutonium in a glovebox and quickly spread to other combustible materials in the glovebox. The fire department received alarms from heat detectors in the facility at 2:27 pm. Responding promptly, the fire department encountered dense smoke and congested conditions which hampered their ability to locate the fire and effectively direct fire fighting efforts. Because of a concern for potential nuclear criticalities, the use of water for fire-fighting had been prohibited except as a last resort. For this reason, automatic sprinkler protection had not been installed in this particular facility, although the new plutonium production facility, which was under construction at the time of the fire, was being provided with automatic sprinklers. Initial fire attack was made with carbon dioxide extinguishers but they were ineffective.

Fueled by plutonium and 600 tons of combustible shielding, and fanned by the uninterrupted ventilation system, the fire continued, unabated. Plastic glovebox windows burned out. The smoke plugged some filters which allowed the normal airflow to reverse direction. Plutonium oxide was released into the room.

Despite precautions against the use of water to fight fires in plutonium facilities due to the concern for potential nuclear criticality, the fire chief, weighing the relative risks, made the command decision to use water less than ten minutes after the fire alarm was received. The fire department used fire water hose streams throughout the duration of the fire fighting effort. The fire, which spread extensively through the glovebox lines, was brought under control by 6:40 pm, over four hours after the initial alarm.

Despite the extensive use of water delivered by fire hoses, and substantial quantities of fissile plutonium, no nuclear criticalities occurred. There were no lost-time injuries from the fire due to the fire-fighting efforts. Since the fire occurred on a Sunday, there were few people in the facility. Damage to the building and equipment was extensive. The fire was reported to have consumed nearly six tons of combustible material in addition to the combustion of plutonium. In addition to smoke and heat damage, the facility was heavily contaminated by plutonium. Plutonium was also tracked out of the building by fire fighters. There was detectable ground contamination but no evidence of plutonium contamination beyond the plant boundaries. The initial facility restoration cost was estimated to be $45 million. Of that cost, about $26 million is attributed to fire damage, clean-up, and Pu recovery.

Paducah Gaseous Diffusion Plant Fires
November 11, 1956 and December 13, 1962

Sprinkler protection was not provided in the gaseous diffusion buildings due to the lack of combustible contents and, what was believed a the time to be, non-combustible construction. On November 11, 1956, an intense, but localized, fire was initiated by a compressor gas seal leak. This fire subsequently ignited the combustible, built-up roofing system and spread throughout the building. As a result, the entire 67,000 sq. ft. of the roof was destroyed. The total loss was $2,100,000: the fourth largest loss from all causes which had been suffered by the Atomic Energy Commission. One fire-fighter was seriously injured.

As a result of this major fire, full automatic sprinkler protection was provided for all gaseous diffusion buildings at three sites. Sprinklers were effective in limiting the loss due to an explosion which later occurred at the Paducah plant.

On December 13, 1962, an explosion occurred in a process cell at the Paducah plant. The automatic sprinkler systems, which are not designed to protect against explosions, responded to the energy released by the explosion and the hot steam which was generated, by the opening of 2341 sprinkler heads. The sprinklers controlled the fire such that only a single hose line was necessary to effect extinguishment. The explosion caused damage totaling $2,900,000. It has been estimated that the loss would have been on the order of $160,000,000 if sprinklers had not been provided to prevent the propagation of an ensuing fire.

Metallic Plutonium Fire

In his book, Living with Radiation: Problems of a Nuclear Age for the Layman, Vol. 2, Fire Service Problems, F. C. Brannigan, a former AEC fire protection engineer, described a "Small Metallic Plutonium Fire Leads to Major Property Damage Loss." A small amount of pyrophoric plutonium was reported to have spontaneously ignited in a dry box. A watchman discovered the fire which involved the plutonium, combustible parts of the dry box, and rubber gloves. Fire fighting was delayed because of the plutonium which was known to be processed in the facility. Carbon dioxide extinguishers were used without effect. Despite the uncertainty of the potential nuclear criticality effects, water spray was eventually applied to the fire and the fire was controlled.

Brannigan concluded that the significance of the incident was two-fold:

> "The dry box fire discussed above had two serious consequences: (1) It allowed escape and dissemination of considerable plutonium contamination throughout the immediate area; (2) it also burned through the combustible CWS filter at the dry box permitting flames and some unburned combustible gases to pass through ventilating ductwork to the large main bank of filters which were of combustible type."

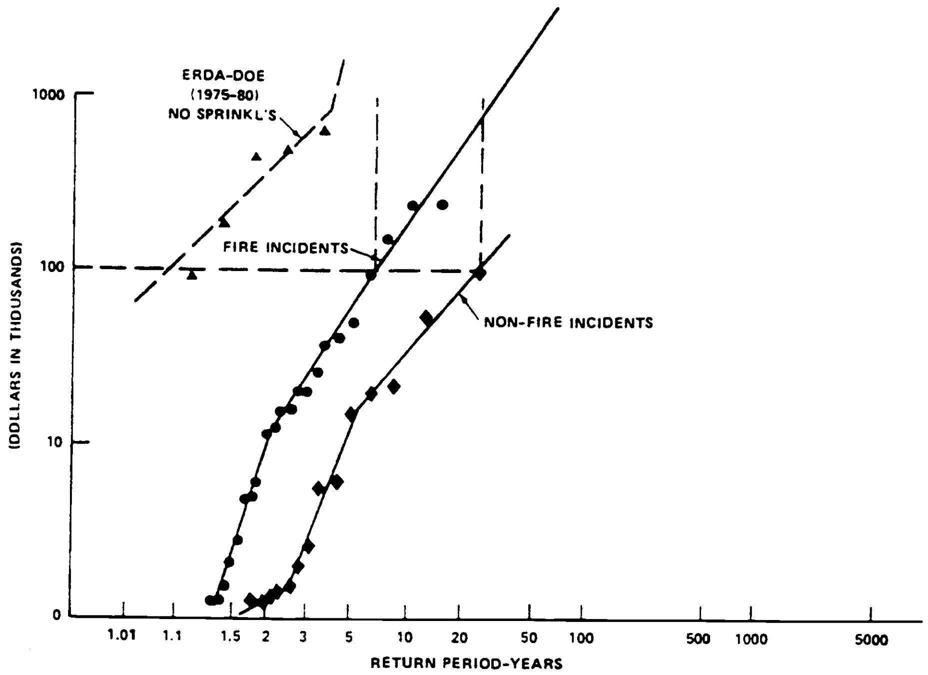
He also commented on the relative risks associated with such installations and the appropriate balance of precautions and protection which should be provided:

> "It is quite probable the provisions of one or two automatic sprinklers within the dry box involved in the fire would have permitted earlier fire detection, much earlier establishment of fire control, and limited fire and contamination damage to immediate surroundings. The provision of automatic sprinklers admittedly may introduce new risk of contamination spread in water runoff and, in the case of fissionable materials, and danger of inducing an accidental criticality incident. The incident provides tangible evidence to support the belief that failure to provide automatic fire detection and control measure for radiological risks will in general result in a level of personal injury and property damage risks exceed that which would exist if automatic fire detection and control devices were used."

4.2.3 Frequency - Statistical data

Overall, the Department of Energy has enjoyed a favorable fire protection history. However, fires, including large loss fires, have not been infrequent events on DOE facilities. Former DOE Fire Protection Manager, Walter W. Maybee, collected, analyzed, and published information on fire frequency and severity in DOE/EP-0052, Automatic Sprinkler System Performance and Reliability in United States Department of Energy Facilities, 1952-1980. In his data base, Maybee included 633 fire protection-related incidents in DOE and predessor agency facilities. The data base did not include fires which resulted in "no loss" or property damage losses less than $1,000, which are not required to be reported to DOE headquarters.

Maybee reported that, on average, the DOE experiences twenty-six fires which exceed $1,000 in property in its facilities each year. He also analyzed the frequency and severity of DOE facility fires using extreme value projects and other statistical tools to project the recurrence period of fire losses. Graphical representation of Maybee's projections are included in this guide as Figures No. 3.



EXTREME VALUE PROJECTIONS

Note: Fire incidents include all property damage losses resulting from fires. Non-fire incidents are those property damage loss resulting from perils other than fire.

Figure No. 3

Based on Maybee's extreme value projections, it is revealed that the projected frequency of fires exceeding $100,000 value in DOE facilities is about 1.4×10^{-1} per year or about once every seven years. For fire losses exceeding $1 million, the projected frequency rate is about 3.3×10^{-2} per year or about once every 30 years. Significant fires are not only credible events in DOE facilities, their recurrence rates are relatively high in risk assessment terms for moderate and high consequence events.

In addition to resulting in property damage, fires in DOE facilities result in personal injuries and deaths. In the same document, Maybee reports that there have been 20 fire deaths reported in DOE and predecessor organizations during the period from 1943 to 1980. Thus, on average, there are 0.54 fire deaths per year. Historically, fire deaths occur slightly more frequently than one death every two years at DOE facilities

4.2.4 Consequences

From the above discussions, the consequences of fires, both historical and potential, should be clear. Fires endanger personnel, result in property damage and impaired operations, result in uncontrolled contamination, and, without quick and properly designed suppression, may result in accidental criticalities.

Personnel injuries are discussed in Section 3.2.3. of this guide. The frequency and magnitude of property damage losses due to fire are also discussed in previous sections of this guide. Figure No. 4 displays a summary of information on the cumulative impact of fires during the period 1952 through 1980. These subjects need not be further elaborated upon in this section.

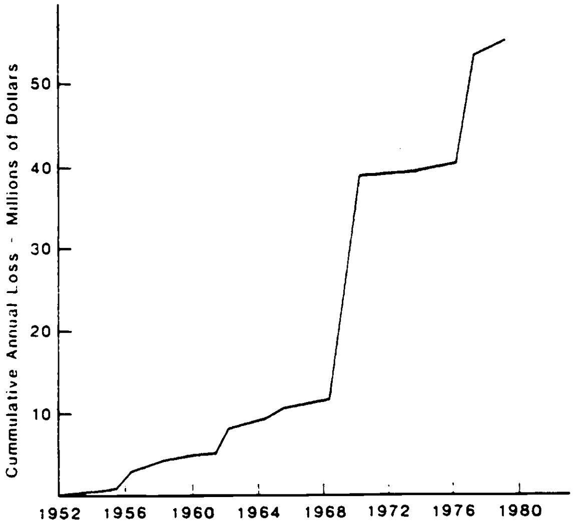


Figure No. 4
Cumulative Fire Loss - 1952-1980

Fires may also constitute a design basis accident. Fires are likely to be a cause of spread of nuclear contamination. Fires can result in the breach of confinement enclosures due to burn-through or failure of gloves, viewing panels, or other primary barriers. Fires can also seriously impact the performance of active ventilation systems design to preclude release of radioactive materials.

