May 28, 2002

MEMORANDUM TO: Mark Reinhart, Section Chief
Licensing Section
Probabilistic Safety Assessment Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

FROM: Eric W. Weiss, Section Chief/**RA/**
Fire Protection Engineering and Special Projects Section
Plant Systems Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

SUBJECT: FIRE HAZARD ANALYSIS FOR FIRE ZONE 98-J, EMERGENCY DIESEL GENERATOR CORRIDOR AND FIRE ZONE 99-M, NORTH ELECTRICAL SWITCHGEAR ROOM, ARKANSAS NUCLEAR ONE, UNIT 1 (TAC NO. MB2872)

The purpose of this memorandum is to provide you a preliminary Fire Hazard Analysis (FHA) for the Fire Zones 98-J and 99-M, Arkansas Nuclear One (ANO), Unit 1. This FHA has been performed as requested by your staff for the Phase 3 Significance Determination Process (SDP) concerning an Unresolved Item (URI) 50-313;368/0106-02 in the ANO Triennial Fire Protection Inspection Report (ADAMS Accession Number ML012330501).

This FHA suggests the postulated fire in Fire Zone 98-J and 99-M could damage the unprotected safety-related cables and alternate control panel before the completion of numerous manual actions required to operate components of redundant trains of equipments to achieve and maintain safe shutdown. The cable associated with redundant trains of components credited in the licensees's FHA for achieving and maintaining hot shutdown conditions were not protected from fire damage by one of the methods specified in Section III.G.2 of Appendix R to Title 10 of the *Code of Federal Regulations* (CFR) Part 50.

The staff concludes that the level of existing protection for the Fire Zone 98-J and 99-M will not provide a level of fire protection equivalent to 10 CFR Part 50, Appendix R, Section III.G.2.

If you require any additional information, please free to contact us.

Docket No. 50-313
License No. DPR-51

Attachment: As stated

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Attachment

Fire Hazard Analysis for Fire Zone 98-J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room Arkansas Nuclear One - Unit 1

Office of Nuclear Reactor Regulation
Division of Systems Safety and Analysis
Plant Systems Branch
Fire Protection Engineering and Special Projects Section

United States
Nuclear Regulatory Commission
Washington DC, 20555-0001

Executive Summary

A Fire Hazard Analysis (FHA) of the Fire Area I, Fire Zone 98J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room at Arkansas Nuclear One (ANO), Unit 1, has been performed. This FHA evaluates the potentially hazardous conditions (increased temperature, radiative heat flux, and smoke layer level) that could exist during a fire. This FHA also assesses the associated damage potential to the cables or equipment of redundant trains of systems required for safe shutdown using the guidelines provided in the National Fire Protection Association, NFPA 805, Appendix C, 2001 edition. Computational methods and empirical correlations have been used in the analysis based on fire dynamics principles to determine the Emergency Diesel Generator Corridor (Fire Zone 98-J) and North Electrical Switchgear Room (Fire Zone 99-M) condition for the different fire scenarios. The purpose of this FHA is to support a Phase 3 significance determination process (SDP) for an Unresolved Item (URI) 50-313;368/0106-02 in the ANO Triennial Fire Protection Inspection Report (ADAMS Accession Number ML012330501).

[redacted]

Region IV inspectors found that the configurations of Fire Zone 98-J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room, in Unit 1 did not meet the separation requirements specified in Title 10 of the *Code of Federal Regulations* (CFR) Part 50, Appendix R, Section III.G.2. Region IV inspectors also found that the licensee had not adopted an approach that provided adequate protection to cables and equipment of redundant trains of systems necessary to achieve and maintain hot shutdown conditions from fire damage as specified in 10 CFR Part 50, Appendix R. The licensee has not analyzed these fires zones for potential mal-operation of equipment that could effect post-fire safe shutdown capability and has not implemented procedures to address potential mal-operations. Rather, the licensee credits a symptom-based approach that relies on the operator's ability to detect each mal-operation as it occurs and perform manual actions as necessary to mitigate its effects.

The effects of fire in Fire Zone 98-J has been analyzed by the staff using the heat release rate (HRR) from a small postulated spill of lubricating oil onto the Emergency Diesel Generator

Corridor floor. The analysis shows that turbulent diffusion flames from the pool fire would impinge the non-qualified Institute of Electrical and Electronics Engineers (IEEE-383) cable insulation resulting in ignition and flame spread of the cables located in the trays. Since the fire detection wires are located on top of cables in the trays, it is expected that significant damage to cables before the heat detection wire activated to provide one of the required cross-zoned signal to automatically actuate the fire suppression system.

Since the Emergency Diesel Generator Corridor provides access to the diesel generator rooms, it is possible that a large pool fire involving significant quantities of lubricating oil could spill near the doorway to the Electrical Equipment Room 111, which upon ignition could damage redundant trains prior to activation of the cross-zoned corridor fire suppression system.

Radiative heat flux from a 100 lb (45.5 kg) transient fire in Fire Zone 99-M could also ignite unprotected safety-related cables. This Fire Zone contains the green train switchgear; however several cables associated with red train safe shutdown also equipment traverse through this Fire Zone. These red train cables are not protected with a 1-hour rated fire barrier and are not separated from red train redundant cables by a minimum 20 feet distance with no intervening combustible. Based on the FHA results hazardous conditions could be expected to occur in a relatively short period of time in this Fire Zone. Under these conditions a fire could damage the alternate shutdown panel.

Based on the results of this FHA, the postulated fire in Fires Zone 98-J and 99-M could damage the unprotected safety-related cables and alternate control panel before the completion of numerous manual actions required to operate components of redundant trains of equipments necessary to achieve and maintain safe shutdown.

The fire modeling performed by the licensee does not provide reasonable assurance that one train of safe shutdown cables will be maintained free of fire damage. This is because the HRR data used in the fire modeling for the source fires (electrical cabinets) is based on the combustion of cable insulation only and neglects the large energy release due to energetic electrical faults.

Therefore, the staff concludes that the level of existing protection for Fire Area I, Fire Zone 98-J and 99-M does not provide a level of fire protection equivalent to 10 CFR Part 50, Appendix R, Section III.G.2 and does not meet 10 CFR Part 50 §50.48 (a)(2)(iii) in that means have not been provided to limit fire damage to structures, systems, or components important to safety so that the capability to shutdown the plant safely is ensured.

Background

A Triennial Fire Protection Baseline Inspection was conducted at ANO, Unit 1 and 2, during the period of, June 11-22, 2001, to review the licensee's (Entergy Operations, Inc.) fire protection program (FPP) for selected risk significant fire areas. During the inspection, emphasis was placed on verification that the post-fire safe shutdown capability and fire protection features provided for ensuring that at least one post-fire safe shutdown success path would be maintained free of fire damage. The inspection was performed in accordance with the U.S. Nuclear Regulatory Commission (NRC) Reactor Oversight Process (ROP) using a risk-informed approach for selecting the fire areas and attributes to be inspected. As a part of this approach, the inspectors used a significance determination process (SDP) to evaluate the significance of the potential fire risks to the operating reactor as required by NRC Inspection Manual (NRC Inspection Manual, Chapter 0609F, Appendix F, 2001). A key step in the SDP is determining whether a credible fire scenario is possible.

Region IV inspectors found that the configurations of Fire Zone 98-J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room, in Unit 1 did not meet the separation requirements as specified in Title 10 of the *Code of Federal Regulations* (CFR) Part 50, Appendix R, Section III.G.2 [NRC Inspection Report 50-313/01-06; 50-368/01-06, August 20, 2001 (ADAMS Accession Number ML012330501)]. Region IV inspectors also found that the licensee had not provided adequate protection to cables and equipment of redundant trains of systems located in the same fire area necessary to achieve and maintain hot shutdown conditions free from fire damage as specified in 10 CFR Part 50 Appendix R. Rather, the licensee relied on manual actions to mitigate the effects of a fire on cables associated with equipment necessary for achieving and maintaining hot shutdown conditions. This is inconsistent with the requirements specified in 10 CFR Part 50, Appendix R, Section III.G.2.

There are numerous manual actions that are required in Fire Zones 98-J and 99-M and the licensee did not implement procedures for coordinating these actions. In addition, the licensee did not provide any information to the operators concerning which of these manual actions are time critical. The licensee did not submit an exemption/deviation for the use of manual actions (in lieu of the requirements of 10 CFR Part 50 Appendix R) and as such there was no NRC staff review prior to the inspection team's findings.

Region IV assessed the significance of these findings using the SDP. The Phase 2 SDP results for the finding pertaining to the Fire Zone 98-J resulted in 7 yellow sequences, 16 white sequences, and 5 green-next-to-white sequences. The Phase 2 SDP results for the finding pertaining to the Fire Zone 99-M resulted in 1 yellow, 15 white, and 0 green-next-to-white sequences (ADAMS Accession Number ML012530361).