Smoke and large soot particles associated with the burning of hydrocarbons may quickly clog filter media. Such clogging of filters, and subsequent over-pressurization of the filters, can and has resulted in breaching of filters and release of radioactive contamination.

Ventilation systems designed for confinement control can handle air-flows and pressure transients under normal conditions and limited range of abnormal conditions. Hot, expanding gases resulting from energy released during fires, as well as the production of large quantities of smoke and volatiles from the fire, concurrent with impairment of the ventilation system due to fire products, can result in pressurization of the confined volume and unanticipated and uncontrolled flow reversals.

Air-borne contamination is difficult to control. The ability to control contamination can be significantly impacted by a fire and the potential to effect control seriously diminished if early fire intervention is not provided.

Fires may also result in accidental criticalities. Some examples of fire consequences which may lead to criticality accidents are discussed in Section 6.0 of this guide.

4.3. Discussion of Fire Suppression Systems

4.3.1 DOE History

The history of performance of automatic sprinkler systems in government-owned nuclear facilities is well documented. The previously cited Maybee report documents the performance of sprinklers, which are the principle fire protection system used to protect nuclear facilities since the founding of the Atomic Energy Commission in 1947. The data collected and analyzed in that report include nearly 600 fire protection-related incidents and over 100 fires. The performance of automatic sprinkler systems, as documented by Maybee, an summarized blow, has been outstanding.

4.3.2 Statistical Data on Sprinkler Systems

4.3.2.1 Successful Operation

The Maybee report confirms that automatic sprinkler systems have been extremely successful in controlling fire losses in government nuclear facilities. The data demonstrate that automatic sprinkler systems are more than 98% effective in controlling or extinguishing fires. Contrary to some popularly held beliefs fostered by and misrepresented by the Motion picture and television industries, most fires do not result in the operation of large numbers of sprinkler heads and do not result in massive releases of water. About one-third of all fires occurring in sprinklered, government nuclear facilities were completely extinguished by the operation of a single sprinkler head. Greater than 92% of all fires were controlled or extinguished by the operation of six or fewer sprinkler heads.

Furthermore, there has been no loss of life due to fire in sprinklered, government nuclear facilities.

The magnitude of property damage losses from fire in a sprinklered building is about one-fifth of the losses in unsprinklered buildings. This fact is particularly significant in light of the fact that it is the facilities which have a high loss potential which are provided with automatic sprinkler protection.

4.3.2.2 System Failures

The Maybee study reported only two cases where an installed sprinkler system did not control or extinguish fires. One involved a dust collector for which the sprinkler system control valve had been shut due to cold weather and in which pyrophoric dusts spontaneously ignited. The second involved a massive failure of a large electrical transformer which broke a 3-inch sprinkler main which prevented the systems from controlling the ensuing fire.

The fact that automatic sprinkler systems are not prone to frequent inadvertent actuations has been supported by studies by the National Fire Protection Association, the Center for Fire Safety Studies at Worcester Polytechnic Institute, the Electric Power Research Institute, and the U.S. Department of Energy.

The previously cited Maybee report also addresses reliability and presents a high degree of statistical significance. The investigation included over 4200 sprinkler systems. In terms of operating history, it included 30,000 system-years or 4.7 million sprinkler head-years of experience. The data analysis included both the effectiveness of sprinkler operations to control fires and the reliability of sprinkler systems to remain functional without inadvertent operation.

Among other topics, the Maybee report addressed "failure" or leakage of closed-head sprinklers. Established by the vast data base, it was concluded that the probability of a sprinkler head failing due to leakage from all causes is 2.2×10^{-6} per year. In risk assessment terms this represents an extremely low frequency event.

To put this in perspective, many risk analysts consider events with a probability of occurrence of 1×10^{-6} per year or less as "incredible" and need not be addressed in quantitative risk assessments. On this basis, the likelihood of an individual sprinkler head leaking is considered to be barely credible.

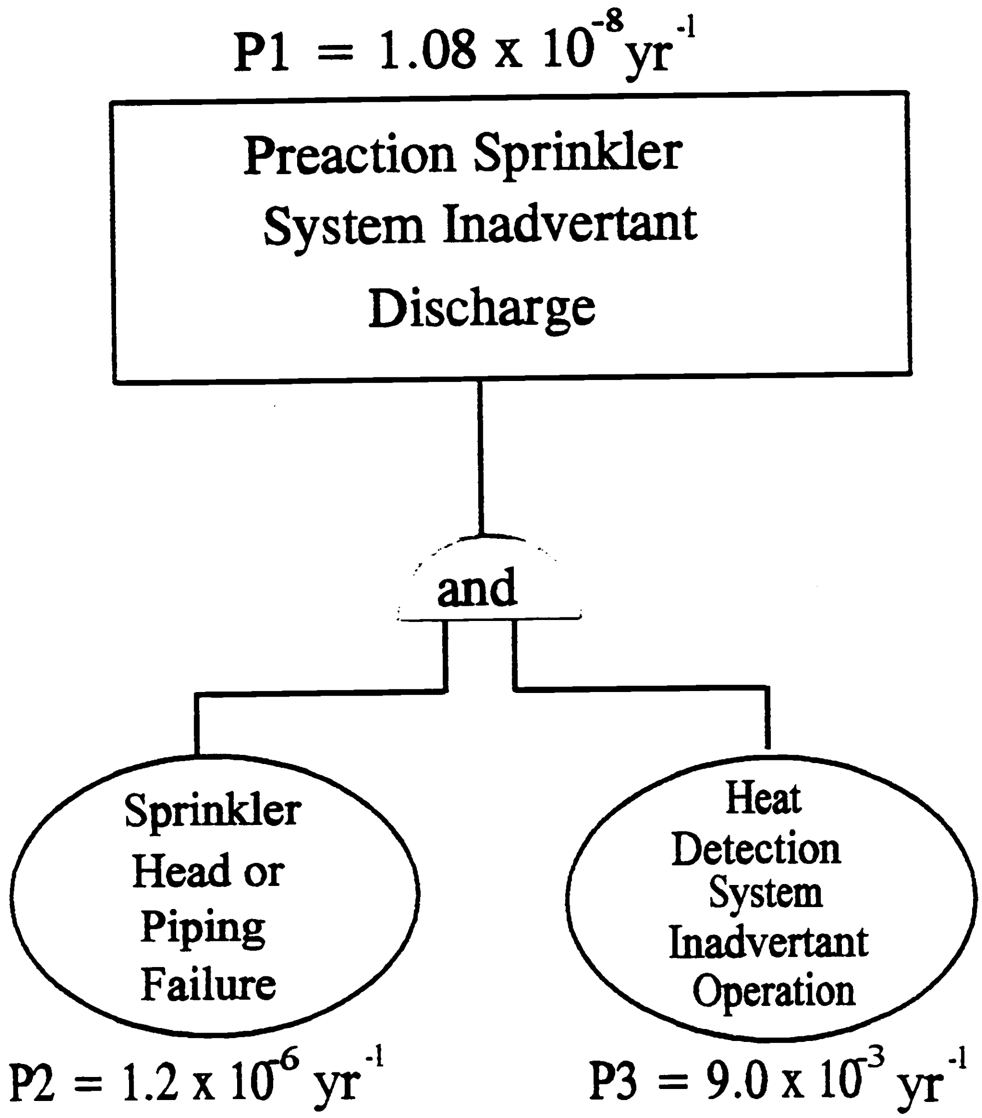
A similar study was conducted by Mr. Edward A. Sawyer at the Center for Fire Safety Studies at the Worcester Polytechnic Institute. Mr. Sawyer's

Master of Science Thesis was Failure Analysis of Inadvertent Operations of Fire Protection Systems Including Design Recommendations. Sawyer's study included 556 inadvertent actuations of fire protection systems as reported by the U.S. DOE, the Institute for Nuclear Power Operators, the U.S. Nuclear Regulatory Commission, and through personal communications with fire protection professionals in the nuclear power industry. Sawyer's investigation included all causal affects including adverse environmental conditions. Based on his study, Sawyer concluded that the probability of inadvertent opening of a fusible element of a sprinkler head is 1.2×10^{-6} per year. This reported probability is the same order of magnitude as cited in the DOE report.

A third major study was conducted on behalf of the Electric Power Research Institute. This report was published in 1985 as EPRI NP-4144, Turbine Generator Fire Protection by Sprinkler Systems. Among its many conclusions regarding sprinkler system reliability, the EPRI report concluded that the probability of fusible link operated sprinkler head failing in the open position is 9.8×10^{-6} per year. Independently, this study found the probability of sprinkler head leakage to be of the same order of magnitude as the other two studies.

Inadvertent operation of closed-head sprinkler systems do occur, but the frequency of such occurrences can be predicted on a finite frequency. Data support the fact that the probability of a single, closed-head failing and discharging water in the absence of a fire is so low as to be practically incredible.

While the statistical reliability of a wet-pipe sprinkler system is exceptionally high, the reliability of a sprinkler system to preclude inadvertent discharge of water can be further enhanced by the provision of a pre-action sprinkler system. Pre-action systems are designed primarily to protect properties where there is a serious danger of water damage in the unusual event that water may be inadvertently be released due to sprinkler head or piping failures. In the pre-action system, closed-head sprinklers are used and a control valve holds back water from the sprinkler piping. It requires the independent operation of a sprinkler head or pipe failure **-AND-** actuation of a separate fire detection system to open the control valve before water will be discharged. The resultant combined probability, i.e., the probability of a pre-action sprinkler system inadvertently discharging water, is 1.08×10^{-8} per year. (See Figure No. 5.)



$$P1 = P2 \times P3$$

Probability of Preaction Sprinkler System Inadvertant Discharge

FIGURE NO. 5

The EPRI study presents similar data for a pre-action system. That report states that the combined probability of inadvertent pre-action valve actuation due to spurious operation of a heat detector and a fusible sprinkler head failing in the open position is less than 10^{-8} per year. Both the Sawyer and EPRI studies conclude that the generic probability of a pre-action system failing in such a manner as to result in discharge of water under non-fire conditions is far below the accepted criteria for credibility. The drawback, however, of a pre-action system is that sprinklers, detectors, and control valves must all function properly to control a fire, reducing the probability of success. Therefore pre-action should be used only where water damage is an overwhelming concern.