Subsequent to the Region IV Triennial Fire Protection Inspection, the licensee submitted a letter, 0CAN090103, dated September 28, 2001 to NRC, response to the Unresolved Item(URI) 50-313;368/0106-02 in the ANO Triennial Fire Protection Inspection Report (ADAMS Accession Number ML012710489) and provided an evaluation to justify the use of manual actions to operate components of redundant trains of equipments in Fire Zones 98-J and 99-M to achieve and maintain safe shutdown in the event of a fire.

By memorandum dated September 10, 2001, (ADAMS Accession Number ML012530361), Region IV transmitted a Task Interface Agreement (TIA) 01TIA11 to the Office of Nuclear Reactor Regulation (NRR) concerning URI 50-313;368/0106-02 in the ANO inspection report, which states, "The acceptability of the use of manual actions in lieu of providing protection for cables associated with equipment necessary for achieving and maintaining hot shutdown (for Fire Zones 98-J and 99-M) for meeting 10 CFR Part 50, Appendix R, Section III.G.2 is an unresolved item pending further NRC review. The significance of this issue is also part of this unresolved item".

Region IV requested that NRR perform a Phase 3 significance determination of the fire protection inspection findings (URI 50-313;368/0106-02) concerning Fire Zone 98-J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room and provided a list of components in Fire Zones 98-J and 99-M to use in the evaluation of the Phase 3 significance determination.

In responding to the URI 50-313;368/0106-02, the licensee performed a fire modeling and hazard analysis to assess potential hazards using EPRI TR-100370, "Fire-Induced Vulnerability Evaluation (FIVE) Methodology," and EPRI TR-100443, "Methods of Quantitative Fire Hazard Analysis," for significance determination of fire risk in the Fire Zones 98-J and 99-M in an attempt to justify the use of manual actions to operate components of redundant trains of equipments. This evaluation was submitted to NRR for the review.

The FIVE methodology was developed with the explicit requirements that it support a probabilistic risk assessment (PRA) for NPP fire analysis as required by the NRC Generic Letter (GL) 88-20, Supplement 4. NRC approved FIVE methodology to use as a screening tool required for fire PRA to conduct Individual Plant Examination of External Events (IPEEE).

In this fire modeling analysis, the licensee modeled fires in Fire Zone 98-J using 480V motor control centers (MCCs), DC distribution panels, battery chargers, small totally enclosed cabinets, and a dry transformer associated with 480V load center. Fire Zone 99-M was modeled using 4160V switchgear, 480V MCCs, inverters, and electrical cabinets that contained cables. The values of heat release rates (HRR) used to calculate heat fluxes to the target (open cable trays) derived from the electrical cabinets (source fire) was either 68.60 kW and 200.50 kW (65 or 190 BTU/sec) dependent on type of cable installed. These values are based on the guidance provided in Electric Power Research Institute (EPRI) report SU-105928, "A Supplement to EPRI Fire PRA Implementation Guide (TR-105928)". In addition, the licensee assumed HRR for emergency chiller compressor lube oil 314 kW (203 BTU/sec) and 68 kW (65 BTU/sec) for motor associated with chiller but failed to model any fire using these HRR.

The staff takes exception to the licensee HRR values used in fire modeling for the source fires, (electrical cabinets) i.e., both 68.60 kW and 200.50 kW (65 and 190 BTU/sec). The EPRI published data focuses on the HRR contributions of combustibles in the electrical cabinet (only cable insulation) and neglects the large energy release based on the amperes squared multiplied by time (I^2t). Experience has demonstrated, most recently at San Onofre Nuclear Generating Station (SONG) Unit 3 Fire, February 3, 2001, (ADAMS Accession Number ML 011130255) that heat from an electrical fault in a cabinet can vaporize copper conductors and destroy surrounding metal cabinets. For medium- and high- voltage applications preliminary NRC research indicates that these HRR values [68.60 kW and 200.50 kW (65 and 190 BTU/sec)] may be under predicting by a factor of 1000.

Using realistic assumptions and expected fire scenarios, the staff has performed a FHA to evaluate potential damage associated with specific fires in Fire Zone 98-J, Emergency Diesel Generator Corridor and Fire Zone 99-M, North Electrical Switchgear Room. This FHA involves using more realistic analytical evaluation techniques in order to quantify the potential impact of fire scenarios on these two Fire Zones.