4.3.2.3 Non-fire Water System Failures

The Maybee study also addressed "water damage" incidents due to sprinkler systems as compared to damage due to failures of other, non-fire protection, water systems. The study evaluated sprinkler system water damage incidents and non-fire protection water system damage incidents reported in the DOE during the period 1970-1980. The data show that, the number of non-fire protection water damage incidents exceeds the number of sprinkler system water damage incidents by a factor greater than 1.5. Furthermore, the average water damage loss reported for non-fire water system incidents was more than four times that of sprinkler system water damage incident. Only two of the sprinkler water damage losses exceeded $10,000, whereas six non-fire system losses exceeded $10,000. Not only do non-fire water system leakage incidents occur at a higher frequency than fire protection leakage incidents, the magnitude of the impact of non-fire water system leakage incidents is much greater.

There may be a number of factors which result in the much higher reliability for sprinkler systems. Among them are:

1. Automatic sprinkler systems are almost universally designed as engineered systems. Nearly all sprinkler systems are designed by cognizant professional engineers or certified technicians in accordance with stringent NFPA standards. Many other plumbing systems are not designed and installed under the same level of engineering and design attention.

2. Sprinkler system components are required to be listed or approved by nationally recognized testing laboratories. This help to assure high quality and reliability of components. For example, UL 199 Standard for Automatic Sprinkler Heads requires that sprinkler head specimen be tested for not only for performance in response to fires but also for reliability to prevent inadvertent operation. Among the supplemental tests required by UL 199 are 875 psi hydrostatic tests, 30-day cycle water hammer tests, 1500% overload strength test for the heat responsive element, cold soldering tests, and operating temperature tests. Few, if any, standard plumbing fixtures are so rigorously tested and qualified.

3. The NFPA has rigorous standards for inspection and test of sprinkler systems. New installations are inspected and tested at a minimum of 200 psi for two hours with no allowable leakage. All sprinkler systems are required to be inspected and functionally tested at least quarterly. Non-fire protection water systems are not tested and inspected as vigorously as fire protection systems.

4. Sprinkler systems are usually provided with continuous supervision. If an abnormal condition occurs, such as the flow of water, an immediate signal is sent to a constantly attended location and emergency personnel dispatch to take appropriate action, reducing the potential for severe damage.

4.3.3 Consequences Of Fire Suppression System Actuations

The consequences of water discharge on the potential for nuclear criticality are much the same regardless of whether the water is from fire protection or non-fire protection sources. As cited in the previous section of this guide, the quantity of accidental discharge from non-fire water systems is generally much greater than that for fire water systems. Two factors control the quantity of water discharge in the unlikely event of an inadvertent actuation of a sprinkler head:

1. For closed-head sprinkler systems, when one sprinkler head actuates, all other sprinkler heads do not actuate simultaneously. While this fact is obvious to the fire protection professional, it is not obvious, and may need to be explained, to persons not familiar with sprinkler systems. Thanks to Hollywood and television, it is a very widely held belief that in the event of a fire or other actuating influence, all sprinkler heads discharge simultaneously, as in the case

of an open head deluge system. This contributes to the unfounded fear of "flooding" with huge quantities of water from closed-head sprinkler systems.

2. Sprinkler heads actually limit the rate of flow from sprinkler systems. The carefully calibrated orifice of sprinkler heads provides at throttle on water flow. While fire protection professionals are cognizant of this factor in designing systems for minimum discharge rates, this factor needs to be expressed in terms of **maximum** discharge rates with respect to flooding concerns.

   For example: A single, 1/2-inch nominal sprinkler head may be connected to a water supply system with a static pressure of 140 psi and with a fire pump rated at 2000 gallons per minute and a churn pressure of 100 psi. Someone not familiar with fire protection systems may be concerned that the sprinkler head will discharge up to 2000 gpm. This is obviously not the case. Due to the throttling by the orifice, a sprinkler head on such a system could never discharge at a rate greater than about 66 gpm.

The potential consequences water discharge on nuclear criticality are likely to be the same regardless of whether the water comes from non-fire protection systems or from fire protection systems and regardless of whether a fire protection system water discharge is due to accidental release of water or due to discharge in response to an actual fire. Factors which influence the effects of water discharge on fissile materials in amounts and forms for which water may affect the neutron multiplication factor include the depth of water accumulation, the film thickness of water which may be achieved, the size of water droplets, and the density of water mist.

For open floor areas, it is very unlikely that water discharged from fire protection systems would accumulate to a depth which would result in an accidental criticality in combination with the release of fissile solutions. The estimated critical, infinite slab thickness of homogeneous, water-moderated solutions of ^{235}U is greater than 4 cm. (over 1-1/2 inches). The estimated critical, infinite slab thickness of homogeneous, water-moderated solutions of Pu is greater than 5 cm. (over 2 inches).

Thicknesses less than these will not result in criticalities. These allowable slab thicknesses **assume** a homogeneous solution of the fissile material throughout the liquid. It is unlikely, even assuming release of the fissile material into the water, that homogeneity would be achieved. Fire protection water would likely reduce the concentration of fissile nitrate solutions, thus lowering the density of the fissile material. The result would be that an even thicker slab thickness would be required prior to any accidental criticality occurring.

The above applies to fissile solutions. The same, and greater magnitudes of water reflector thickness apply to fissile metals. For example, empirical data[2] indicate a sphere of up to 5.79 kg of metallic Plutonium with 5.2 wt% ^{240}Pu can be immersed in greater than 30 cm. (11.8 in.) of water without exceeding critical limits.

As a non-viscous liquid, water does not naturally accumulate to depths approaching these limits. In the absence of a source of confinement, water will not collect to depths which would adversely impact the potential for a nuclear criticality. Where artificial water confinement systems are provided, the depth, area, and volume can be adjusted and optimized to accommodate criticality and other limits. Where sumps, drains, or other localized water accumulation points exist where both water and fissile materials may commingle, the size of the sump may be adjusted to not exceed critical dimensions or a neutron poison such as borosilicate glass rachig ring may be provided to prevent criticality.

For a criticality to occur in a layer of water, it would be necessary that the water be at a depth greater than the infinite slab thickness, that the fissile material in an amount and density be released into the water, and that the fissile material be homogeneously distributed in solution. This combination of events (water discharge plus slab thickness exceeded plus fissile material release plus homogeneous solution), while possible, is unlikely.

Water may also accumulate as a film on vertical surfaces. Low adhesion and low viscosity of water result in very thin water film thicknesses being developed. Fire protection research into the ability of water discharged from automatic sprinkler systems to provide a coating over surfaces has been performed by the Factory Mutual Research Corporation. Factory Mutual reported that the maximum film thickness achieved in the research, discharging plain water at a rate of 0.50 gallons per minute, per square foot, was approximately 0.55 mm. This water thickness is considered to be negligible.

Individual water droplets discharged from automatic sprinkler systems are also of

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[2] Paxton, H.C., and Pruvost, N.L., Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, LA-10860-MS, Los Alamos National Laboratory, 1987.

definable nominal size. The deflector on standard-spray, automatic sprinkler heads is designed for efficient distribution of water droplets for fire fighting purposes. Factory Mutual Research Corporation as measured sprinkler drop sizes and has found that the median drop size for 1/2 inch sprinklers discharging at 30 psi is 0.86 mm. Further, Factory Mutual has demonstrated that the median drop size for 1/2 inch sprinklers varies inversely with the one-third power of the pressure. Thus, median drop sizes can by calculated by the expression:

$$d_m = (0.86)\,(30/P_0)^{1/3}$$

Where:

d_m = median drop size (mm)

P_0 = operating pressure (psi)

It is not these small, individual drop which have much influence on moderation and reflection of neutrons but rather it is the integrated effect of the water mist. Standard calculational methods allow nuclear criticality safety specialists to calculate the effects of water mist densities on the potential for nuclear criticality. For most fissile material configurations, the density of the water mist has an insignificant effect on the neutron multiplication factor. For some arrays, particularly arrays of low-enriched uranium, light-water reactor fuel assemblies, low density water moderation may be of some interest. For those situations, the maximum water mist density which may be created by the discharge of a sprinkler system may be calculated by a fire protection engineer knowledgeable in hydraulics and sprinkler operating principles. This information can be shared with the nuclear criticality safety specialist to assure that safe margins are established in the event of discharge of water from sprinkler systems.

Various generic studies of sprinkler system mist densities for fissile arrays have been published and are listed in the references in Appendix B of this guide. There is general agreement in the literature that the maximum density of a water mist created by sprinkler systems is not likely to exceed an order of magnitude of 10^{-3} g/cm^3. This density is generally too low to affect most fissile arrays.

4.3.4 Calculation of Sprinkler Mist Densities

It is possible to estimate actual sprinkler mist densities which may be achieved in a particular area but specific variables must be addressed. The available water supply will affect the pressure at which the sprinkler head operates as well as the total volume of water which may be discharged. The water supply may vary from a few hundred gallons per minute at 50 psi for a gravity water system to several thousand gallons per minute at over 100 psi for a highly protected industrial facility. The piping arrangement, including the size and length of piping and fittings, may be important in determining hydraulic losses. Room size and height may affect sprinkler spray distribution. The sprinkler head type will influence the discharge rate. The sprinkler spacing will determine the amount of overlap of spray patterns. All of the above factors may need to be evaluated in determining the anticipated sprinkler density.

In order to simplify calculations, it may be necessary to make certain assumptions. In each case, the assumptions result in errors on the conservative side, that is, the calculated mist densities will be higher than those anticipated under actual conditions.

A simplifying assumption which might be made is that there is no hydraulic pressure loss due to friction loss in the piping. Losses in piping will result in lower pressures and thus result in lower discharge rates. Neglecting piping losses results in calculated discharge densities which will be higher than actual. If deemed necessary, more realistic discharge rates can be estimated using friction loss formulas for pipe losses. Fire protection engineers routinely include such calculations in determining sprinkler discharge rates.

Most fires are controlled by the operation of two sprinkler heads, or less. Single head sprinkler operation results in the highest per head discharge rate. However, in the worst case, it should be assumed that multiple heads operate. This results in overlapping of discharge patterns and in localized, higher density regions. Depending upon sprinkler spacing, as many as four to six spray patterns may overlap.

Fall times for droplets within the sprinkler mist can be estimated as a function of drop size, or more fundamentally as a function of the water pressure, and sprinkler height. Experimental terminal velocities for drops in air vary from 4.054 m/s for 1 mm droplets to 9.296 m/s for 5 mm droplets.

With the proper input data and assumptions, further calculations are not complex. Water discharge rates are proportional to the square root of the water pressure. The volume through which the discharge occurs can be approximated by that of a paraboloid defined by the discharge area and height of the sprinkler head. The volume rate of discharge of water from the sprinkler head distributed throughout the volume enclosed by the discharge pattern indicates the water/air density which is present due to sprinkler discharge. The resultant density must be further adjusted for overlap of discharge patterns from individual sprinkler heads.