Objectives

Plant Systems Branch (SPLB) has performed a Fire hazard analysis (FHA) of the ANO, Unit 1, Fire Zones 98-J, Emergency Diesel Generator Corridor and 99-M, North Electrical Switchgear Room to evaluate the potentially hazardous conditions (increased temperature, radiative heat flux, and smoke layer height) that could exist during fire and assess the associated damage to the cables or equipment of redundant trains of systems necessary to achieve and maintain hot shutdown conditions in using the guidelines provided in National Fire Protection Association, NFPA 805, Appendix C, 2001 edition.

The objective of SPLB's FHA is to determine if a fire scenario could potentially cause failure of the cables and redundant trains of required safe shutdown equipment system.

Assumptions and Limitations

(1) Information on the potential fuel load present in Fire Zones 98-J and 99-M is based on the information provided by the licensee. It is assumed that the documentation, drawing, and plans that were provided are accurate.

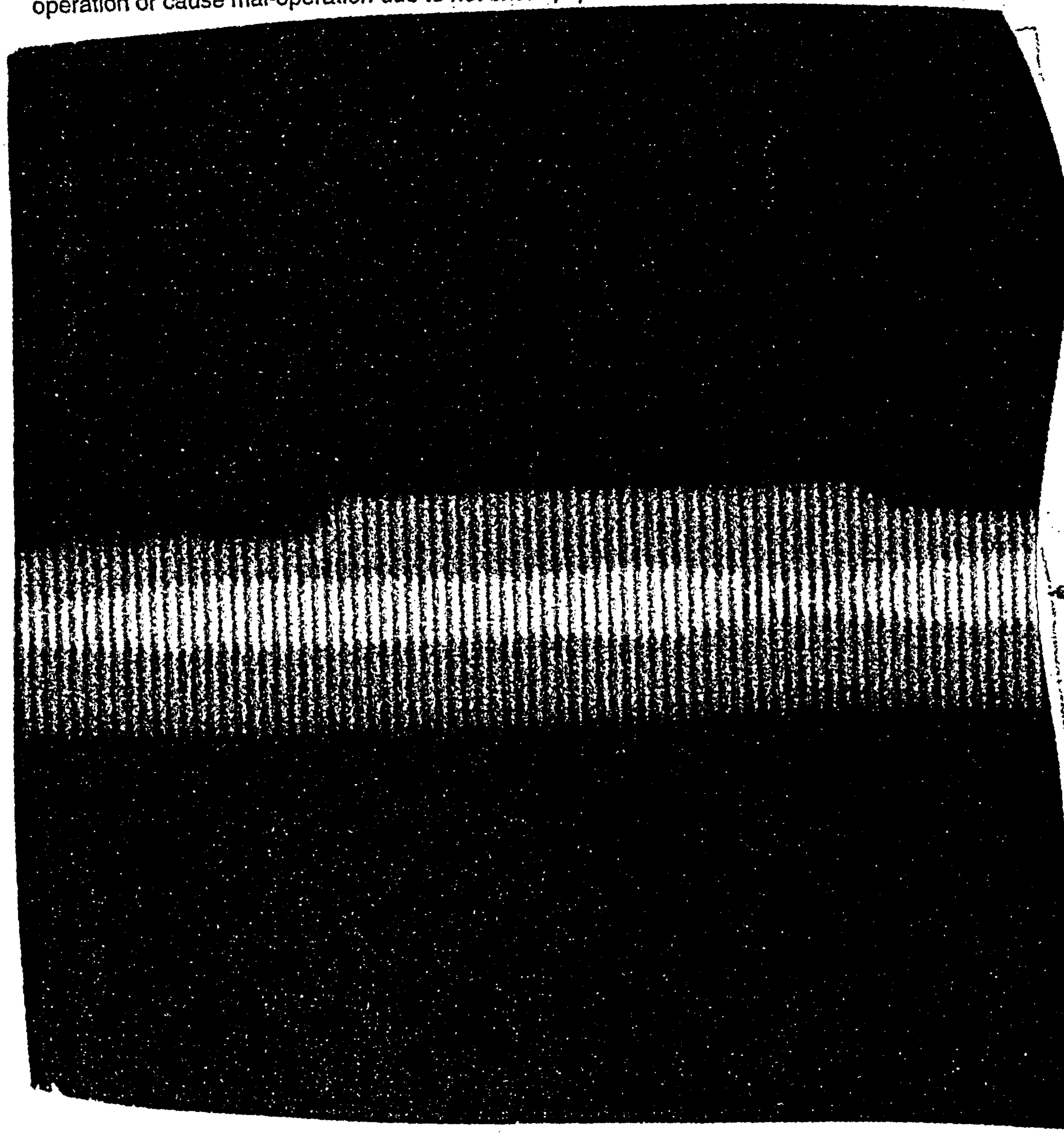
(2) In keeping with sound engineering practice in the absence of technical information, conservative worst case assumptions are made regarding the fuel loading, fuel package HRRs, and fire spread.