While calculations may be relatively straightforward, they do require careful consideration of the significant input variables as well as knowledgeable application of reasonable assumptions. With this in mind, it is recommended that evaluation of anticipated sprinkler mist densities in air be performed by experienced fire protection engineers knowledgeable in sprinkler system hydraulics and water discharge dynamics.

4.4 Discussion of "Risk"

4.4.1 Definition

In a quantitative sense, risk is a function of the *probability* of loss or injury to people and property and the *magnitude* of the consequences of the loss or injury. Risk may be expressed as the product of the frequency and magnitude of undesirable consequences:

$$\mathit{risk}\left[\frac{\mathit{consequence}}{\mathit{time}}\right] = \mathit{frequency}\left[\frac{\mathit{events}}{\mathit{unit\ time}}\right]\mathit{magnitude}\left[\frac{\mathit{consequence}}{\mathit{event}}\right]$$

In nuclear risk assessment usage, there is general acceptance that risks which occur with a frequency less than 10^{-6} events per year are considered to be "incredible" and need not be further addressed, regardless of their consequence. This is not intended to infer that such events will not happen, but rather is intended to suggest a risk acceptance level where it is not deemed economically prudent to pursue further risk reduction.

In dealing with quantitative risk expressions, the fire protection professional and the nuclear criticality specialist need to be aware of the subtle differences in the expression of risk as described in the paragraph above. The conventional wisdom of the general population is that sprinkler systems leak and accidentally discharge water under conditions other than fire. Given the very large population of automatic sprinkler systems installed in the U.S., this is a very true observation. However, on an individual fire protection system installation basis, the probability of a sprinkler system discharging is so extremely low, as cited in Section 4.3.2.2 of this guide, as to be approaching the incredible.

4.4.2 Criticality Frequency vs. Consequences

As reported in Section 4.1.3 of this report, the overall frequency of criticality accidents in processing facilities is low, with a mean occurrence frequency of one event per 6.25 years. The consequences of criticality accidents has been very low. Section 4.1.4 of this guide discusses the consequences of nuclear criticalities. Direct property damage and nuclear contamination resulting from accidental criticalities has been minimal. There has been no reported off-site contamination from accidental criticalities, thus the health of the general population has not been adversely affected by these accidents. There have been two fatalities as a direct result of radiation exposures from process criticality accidents. Beyond the two fatalities, other workers health has not been significantly impacted by these events.

Every effort should be made to avoid a criticality accident. However, it must be kept in mind that the frequency of accidental criticalities is low and the consequence of accidental criticalities is very low. The resultant overall risk of criticality events is very low.

4.4.3 Fire Frequency vs. Consequences

Section 4.2.3 of this guide addressed the frequency of significant fires in the DOE. Fires are high frequency events with an average of 26 significant fires reported annually. Many others are controlled or extinguished before reaching significant size. Large loss fires, those resulting in property damage in excess of $100,000, have a frequency of recurrence of 1.4 x 10^{-1} events per year and catastrophic fires, those resulting in damage in excess of $1 million, have a projected frequency of recurrence of 3.3 x 10^{-2} per year. Fires have, historically, had significant impact. Fires contribute to the spread of nuclear contamination and may contribute to the likelihood of an accidental nuclear criticality.

Fires are high frequency and high consequence events. The combined effect is that fire is high risk peril.

4.4.4 Combined Risk

Although critical experiments are beyond the scope of this guide, a criticality incident and a fire which occurred in a Hanford Works facility in 1951 provides an interesting perspective. On November 16, 1951, a critical experiment was being conducted with 1.15 kg of plutonium in the form of plutonium nitrate in a 20 inch diameter, unreflected aluminum sphere. As a result of over-withdrawal of the control rod, a criticality of 8×10^{16} fissions occurred prior to reinsertion of the cadmium rod by the scram circuit. As a result of the criticality, there were no personal injuries and no significant property damage, although there was some contamination due to leakage of the plutonium nitrate solution. The facility had been nearly decontaminated within a few days when a fire occurred involving nitric acid soaked rags in the facility. Although the criticality did not damage the facility, the fire resulted in abandonment of the building.

Both the fire safety and nuclear criticality safety disciplines share a common external perception. Both disciplines are perceived as constraining productivity. All safety disciplines need to weigh the needs to provide a safe working environment against the operational needs of the DOE missions. They also need to weigh the relative weights of the safety risks presented by various hazards, including those which exist outside of their primary areas of responsibility.

In generic sense, the facts presented in the preceding two sections indicate that the fire risk far exceeds the risk of accidental nuclear criticality. It must be recognized, however, that this generic conclusion cannot be arbitrarily applied to individual facilities. Each facility handling fissile material must have specific evaluations of the fire and criticality risks presented in order to assess the relative risk of each peril so that intelligent protection decisions can be made. Section 7.0 of this guide presents a methodology for assessing fire and criticality risks as a decision tool in determining an appropriate level of fire protection to be provided in facilities handling fissile materials.

5.0 FIRE SAFETY AND CRITICALITY SAFETY REQUIREMENTS

5.1 Criticality Safety

The DOE provides requirement and guidance on nuclear criticality safety in DOE Orders, referenced national consensus standards, and DOE guides. DOE Orders 5480.4, 5480.24, and 6430.1 each address some aspects of nuclear criticality safety.

DOE 5480.4, 5-15-84, Environmental Protection, Safety and Health Protection Standards, establishes the ES&H standards applicable to DOE operations. Attachment 2 to that Order establishes standards which are mandatory as policy requirements. ANSI N16.1-1975, "Safety Standards for Operation with Fissionable Materials Outside Reactors" is designated as a mandatory standard. (Note. ANSI N16.1 was redesignated as ANSI/ANS 8.1 in 1983 and reaffirmed as ANSI/ANS 8.1 in 1988.) Attachment 3 to DOE 5480.4 includes referenced standards as good practice to be followed in DOE facilities. ANSI/ANS 8.7-1975, "Guide for Nuclear Criticality Safety in the Storage of Fissile Materials."

Up until the adoption of DOE 5480.24, Nuclear Criticality Safety, in 1992, the ANSI/ANS standards provided the only stand-alone requirements for nuclear criticality safety. On February 17,1993, DOE Office of Nuclear Safety Policy and Standards furnished Interpretive Guidance for DOE Order 5480.24. Together, DOE 5480.24 and the Interpretive Guidance must be consulted for current DOE policy on nuclear criticality safety. There is nothing in this fire protection guide which conflicts with DOE 5480.24 and the interpretive guidance on that order. Some significant aspects of the Order and guidance are included in this fire protection guide.

Contractors are required to comply with the mandatory criteria contained in the ANS 8. standards. (Section 7.)

The "double-contingency principle" in ANSI/ANS 8.1, 4.2.2 has been modified to be a mandatory requirement, not a recommendation. (7.a.(2)(a) It requires:

> Process designs shall incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible. Protection shall be provided by either (a) the control of two independent process parameters (which is the preferred approach, if practical) or (b) a system of multiple (at least two) controls on a single parameter.

> In all cases, no single failure shall result in the potential for a criticality accident. The basis for selecting either approach shall be fully documented.

This principle is exceptionally important from the fire protection/criticality safety risk evaluation standpoint. Under such a principle, discharge of fire protection water, by-itself, should not result in a condition which would create an unsafe condition from a criticality standpoint. Under this principle, it would require that some other parameter be also changed prior to a potentially unsafe condition occurring. For example, in addition to the discharge of water, there would have to be a concurrent change such as the release of fissile material from its container, or a concurrent breach of a fissile material container allowing in-flow of water, or a change in shape, concentration or density of fissile material, or other similar change.

Further, where a pre-action sprinkler system is provided, it would, by definition, meet the requirements for double-contingency failures. Under non-fire conditions, a pre-action system will not release water unless the piping system is breached and an independent actuation of the heat detection system occurs.

The "geometry control" recommendation of ANSI/ANS 8.1, 4.2.3, is also modified by 5480.24 (7.a.(2)(b) to be a mandatory requirement:

> "As a first priority, reliance <u>shall</u> be placed on equipment design in which dimensions of the contained fissionable material and spacing between equipment are limited by passive engineering controls. Where geometry control is not feasible, the preferred order of controls is other passive engineering controls, active engineering controls, and administrative controls. . . The basis for not selecting geometry control shall be fully documented."

This requirement also has significant implications of fire protection/nuclear criticality safe evaluations. It is required that, where practical, fissile systems rely on geometry control, not moderation control, to achieve criticality safety. In such as system, the system remains critically safe under all conditions of moderation, including all conditions resulting from the application of water during fire fighting activities. An exception to the use of geometry control must be fully documented.

Section 7.c of 5480.24 requires that contractors provide fully documented, detailed criticality safety analyses for fissile operations. Some of the pertinent items required to be included in the document analysis are summarized below:

1. A description, using appropriate sketches or drawing, of equipment and facilities

in which the hazard of criticality exists. This information may be useful to the fire protection engineer in developing an effectual fire hazard analysis and in providing assistance to the criticality safety specialist. It may also be useful to fire emergency response personnel in establishing pre-emergency plans for fire response.

2. A statement of the chemical an physical form of fissionable material and degrees of moderation. This information may also be useful to the fire protection professional in cooperating with the criticality safety specialist in an integrated approach to fire and criticality safety.

3. A statement of the maximum quantities of fissionable material. Useful information for use in the screening methods outlined in Section 7.0 if this fire protection guide.

4. An analysis of criticality incident scenarios and their impact on health and safety of the workers and/or public. This information is useful in evaluating relative health and safety risks due to criticality and other hazards.

5. An description of the safety control parameter which are intended to prevent criticality resulting from events such as: accumulation of fissionable material in scrap or waste, lathe turnings, crucible slag, sumps, filters, etc. Also included shall be the description of the technical practices used to prevent exceeding the safety control parameters. This is specifically the type of information which can be used to perform an integrated fire protection/nuclear criticality safety evaluation of a fissile facility.

DOE 5480.24 and Interpretive Guide introduces, indirectly, the issue of the credibility of fires and fire fighting activities resulting in a nuclear criticality. The interpretive guide interprets "criticality accident" as meaning "credible criticality accident." The possibility that fire protection activities might, under some unlikely conditions, result in a criticality accident, should not be interpreted as justification to preclude the provision of fire protection. There must be demonstrated that there is some logical, and credible, mechanism for fire protection or fire fighting to result in a criticality and that the resulting consequences outweigh the consequences of failure to provide adequate fire protection.

In addressing the need for criticality alarm systems, Section 7.b(1) of 5480.24 establishes a credibility threshold for criticality accidents as a probability of not greater than 10^{-6} events per year. The same credibility criterion could also be applied to fire protection system-induced criticality accidents. As discussed elsewhere in this fire protection guide, the probability of an inadvertent water discharge from a fire protection system also resulting in an accidental nuclear criticality has a probability of occurrence which will often fall below this credibility threshold.

Section 7.f of DOE 5480.24 specifically addresses "Guidelines for Fire Fighting." It is interesting that the Order does not address other specific design basis accidents which might result in criticality accidents. In the area of fire fighting, the Order requires:

> "Contractors shall establish guidelines for permitting fire fighting water or other moderating materials used to suppress fires within or adjacent to moderation controlled areas. **These guidelines shall be based on comparisons of risk and consequences of accidental criticality with the risks and consequences of postulated fires for the respective area(s).** (emphasis added) The basis for the guidelines shall be fully documented in a DOE approved Safety Analysis."

This paragraph recognizes that, despite the requirement for first priority reliance on geometry control, there may be areas where moderation control is practiced as the controlling parameter to prevent criticality. For those particular areas, special guidelines must be prepared by the M&O contractor which permit the used of water for fire fighting. Prohibiting the use of water to fire fires is not a recognized option. As written in this order, areas where moderation is not a controlled factor, guidelines for the use of water for fire fighting is not specifically required.

The key issue raised is that the "risk and consequence" of accidental criticality and postulated fire must be compared. Section 3.0 of this guide provides some historical data which may be of use. This may be done qualitatively or quantitatively but is required by the order. This approach is further discussed in Section 7.0 of this fire protection guide.

DOE 6430.1A, General Design Criteria, also addressed nuclear criticality safety. Portions of DOE 6430.1A applicable to both nuclear criticality safety and fire protection are addressed below under "Fire Protection".

5.2 Fire Protection

DOE Order 5480.7A, Fire Protection, and DOE 6430.1A, General Design Criteria, both address factors associated with overall fire protection of DOE facilities.

DOE 5480.7A, the primary DOE Order addressing fire protection, addresses nuclear criticality. In Section 9.b(1) where it states, "Fire Protection systems shall be designed such that their actuation will not damage safety class systems or cause a criticality accident." It mandates that automatic fire suppression systems be provided to protect all new structures exceeding 5,000 sq. ft. and all structures having a maximum possible fire loss exceeding $1 million. Sprinkler protection is also mandatory where required by the Life Safety Code, NFPA 101.

DOE 6430.1A, General Design Criteria, addresses fire protection by sprinklers and nuclear criticality safety in two areas, Section 1300 and 1530. Applicable sections of DOE 6430.1A. are quoted below, in bold type. Following each section quoted is a discussion of the requirement.

1300-4 NUCLEAR CRITICALITY SAFETY

> **"An assessment of a design shall be made as early as practical to determine if the potential for nuclear criticality exists. When such potential exists, the design of nuclear criticality control provisions, including equipment and procedures, shall meet, as a minimum, the requirements of DOE 5480.5 and the ANS 8 series on Nuclear Criticality Safety."**

An important principal contained in both of these mandated documents is the double-contingency principle. The principle calls for controls that assure that no single mishap - regardless of its probability of occurrence - can lead to an accidental criticality. That is, it requires that two unlikely, independent, and concurrent changes in process conditions occur before and accidental nuclear criticality is possible. This is an important principle to be recognized where pre-action sprinkler systems are provided. Since the pre-action sprinkler piping system is independent of the fire detection system and failure of both the independent mechanical and electrical systems must occur prior to release of water due to system failure, accidental water leakage from a pre-action system would, in itself, be considered a double-contingency failure as defined in the standards.

> **"Nuclear criticality safety shall be achieved by exercising control over both the quantity and distribution of all fissile materials and other materials capable of sustaining a chain reaction, and over the quantities, distributions, and nuclear properties of all other materials with which the fissile materials and other materials capable of sustaining chain reaction are associated. Design considerations for establishing such controls shall be mass, density, geometry, moderation, reflection, enrichment, interaction, material types, and nuclear poison."**

This paragraph allows considation of the neutron moderation and reflection effects of sprinkler water in the design for achieving criticality safety.

> **"The design shall ensure that material shall not be displaced or allowed to accumulate to form a critical mass in the event of a an internal or external accident. The design shall emphasize geometrically favorable compartments or spacing to minimize reliance on administrative control, and shall prevent the unsafe accumulation of moderator or reflection materials (e.g., water from a fire sprinkler system)..."**

Displacement caused by fire (e.g., structural failure) or by manual firefighting must not result in a critical arrangement of fissile materials. Displacement by fire suppression systems is unlikely.

Sprinkler water droplets discharged from a standard upright sprinkler head possess very little momentum to cause movement of materials. Experimental terminal velocities for sprinkler droplets in air have been measured by the Factory Mutual Research Corporation to be 4.054 m/s for 1 mm droplets. The small mass and low velocity of sprinkler droplets result in little energy to be transferred to impacted materials to cause movement. Water spray nozzles may exert higher impact forces which may need to be considered and can be calculated or experimentally measured.

The emphasis of this paragraph is to assure safe geometry. This geometry must be maintained under all credible accident conditions which should include a design basis fire. The effect of fire in changing fissile material geometry may present a much higher safety risk that of any fire suppression activity.

The potential for accumulation of water is covered in a subsequent paragraph of this section of the Order and discussed below.

> **"Process designs shall incorporate sufficient factors of safety so that at least two unlikely and independent concurrent changes must occur in process conditions before a criticality accident is possible."**

This is a re-statement of the double-contingency principle which provides added emphasis to the importance of this principle

"Structures, systems, and components that provide nuclear criticality safety shall be designed as safety class systems and be capable of performing their criticality safety functions during and following design basis accidents and events."

One Design Basis Accident is the Design Basis Fire. When analyzing criticality safety, the most severe fire must be postulated, assuming fire suppression system failure unless the suppression system is a safety class system to assure that criticality safety is maintained.

"Nuclear criticality safety shall be controlled, in decreasing order, by geometric spacing, density and/or mass limitation, fixed neutron absorber, soluble neutron absorber, and administrative control."

It should be noted that control of moderator (e.g., sprinkler water) is not one of the factors required to be controlled for criticality safety.

"Locations where a potential critical mass could occur in the event of accidental flooding by water from fire protection systems shall be protected by geometrically favorable curbed areas or collection systems."

This paragraph does specifically allows for the use of water fire protection systems and requires other means of control be used to assure criticality safety.

"Where frequency estimates for a specific operation at a specific location shows the frequency of a criticality accident to exceed 10^{-6} per year, the combination of shield design and facility layout shall minimize radiation doses to adjacent work stations and exit routes."

This paragraph introduces the concept of relative risk by establishing a limiting frequency of occurrence of event of 10^{-6} per year. As cited in Section 4.3.2.2 of this guide, published data indicate that it is not credible to anticipate that the introduction of water moderator due to sprinkler head leakage will contribute to a criticality accident at a frequency greater than the limit established in this paragraph.

1530 FIRE PROTECTION

1530-2.3.2 Criterion I

"Whenever the maximum possible fire loss exceeds $1 million, automatic fire suppression systems shall be provided."

Without exception, automatic fire suppression must be provided where the maximum possible fire loss within a single fire area exceeds $1 million. ANSI/NFPA 801, Fire Protection Practice for Facilities Handling Radioactive Materials, states, "Automatic sprinkler protection provides the best means for controlling fires involving combustible occupancies and should be provided unless it can be shown that their operation will definitely create a situation more hazardous than that brought about by uncontrolled fire."

1530-99 SPECIAL FACILITIES

1530-99.0 Nonreactor Nuclear Facilities - General

"Fire suppression systems shall not: (1) prevent a facility from achieving and maintaining a safe shutdown condition, (2) prevent the mitigation of DBA consequences, or (3) cause an inadvertent nuclear criticality."

This paragraph introduces the concept of a potential conflict between fire safety and criticality safety. However, this paragraph does not state that sprinkler systems shall not be used where the potential for an accidental nuclear criticality exists, but rather implies that the fire suppression system and the fissile material arrangement and criticality control scheme must be compatible. Section 1530-2.3.2 has previously established the mandatory requirement for automatic fire suppression and Section 1300-4 mandates that criticality control be maintained under credible accident conditions by geometry and mass control, neutron absorbers, and administrative controls. The criticality controls, as required, must be integrated to function in concert with the appropriate, required fire suppression system.

"When the use of water sprinkler coverage is precluded because of nuclear criticality or other hazards, nonaqueous extinguishing systems (i.e., inert gas, carbon dioxide, high expansion foam, or halogenated organics) shall be used."

If, after careful and knowledgeable study, it is determined that the fire hazard cannot be reasonably eliminated and criticality control cannot be established with the introduction of low-density moderation due to sprinkler discharge, then some other form of automatic fire suppression should be provided. It should be noted that fire fighting foam is not a non-aqueous material as stated in the Order and that both foam and "halogenated organics" contain hydrogen which will thermalize neutrons. The relative density of hydrogen atoms in foams and halons is much lower than that of "plain" water, thus the moderating and reflecting power of foams and halons is less.

> "**Automatic water sprinkler coverage shall be provided throughout the facility except in areas where nuclear criticality or other hazards specifically preclude its use or where Halon systems are required to reduce water damage.**"

This paragraph establishes that water sprinkler systems provide the most appropriate form of fire protection for general area usage. The determination of whether the presence of fissile material precludes the use of sprinklers is discussed in a previous paragraph.

6.0 NUCLEAR CRITICALITY CONSEQUENCES OF NON-SUPPRESSION OF FIRES

In some cases, it has been postulated that the perceived risk of accidental nuclear criticality so far out-weighs the risk or consequences of a fire that effective fire suppression activities must be prohibited. The somewhat simplistic solution proffered is "let it burn", sometimes without due recognition of the increased risk presented by such a resolution.

Clearly, the "let it burn" rationalization will, in many instances result in a much greater property damage loss than would occur if prudent fire intervention methods were employed. It also increases the risk of direct and indirect personal injury due fire and fire products.

As discussed in Section 4.4.4 of this guide, the potential for loss of confinement and spread of nuclear contamination is increased by uncontrolled fires. This will lead to increased risk of injury and harm to on-site workers and the off-site population.

Moreover, the decision not to suppress fires in facilities containing fissile material will not necessarily preserve the criticality safety "status quo" which is desired. Uncontrolled fires may increase the risk of accidental criticalities. The risk of nuclear criticalities due to fires as a design bases accident may not have been fully analyzed.