(3) It should be recognized that a detailed evaluation of potential ignition sources is not included in the analysis. Fire sources were identified by the licensee in the submittal. Also, a probabilistic risk assessment is considered outside the scope of this analysis.

(4) This analysis assumes that the ignition occurs. [Note: the ignition frequency of fires resulting from an ignition source is accounted for in the SDP, Ignition Frequency (IF) term]. Further, it is assumed that the fire occurs in the Fire Zones 98-J and 99-M will burn without immediate intervention from the plant fire brigade. In the absence of technical information, conservative worst case assumptions are made regarding the fuel loading, HRRs, and fire growth and spread in fire zones.

Fire Zones Description

The Fire Area I located at 372'-0" elevation in the auxiliary building contains multiple Fire Zones. The two Fire Zones of concerns are 98-J and 99-M. These Fire Zones contain safety-related cables associated with redundant trains of components and systems necessary to achieve and maintain hot shutdown conditions (including associated non-safety circuits that could prevent operation or cause mal-operation due to hot shorts, open circuits, or short to ground).



The switchgear room is protected with only smoke detection system, there are no fixed automatic fire suppression systems in this room. Smoke detectors are provided at the ceiling level which alarm in the MCR. A fire hose reel and portable CO_2 extinguishers are also provided for manual fire fighting. The combustibles assumed to be in this area include cable insulation and jacket material in open cable trays (cables are non-qualified IEEE-383) and an allowed 100 pounds (45.5 kg) of transient combustibles. Transient combustibles in excess of 100 pounds (45.5 kg) and flammable liquids require the attendance of a continuous firewatch by the plant procedures. This fire zone is normally unoccupied except for inspections, shift tours and maintenance activities [ANO, Unit 1, Fire Hazard Analysis (ADAMS Accession Number ML003702077)].

Ignition Sources Fire Characterization

It is not a sound safety engineering practice to rely on controlling the fire hazards solely by attempting to control or limit potential ignition sources. The ignition sources that may cause the most damaging fires could also be the result of multiple failure modes. Thus, ignition sources are identified to demonstrate their existence and to provide a basis from which to assume ignition of fuel sources. Particularly in any location where electrical energy is distributed and used, components and connections are potential fire ignition sources. This issue was discussed in May 29, 1980, Federal Register notice for the Proposed Rule of 10 CFR Part 50 Appendix R:

> *"The guidelines in both the BTP 9.5-1 and Appendix A to BTP 9.5-1 were developed to provide a fire protection program that has two basic objectives:*
>
> *1. to identify and distinguish between those consequences of fire that are acceptable and those consequences that are not.*
>
> *2. to provide necessary means to minimize all consequences of fire and to prevent unacceptable consequences from occurring.*
>
> *With respect to the first objective, the phenomenon of fire is believed to be sufficiently well understood to permit evaluation of existing and potential fire hazards and probable extent of damage should a fire occur. Such evaluations are useful in assessing the possible consequences of fire in a given area. However, the phenomenon of fire is so unpredictable in occurrence and development that measures to prevent unacceptable consequences may not be omitted on the basis of low probability of occurrence. The minimum fire protection requirements for nuclear power plants must be established not only to identify fire hazards but also to protect against unacceptable consequences of fire".*

The NRC fire protection requirements in 10 CFR Part 50 and the supporting guidance address fires due to energetic faults. Energetic electrical faults can result in explosions, arcing, fire, ionized gases, smoke, spurious actuation of circuit breakers, other circuit failures, collateral damage to adjacent equipment, and latent equipment failures independent of the fire.

General Design Criterion (GDC) 3, "Fire Protection," of Appendix A to 10 CFR Part 50 requires that structures, systems, and components important to safety be designed and located to minimize, consistent with other safety requirements, the probability and effects of fires and explosions. Section 50.48, "Fire Protection," of 10 CFR Part 50 requires that each operating NPP have a fire protection plan that satisfies GDC 3 of Appendix A to 10 CFR Part 50.