Fires are likely to effect several levels of nuclear criticality safety "defense-in-depth." Common-mode failures due to fires may compromise "double-contingency" systems from a single fire event. For example:

1. Fires may result in loss of concentration control.

   Heat from fires may cause evaporation of diluents thus resulting in higher concentration of fissile materials in solution.

   In solvent extraction operations, the fire may consume combustible solvents, with resultant increase in fissile content.

2. Fires may result in loss of geometry control.

   In closed systems, heating from exposure fires may result in high internal pressures causing geometry distortions or rupture.

High temperatures for fires exposing of borated polyethylene or CPVC vessels containing fissile solutions may result in softening of the plastic causing geometry distortions.

Fissile materials in "bird-cages" or in light metal racks may be easily distorted by high temperature fire exposures of relatively short duration.

3. Fires may result in loss of spacing control

   Light racks or shelving units may be distorted due to fire exposure resulting in spacing limit violations.

   Arrays may collapse under fire exposure.

4. Fires may result in loss of fixed neutron absorber.

   Fire may destroy borated PE materials needed for neutron absorption.

5. Fires may result in unplanned transport of fissile material into unfavorable geometry.

   Fire exposure may result in leakage of solutions across valves into unsafe vessels.

   Fire exposure may result in rupture and release of solutions from safe vessels to unfavorable surrounding areas.

6. Fires may result in increases in neutron moderation.

   Process and sanitary pipes and system components are likely to fail and release their contents either from the heat of an unmitigated fire or from the collapse of structural components.

7. Fires eventually have to be extinguished by the fire department. The uncontrolled discharge of water from hose streams is much more likely to cause a criticality accident than is the controlled discharge from a fixed suppression system.

7.0 GUIDELINES FOR EVALUATION AND DESIGN OF NEW OR EXISTING FACILITIES

Each facility handling fissile material must have specific evaluations of the fire and criticality risks presented in order to assess the relative risk of each peril so that intelligent protection decisions can be made on alternative means of protection. This section of the guide presents a methodology for assessing fire and criticality risks as a decision tool in determining an appropriate level of fire protection to be provided in facilities handling fissile materials.

Appendix D of this guide presents a suggested logic diagram to be used in evaluating fire protection where fissile materials are present. It presents a step-by-step logic process in evaluating the overall need for fixed fire protection, the impact of fires or fire suppression systems on nuclear criticality safety, and assessment of the relative risk presented by the fire protection and nuclear criticality perils. It presents a rational approach in decision analysis to determine appropriate levels of fire protection to be provided in a balanced context with the nuclear criticality hazard.

The first step in the evaluation process is conducted by the fire protection professional, without any necessary input from the nuclear criticality safety specialist. In this step, the need for fixed, automatic fire suppression for the facility is determined in accordance with the requirements of DOE 5480.7A. If fixed fire suppression is determined to be unnecessary, the evaluation process is terminated.

If automatic suppression system(s) are required, the fire protection professional should determine if the hazard is best protected by automatic sprinklers. If non-aqueous fire protection systems are determined to be more appropriate, the evaluation process suggested by this decision management system is terminated.

If it is determined that automatic sprinkler protection or other aqueous suppression system should be provided for the fire hazard present, then further evaluation is needed. The next several steps of the decision process are best performed by the nuclear criticality specialist.

The first step of this portion of the evaluation is to determine whether the total mass of fissile material in the area exceeds the critical mass necessary to result in criticality. If it is not likely that a critical mass will be present, then fire protection by any reasonable means may be safely provided and no further evaluation is required.

In the next step, it is determined whether the operations with fissile materials are being

In the next step, it is determined whether the operations with fissile materials are being performed by complying with the single-parameter safety limits established by ANSI/ANS 8.1 and summarized in Appendix C of this guide. If the single-parameter limits are effectively implemented, any additional moderation due to fire suppression activities will not result in risk of nuclear criticality. Any form of fire protection may be provided without further criticality conflict.

It is at this point that joint evaluation by both the fire protection professional and the nuclear criticality specialist is required. Throughout the remainder of the decision process, it is important that both discipline cooperatively assess the situation presented by the fissile material process. Because of the specialty aspects of each of the disciplines, it is not desirable that either of the disciplines should attempt to complete the decision-making process without full and complete input for the other discipline specialist.

If it is determined by the criticality safety specialist that geometry control is to be employed to assure criticality safety, it is necessary to determine whether a credible fire can result in a change of fissile geometry in the facility. This fire consequence analysis should be conducted by a fire protection professional cognizant in fire effects evaluations. If it is determined that fire-induced geometry changes may be criticality unfavorable, automatic fire suppression should be provided.

In this case, where automatic sprinkler protection is determined to be warranted to protect against accidental criticalities due to fires. a joint evaluation of the effects of sprinkler water on criticality potential should be performed by both the fire protection professional and the nuclear criticality specialist. First it should be determined if criticality safety can be assured (i.e. double contingency) without regard to moderation control. Using standard and accepted nuclear criticality calculational techniques, the nuclear criticality specialist can determined the influence of partial moderation by sprinkler mists on effective neutron multiplication factors. The fire protection professional can used hydraulic calculations and sprinkler characteristics to determine the rate of maximum possible water application and mist density rates. Together, they can evaluate the credibility and consequences associated with fire protection water discharge.

If it is determined that water mists which will adversely affect criticality safety are not credible. then the credibility of flooding scenarios which will adversely affect nuclear criticality safety must be jointly evaluated. This evaluation must include the credibility and effects of flooding of primary material confinements such as cans, flooding of secondary confinements such as gloveboxes. and flooding of floor surfaces and sumps.

If, based on this logical progression of evaluation, it is determined that criticality accidents are not credible due to water, then automatic sprinkler protection should be provided. If the criticality risk is determined to exceed the fire risk, based on sound evaluation techniques, then automatic sprinkler protection should not be provided. The fire protection professional should explore alternative means for fire risk reduction such that both criticality safety and fire safety goals are achieved.

8.0 GUIDELINES FOR FIRE PROTECTION RESPONSE FOR FACILITIES HANDLING FISSILE MATERIALS

8.1 General Precautions

In a fissile materials area, the fire fighter should try to minimize any changes in equipment and surroundings to prevent geometry changes which may be unfavorable from a criticality standpoint. The potential for geometry changes can be reduced by using low water pressures, using spray nozzles in the full-spray position, and by minimizing the excessive use of prying tools. Re-entry should be made only with permission of the director of the emergency operation and the responsible radiation protection officer. While SCBA limits will tend to limit periods of potential exposure, other, more stringent limits may be set by the radiation protection officer.

Just as one should maintain a safe distance from any potential radiation source, fire fighters should attempt to provide separation between themselves and fissile materials in the event of an accidental criticality. In general, personnel which are located 15 ft. or more from a nuclear criticality are likely to be outside of the range where a lethal radiation flux would be created in the event of criticality accident. During any fire hose evolutions, the fire fighter is likely to be more than 15 ft. from any fissile material at which the hose stream is directed. However, the fire fighter must also be aware of the locations of any other fissile materials in the room, such as at the back and side of the fire fighter, in order to maintain as safe distance from any co-located fissile material. **If a criticality should occur, the duration of exposure will effect the dose. If a criticality alarm should activate during fire fighting operations, the fire fighter should immediately evacuate the area in order to reduce potential radiation exposure.**

8.2 Pre-Emergency Planning

The precautions discussed above are best implemented by an effective pre-emergency plan. Pre-emergency fire response plans should be developed for all facilities. It is important that for facilities storing or handling fissile materials specifically address the criticality aspects of fire suppression activities in the area.

It is beneficial to know before the time of an emergency in which areas fissile materials are located which may be subject to accidental criticalities. Responding emergency personnel should know the specific location where fissile materials may be specifically encountered within the facility. The form of fissile material and criticality control measures should be identified. Limitations, if any, on fire fighting activities should be identified.

It may be advantageous in reducing the risk in responding to fires in fissile material areas, to have previously identified and categorized the special fire suppression and nuclear criticality aspects of the facility, prior to any emergency. In Section 7.3 of this guide, a suggested guide for classification of fissile areas for fire fighting is presented.

8.3 Fire Fighting Classification of Fissile Areas

Section 8.1 of this guide discusses some general approaches to risks associated with fire fighting in nuclear facilities, and in particular facilities containing fissile materials. It is recognized that each fissile area is unique and may have special fire fighting characteristics. In some facilities, there may be no need for fire fighting limitations due to the presence of fissile materials. In others, the nuclear criticality controls may be so delicately balanced that all fire fighting must be carefully restricted. It is strongly advised that each facility be evaluated by both fire protection professionals and nuclear criticality specialists to determine the levels and methods of fire suppression activities may be used. Section 7.0 of this guide provides a logic structure which may be used in that type of evaluation.

Based on the combined evaluation of the fire protection and criticality specialists, facilities may be classified by their relative propensity to result in an accidental criticality due to fire suppression activities. A suggested classification system is presented in Table No. 8-1.

TABLE 8-1

RECOMMENDED FIRE FIGHTING CATEGORIES
FOR FACILITIES HANDLING FISSILE MATERIALS

CATEGORY	FACILITY CRITICALITY CHARACTERISTICS
A	No likelihood of criticality if water is used for fire fighting. Quantity of fissile material is too small.
B	Minimal likelihood of criticality if water is used for fire fighting. Total fissile mass in area exceeds critical mass but materials are distributed or in dilute solutions such that accidental criticality is extremely unlikely. Geometry, volume, or concentration control.
C	Under reasonably foreseeable conditions, the addition of water could cause criticality. Credible conditions anticipated during fire fighting could result in re-arrangement of material which, in the presence of water in the form provided by fire fighting, might result in criticality. Geometry, volume, or concentration control.
D	Fissile materials present under moderation control to prevent criticality. Addition of water would likely result in accidental criticality.

In this classification system, facilities are categorized from Class A to Class D Fissile Fire Fighting Classification. In Class A facilities, there is no danger of accidental criticality even though there are fissile materials present. In Class D facilities, moderation controls on criticality prohibit the use of water in all forms. Class B and Class C facilities have intermediate criticality risks, as identified in the figure.

Once so classified, the allowable fire suppression activities can be identified which can be associated with each classification. The generally acceptable fire fighting response for each classification illustrated in Table No. 7-2

TABLE NO. 8-2

FIRE FIGHTING RESPONSE TO FISSILE AREA CATEGORIES

CATEGORY	FIRE FIGHTING RESPONSE
A	No restrictions on the use of water for fire fighting.
B	Use of water for fire fighting permissible but quantities and pressures should be minimized. Care should be exercised to prevent re-arrangement of equipment and materials.
C	Use of water should be limited to pre-planned use - OR - as a last resort to prevent a more severe consequence
D	Water should not be used. Alternate. non-aqueous fire suppression agents. only. may be safety used. Dry chemical. dry powders. carbon dioxide. and halon extinguishers are acceptable.

APPENDIX A

SUMMARY OF CRITICALITY ACCIDENTS IN PROCESS OPERATIONS

SUMMARY OF CRITICALITY ACCIDENTS IN PROCESS OPERATIONS

For background purposes, some criticality accidents are briefly discussed below.

Y-12 Plant
Oak Ridge, TN
June 16, 1958

Process piping was being flushed with water which was collected in a 55 gallon drum. Due to an improper valve line-up, a quantity of enriched uranium solution was accidentally transferred into the drum. As additional water was added to the drum, the solution became critical. A succession of bursts produced 1.2 x 10^{18} fissions over a three minute period. The event continued for about 20 minutes as continued flow of water reduced the concentration of the solution to a sub-critical state. One person, within about six feet of the drum, received a non-lethal dose of 461 rem. Seven others received lesser doses. There was no property damage and no contamination. The plant was returned to operation in three days.

Los Alamos Scientific Laboratory
Los Alamos, NM
DECEMBER 30,1958

Residual plutonium in raffinate and nitric acid wash solutions from four safe vessels were transferred into a 38 inch diameter, 225 gallon tank. Within this tank there existed an eight inch thick organic layer containing 3.27 kg of plutonium floating on an aqueous solution containing 60 g of plutonium. When a stirrer in the tank was turned on, the action caused thickening of the organic layer to create a super-critical system. The excursion consisted of a single spike producing 1.5 x 10^{17} fissions. An operator who was looking directly into the tank at the time of accident receive a dose of 12,000 rem and died 36 hours later. Two others received does of 134 and 53 rem. The was no significant damage, although the shock of the event displaced the tank support by 3/8 inch. There was no contamination.

Idaho Chemical Processing Plant
National Reactor Testing Station
October 16, 1959

This operation involved recovery of fissile material from spent reactor fuel in shielded facilities. During air-sparging of a uranyl nitrate solution containing 34 kg of U(93) in safe tanks, about 200 liters of the solution (containing 170 g U/l) was transferred to a 9 ft. diameter, 5000 gallon tank containing about 600 l of water. The resulting criticality produced an initial spike of 10^{17} followed by lower power oscillations over a 20 minute period. During this period nearly half of the water was boiled off. Because of the shielding, none of the operators received significant gamma or neutron doses. Release of fission products resulted to beta exposures of 50 R and 32 R to two persons during the subsequent plant evacuation. There was no equipment damage.

Idaho Chemical Processing Plant
National Reactor Testing Station
<u>January 25, 1961</u>

A uranyl nitrate solution (200 g U(93)/liter) was contained in a 5 inch diameter pipe within a shielded facility. In an attempt to clear some plugged lines, air was introduced into the system. The bubble of air forced about 40 l of the solution into a 24 inch section which was normally above the solution level. The solution in this unsafe geometry resulted in a criticality with a single spike of 6×10^{17} fissions. Because of the shielding, personnel exposures were less than 100 mr. There was no damage to the facility.

Recuplex Plant
Hanford, WA
<u>April 7, 1962</u>

Following an overflow of a plutonium solution, transfer of the solution was made from a sump to an 18 inch diameter transfer tank. About 46 liters of solution containing 1400 to 1500 g of plutonium was transferred to the tank of unsafe dimension. The resultant accidental criticality continued for 37 hours with a total yield of 8.2×10^{17} fissions. The excursion was terminated by the boiling off of about 6 l of water and settling of plutonium bearing organic. One person who was about 5 to 6 feet from the tank at the time of the initial excursion received a dose of 110 rem. Two others received lesser doses. There was no damage or contamination.

United Nuclear Corporation
Wood River Junction, RI
<u>July 24, 1964</u>

Concentrated (240 g ^{235}U/l) uranium contaminated trichloroethane was stored in 5 inch diameter polyethylene bottles identical to bottles containing very low concentration trichloroethane. A bottle thought to contain low concentration solution, but actually containing a high concentration of uranium, was poured into an 18 inch diameter sodium carbonate make-up tank. When the solution was agitated by an electric stirrer, the system went critical. The resultant excursion of 1×10^{17} fissions splashed about one-fifth of the solution to the floor and result in lethal exposure of 10,000 rad to an adjacent operator who died 49 hours later.

An hour and a half later, two men entered the area to drain the tank. When they turned off the stirrer, the change in geometry resulted in a second excursion of 10^{16} fissions. The two men received doses of 60 and 100 rads. Physical damage to the facility from the two incidents was limited to clean-up of the solution.

BNFL Pu Plant
Windscale, England
August 24, 1970

This incident involved a solvent extraction operation for scrap recover of plutonium. Following the transfer of 300 g of plutonium in solution, a small excursion (10^{15} fissions) of brief duration (< 10 s) occurred. About 39 l of solution containing 2.15 kg of plutonium had been previously trapped in the system. One person received an exposure of 2 rads while another was exposed to one rad.

Idaho Chemical Processing Plant
National Reactor Testing Station
October 17, 1970

This incident occurred in a shielded cell containing a solvent extraction process for the reprocessing of spent fuel. A change in concentration in a scrubbing column resulted in 2.7×10^{18} fissions over a half hour period. There was no significant personnel exposure and to damage to process equipment.

APPENDIX B

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REFERENCES

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APPENDIX C

SINGLE PARAMETER LIMITS

TABLE 1
SINGLE-PARAMETER LIMITS FOR UNIFORM AQUEOUS SOLUTIONS OF FISSILE NUCLIDES

Parameter	Subcritical Limit for Fissile Solute				
	$^{233}UO_2F_2$	$^{233}UO_2(NO_3)_2$	$^{235}UO_2F_2$	$^{235}UO_2(NO_3)_2$	$^{239}Pu(NO_3)_4$
Mass of fissile nuclide, kg	0.54	0.55	0.76	0.78	0.48
Diameter of cylinder of solution, cm	10.5	11.7	13.7	14.4	15.4
Thickness of slab of solution, cm	2.5	3.1	4.4	4.9	5.5
Volume of solution, l	2.8	3.6	5.5	6.2	7.3
Concentration of fissile nuclide, g/l	10.8	10.8	11.6	11.6	7.3

TABLE 2
SINGLE-PARAMETER LIMITS FOR METAL UNITS

Parameter	Subcritical Limit for		
	^{233}U	^{235}U	^{239}Pu
Mass of fissile nuclide, kg	6.0	20.1	5.0
Cylinder diameter, cm	4.5	7.3	4.4
Slab thickness, cm	0.38	1.3	0.65
Uranium enrichment, wt% ^{235}U	-.-	5.0	-.-
Maximum density for which mass and dimension limits are valid, g/cm^3	18.65	18.81	19.82

Table 3
Single-Parameter Limits for Oxides Containing No More Than 1.5% Water By Weight at Full Density

Parameter	^{233}UO2	^{233}U3O8	^{233}UO3	^{235}UO2	^{235}U3O8	^{235}UO3	^{239}PuO2
Mass of fissile nuclide, kg	10.1	13.4	15.2	32.3	44.0	51.2	10.2
Mass of oxide, (a)kg	11.7	16.0	18.7	37.2	52.8	62.6	11.5
Cylinder diameter, cm	7.2	9.0	9.9	11.6	14.6	16.2	7.2
Slab thickness, cm	0.8	1.1	1.3	2.9	4.0	4.6	1.4
Maximum bulk density (b)for which limits area valid, g/cm^3	$\frac{9.38}{1-0.085(1.5-w)}$	$\frac{7.36}{1-0.065(1.5-w)}$	$\frac{6.56}{1-0.056(1.5-w)}$	$\frac{9.44}{1-0.086(1-5w)}$	$\frac{7.41}{1-0.065(1.5-w)}$	$\frac{6.60}{1-0.057(1.5-w)}$	$\frac{9.92}{1-0.09(1.5-w)}$

(a) These values include the mass of any associated moisture up to the limiting value of 1.5% by weight.

(b) w represents the quantity of water, in wt%, in the oxide.

Table 4
Single-Parameter Limits for Oxides Containing No More Than 1.5% Water By Weight at No More Than Half Density(a)

Parameter	^{233}UO2[2]	^{233}U3O8{2}	^{233}UO3[2]	^{235}UO2[3]	^{235}U3O8[3]	^{235}UO3[3]	^{239}PuO2[4]
Mass of fissile nuclide, kg	23.4	30.5	34.7	88	122	142	27
Mass of oxide, (b)kg	27.0	36.6	42.4	102	146	174	30
Cylinder diameter, cm	11.9	14.8	16.3	20.4	26.0	28.8	12.6
Slab thickness, cm	1.6	2.2	2.6	5.8	8.0	9.3	2.8