NRC guidance in Regulatory Guide 1.189, "Fire Protection for Operating Nuclear Power Plants," April 2001, Section 4.1.3.6, "Electrical Cabinets," states that electrical cabinets (for example 4.16 kV to 13.8 kV switchgear) present an ignition source for fires and a potential for explosive electrical faults that can result in damage not only to the cabinet of origin but also to equipment, cables, and other electrical cabinets in the vicinity of the cabinet of origin. Regulatory Guide1.189 also states that fire protection systems and features provided for the general area containing the cabinet may not be adequate to prevent damage to adjacent equipment, cables and cabinets following an energetic electrical fault; therefore high voltage cabinets should be provided with adequate spatial separation or adequate physical barriers to minimize the potential for an energetic electrical fault to damage adjacent equipment, cables, or cabinets important to safety.

The NFPA Industrial Fire Hazard Handbook 3rd Edition (Whittington, 1990) states, "In recent years, particularly on high-fault capacity, low-voltage 208Y/120-volt systems, there have been numerous reported cases of arcing fault burnouts in which severe damage to, or complete destruction of, electrical equipment has been caused by the energy released in the arc. Typically, the arcing fault becomes established between a phase and ground, or between phases and ground. The fault arc releases enormous amounts of energy based on the amperes squared multiplied by time (I^2t), with heat so intense that it vaporizes copper or aluminum conductors and destroys the surrounding steel enclosures (melting point temperature of copper and aluminum is 1084 °C (1983 °F) and 660 °C (1220 °F) respectively). Any combustibles stored in the immediate vicinity of the equipment would also be ignited".

The NFPA Fire Protection Handbook, 18th Edition, Table 3-1E provides an overview of 1989 through 1993 structural fires due to electrical distribution equipment reported to U.S. fire departments that were coded as caused by electrical failures (Caloggero, 1997). This statistic shows that 40,350 structural fires were reported to the various fire departments due to electrical distribution equipment involved in ignition (see Table 1).

Table 1
Structure Fire Due to Electrical Failure

(Annual Average of 1989 Through 1993 Fires Reported to the U.S. Fire Departments)

Electrical Distribution Equipment Involved in Ignition	Average Number of Fires per Year
Fixed wiring	15,850
Transformer	790
Meter or meter box	740
Overcurrent protection device (e.g., fuse, circuit breaker)	2,880
Switch, receptacle, or outlet	4,420
Lighting fixture, lamp holder, ballast, or sign	5,130
Cord or plug	7,040
Lamp or light bulb	720
Unclassified type	1,210
Unknown type	1,570

Therefore, a source of ignition which cannot be ruled out is electrical equipment and components. The fire hazard arises from the electrical discharge from equipment/component/cable followed by ignition of surrounding combustibles, namely cable jackets and insulation in this analysis. For the fire scenarios developed in this fire dynamics calculation the source of ignition will be assumed to be an electrical failure.

Significant Fire Sources in Fire Zones 98-J and 99-M

The Fire Zones within the Fire Area I have been identified as potentially posing a serious fire hazard, URI 50-313;368/0106-02. Table 2 provide a list of ignition sources located in Fire Zones 98-J and 99-M. These ignition sources were used in the Phase 2, SDP evaluation and are provided in ANO Triennial Fire Protection Inspection Report.

Table 2
List of Ignition Sources in Fire Zone 98-J and 99-M
ANO Triennial Fire Protection Inspection, Attachment 2, "Phase 2 Significance Determination" (ADAMS Accession Number ML012530361)

Ignition Sources	
Fire Zone 98-J, Emergency Diesel Generator Corridor	Fire Zone 99-M, North Electrical Switchgear Room
Electrical wall-mounted cabinets 125V DC distribution panels Instrumentation cabinets Emergency chiller water pump Switchgear room emergency chiller Battery charger room A/C unit North batter room/Charger room unit cooler South battery room/Charger room unit cooler	4160V switchgear (vital and non-vital) 480 V motor control center 480V load center 120V instrument panel/transformer Y4/X62 Inverter panels Y28, Y22, Y24, and Y25 Switchgear room cooler, VUC 2C and 2D Transformer X6

Fire Scenario Development

The primary combustibles in the Fire Zone 98-J and Fire Zone 99-M are the safety-related non-qualified IEEE-383 electrical cables routed in open cable trays. A characteristic of non-qualified

IEEE-383 cable is the relatively rapid spread of the flame front down the cable when contrasted to IEEE-383 qualified cables. Also non-qualified IEEE-383 cables typically use a thermoplastic polymer in their construction which will ignite at approximately 218 °C (425 °F). A potential fire in 4160V switchgear or electrical wall-mounted cabinets can pose an ignition source to the cable trays in both Fire Zones. The height of the lowest cable tray in the Fire Zone 98-J, Emergency Diesel Generator Corridor is approximately 6 ft (1.82 m) from the floor. The worst case scenario is dominated by the cable trays that are closest to ignition sources. Main ignition sources in the Fire Zone 98-J include, but are not limited to, the electrical wall-mounted cabinets, 125V DC distribution panels, and instrumentation cabinets (see Table 2) and accidental the spill of emergency chiller chilled water pump lube oil and subsequent pool fire.