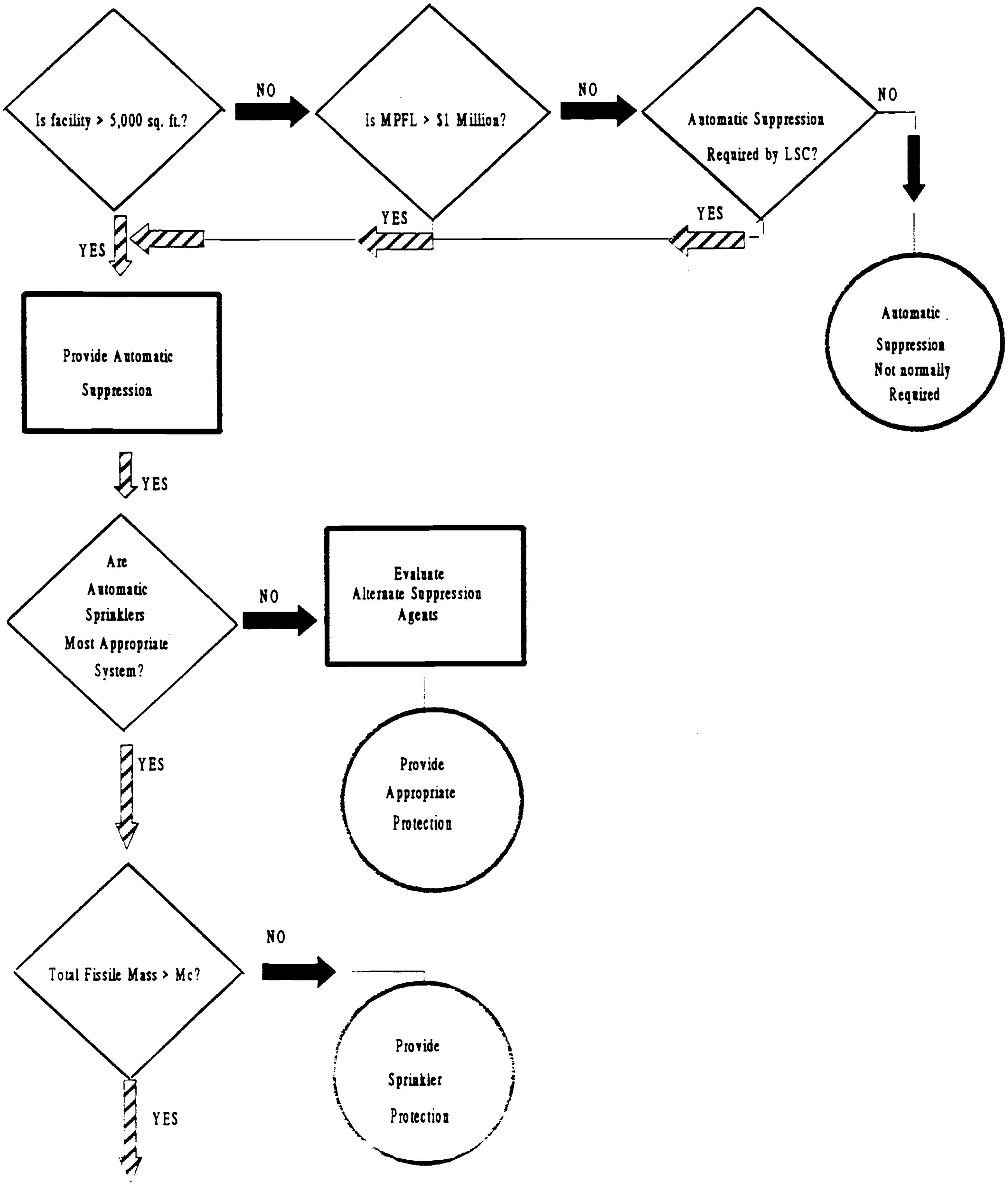
(a) These are half the maximum bulk densities of Table 3.

(b) These values include the mass of any associated moisture up to the limiting value of 1.5% by weight.

APPENDIX D

SUGGESTED LOGIC DIAGRAM FOR EVALUATING FIRE PROTECTION WHERE FISSILE MATERIALS ARE PRESENT

Suggested Logic Diagram for Evaluating Fire Protection Where Fissile Materials are Present



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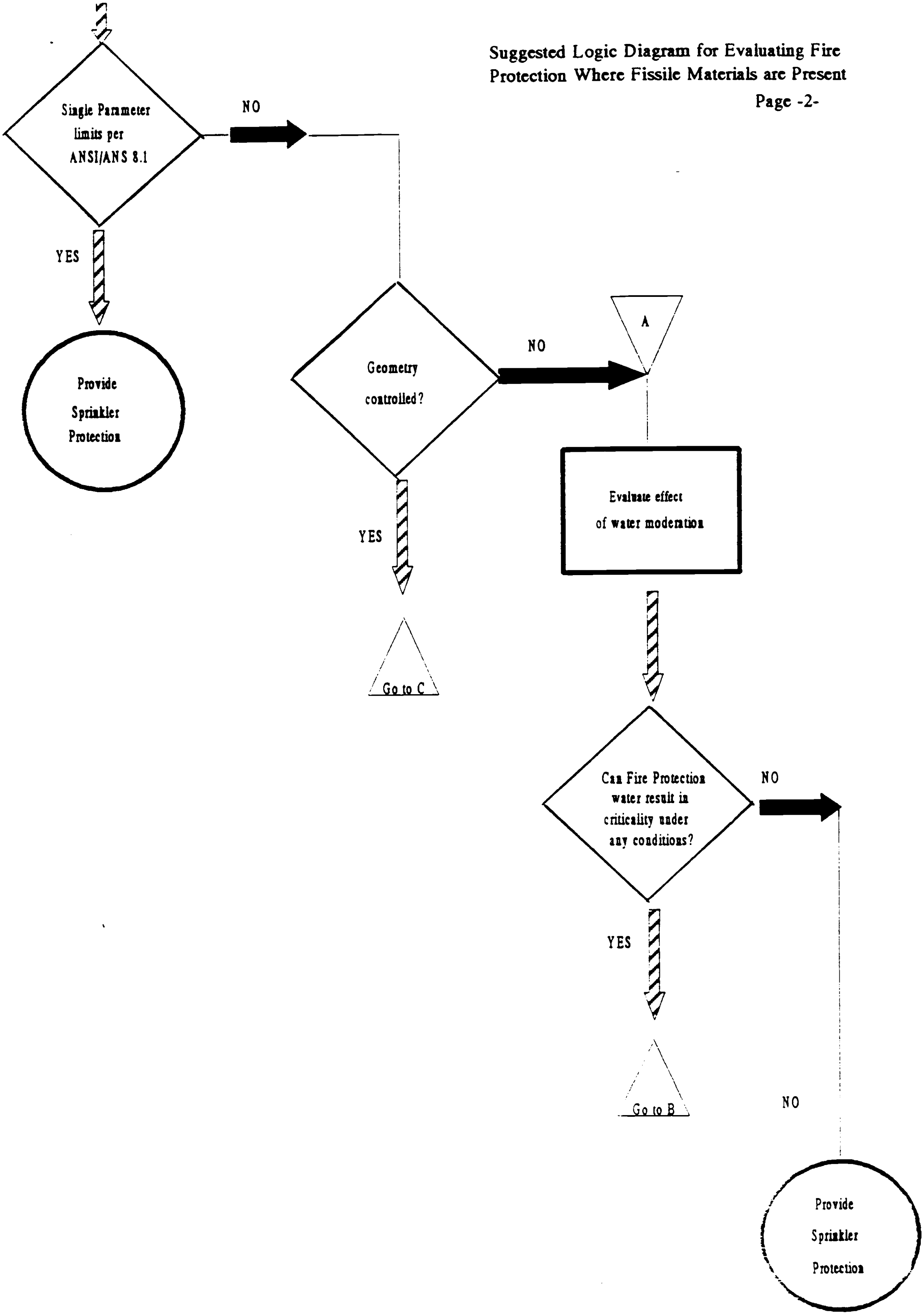
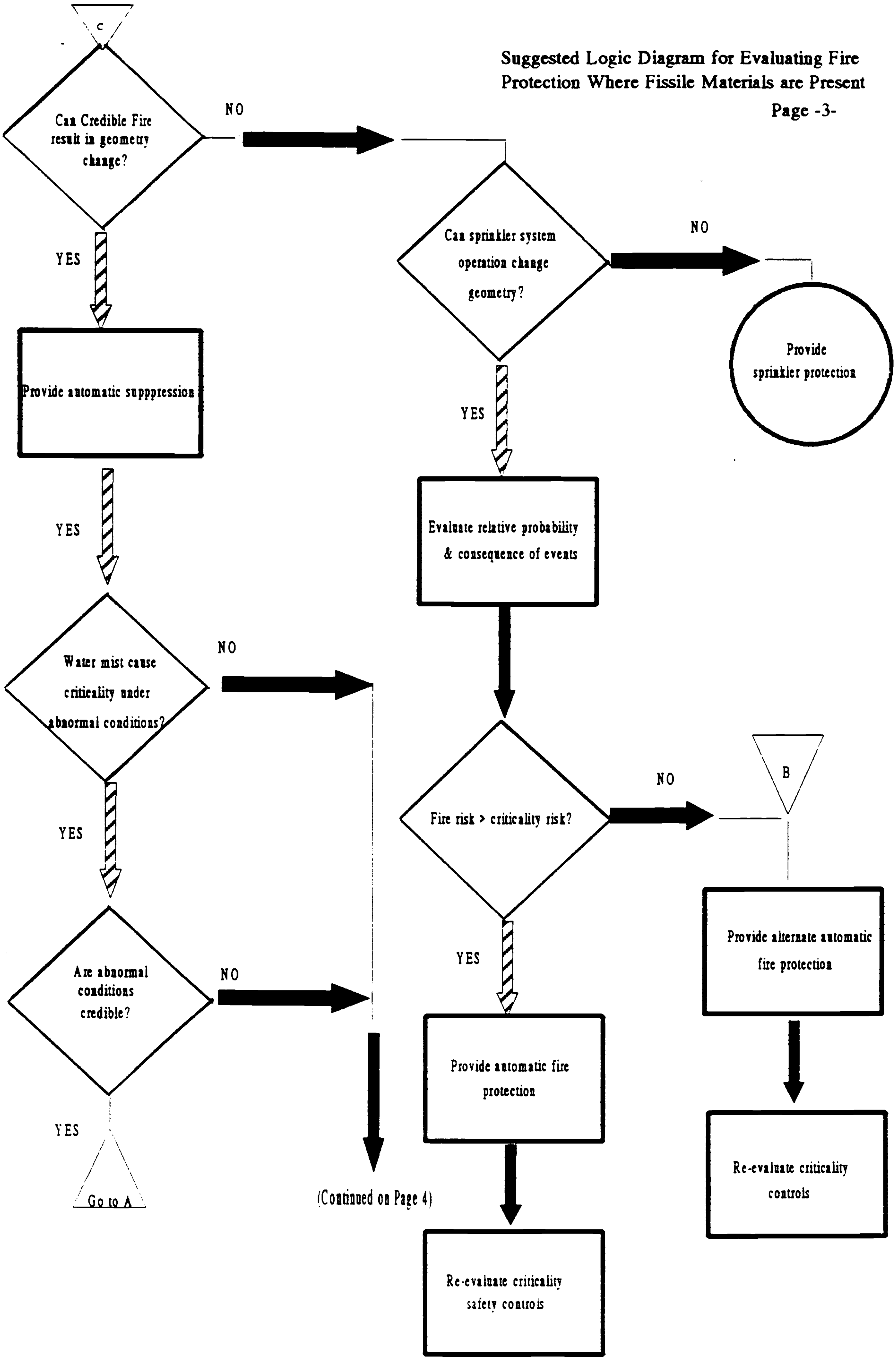
Suggested Logic Diagram for Evaluating Fire Protection Where Fissile Materials are Present



Suggested Logic Diagram for Evaluating Fire Protection Where Fissile Materials are Present



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Suggested Logic Diagram for Evaluating Fire Protection Where Fissile Materials are Present