Ignition sources in the Fire Zone 99-M include, but are not limited to, the 4160V switchgear (vital and non-vital) 480V MCC, 480V load center, 120V instrument panel/transformer Y4/X62, inverter panels Y28, Y22, Y24, and Y25 (see Table 2). Another credible fire scenario is possible from ignition of the 100 pounds (45.50 kg) of transient combustibles that are allowed by plant procedures in Fire Zone 99-M.

The failure of the emergency chiller chilled water pump lube oil pool fire in this fire dynamics analysis is postulated to ignite the in-situ combustibles (cables) in Fire Zone 98-J. Other ignition sources such as hot work during maintenance activities are possible, but beyond the scope of this analysis. The plant allowed 100 pounds (45.50 kg) of transient combustibles was used to model a fire in Fire Zone 99-M.

Heat Release Rate Estimate

An essential component of the FHA is the determination of the HRR characteristics of the critical combustible fuel. As previously stated the critical fuel in Fire Zone 99-J and Fire Zone 99-M is the electrical cable insulation and jacket material in open trays. For this type of analysis, a broad approximation of burning rates is acceptable. For example, post flashover structure analyses are often based on the fire duration or fire severity associated with an aggregate fuel loading (combustible load per unit floor area). However, if it is essential to estimate specific fire effects within an enclosure, a more accurate determination of burning rate characteristics (i.e., HRR) is necessary.

The HRR is not a fundamental property of a fuel and, therefore, cannot be calculated from the basic material properties alone. Estimates of fire source intensities (HRR) can be based either on direct burning rate measurements of similar large fuel configurations or the extrapolation of small-scale test data obtained under simulated thermal conditions. Representative unit HRR values for a number of fuels present in a NPP, e.g., cables, electrical cabinets, flammable/combustible liquids, and transient combustibles have been measured and reported in various reports (Lee, 1981, Lee, 1985, Hill, 1982, NUREG/CR-3192, Nowlen, 1986 (NUREG/CR-4680), Nowlen, 1987 (NUREG/CR-1987), Chavez, 1987 (NUREG/CR-4527/1), Braun *et al.,* 1989, and Babrauskas *et al.,* 1991). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires in NPPs. Cable and electrical cabinet fires constitute the most commonly postulated fixed fuel fires.

The assumptions associated with the HRR estimate included the following:

(1) the initial growth rate corresponding to $\dot{Q} = \alpha t^2$, medium fire growth rate,

(2) the mass available for consumption during the period of peak energy release rate was 80 percent of the total available combustible mass, therefore the remaining 20 percent of the mass loss is attribute to the initial growth period and the decay period.

These assumptions are based on the fact that in real fires, where typically only 70 to 80% of the mass is converted to volatiles that burn almost completely, leaving some char or residue. Additionally, some of the volatiles do not combust completely, leaving some combustible components such as carbon monoxide (CO), soot, and unburnt hydrocarbons in the products of combustion.

Fire Hazard Analysis

The FHA is used to determined the extend of the potential fire damage associated with a realistic worst case fire scenario to Fire Zone 98-J and Fire Zone 99-M and the anticipated failure of safety-related cables or equipment of redundant trains of systems required for safe shutdown. The impact of the fire scenario is analyzed using fundamental fire dynamics principles. The results from this analysis are then used to postulate the potential damage to Fire Zone 98-J and Fire Zone 99-M.

Two fire scenarios were considered in the analysis. They are: (1) a flammable liquid lubricating oil spill fire in Fire Zone 98-J, Emergency Diesel Generator Corridor and subsequent ignition of cables in open trays (conservative realistic worst case fire scenario, because of the significant amount of redundant cables in the Fire Zone, which are not protected against fire damage), and (2) a transient fire [100 pounds (45.50 kg)] in Fire Zone 99-M (conservative realistic worst case fire scenario based on the plant administrative control procedures).

Combustible Liquid Lubricating Oil Spill in Fire Zone 98-J, Emergency Diesel Generator Corridor

Accidental spills of combustible liquid fuel and resulting fires depend on a number of parameters, including the composition of the fuel, the size and the shape of the fire, the duration of the fire, its proximity to the object (target) at risk, and the thermal characteristics of the object exposed to the fire.

A liquid with a relatively high flash points requires localized heating to achieve ignition. Once ignited however, a pool fire will spread rapidly over the surface of the liquid spill area. The area of burning will be a function of the leak rate or the confinement of the spill area. While the burning rate of a given fuel can be affected by its substrate in a spill, any absorption characteristics of the substrate was not considered since the floor is smooth finished concrete. In this analysis it is conservatively assumed that the fuel is spills over the surface of the pedestal and forms a pool with the region of burning maintained at its depth. The effect of this initiating fire event in Fire Zone 98-J (Emergency Diesel Generator Corridor) is evaluated.

The fire scenario is developed for a fire developing from a single gallon of combustible lubricating oil spilled from the emergency chiller chilled water pump. This scenario involves a breach or leak in the pump's oiling system. This event allows the fuel contents of the pump (heated lubricating oil) to spill and spread over the floor.

For the purpose of evaluating the ability of the pool fire to ignite cables in Emergency Diesel Generator Corridor, the worst case scenario is the largest pool area which can burn long enough to cause ignition to cables.

A large number of fire scenarios are possible based on the variable size of the unconfined flammable liquid spill. Larger area spills will burn with a high HRR for a short duration while smaller area spills will burn a lower HRR for a longer duration. The HRR of the fire can be estimated using the following expression:

$$\dot{Q} = \dot{m}\Delta H_{c,eff} \qquad (1)$$

where:

$\dot{Q}$ = heat release rate (kW)

$\dot{m}$ = burning or mass loss rate (kg/sec)

$\Delta H_{c,eff}$ = effective heat of combustion (kJ/kg)

The height of a flame is a significant indicator of the hazard since it directly relates to flame heat transfer and the propensity to impact surrounding objects. As the plume of hot gases rises above a flame, the temperature, velocity, and width of this plume changes due to the mixing of the plume with the surrounding air. The size (height) and temperature of the flame are important in estimating the ignition of adjacent combustibles. Flames are characterized by a highly intermittent pulsing structure, particularly along the perimeter and near the top of the flame. The intermittency is driven largely by the turbulent mixing of air and subsequent combustion, the formation of new eddies and their mixing into the flame. The pulsing behavior affects the temperature of the flame. The temperature at a fixed position will fluctuate widely, particularly around the edges and near the top of the flame. Therefore, flame temperature is usually reported in terms of the average flame temperature or centerline temperature.

The flame height is a quantitative characteristic that is of practical importance in many fire situations. The flame height is normally defined as the height at which the flame is observed at or above fifty percent of the time. Above the fuel source, the flaming region is characterized by high temperature and is generally luminous. Flames from pool fires fluctuate periodically so that the tip of the flame will be significantly different from the length of the continuous combustion (or luminous) region. Consequently, flame height has been defined by various criteria in order to correlate data.

The flame height is also an important characteristic of a fire that may affect fire detection and suppression design, fire heating of building structures, smoke filling rates, and fire venting. The flame height will depend on whether the flame is laminar or turbulent. Short flames generally will be laminar and tall flames turbulent. The following correlation is widely used for determining the flame height of pool fires:

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \qquad (2)$$

where:

H_f = flame height (m)

$\dot{Q}$ = heat release rate of the fire (kW)

D = diameter of the fire (m)

The above correlation can be used for determining the length of the flame extension along the ceiling and can be used when estimating radiative heat transfer to objects in the enclosure.

When a spilled liquid is ignited, a pool fire develops. Provided that an ample supply of oxygen is available, the amount of surface area of the given liquid becomes the defining parameter. The diameter of the pool fire will depend upon the release mode, release quantity (or rate), and the burning rate. For a fixed mass or volume of flammable/combustible liquid, the burning duration t_b, for the pool fire is estimated using the following expression:

$$t_b = \frac{4V}{\pi D^2 v} \qquad (3)$$

where:

t_b = burning duration (sec)
V = volume of liquid (gallons or m^3)
D = pool diameter (m)
v = regression rate (m/sec)

For non-circular pools, the effective diameter D, will be defined as the diameter of a circular pool with an area equal to the actual pool area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (4)$$

where:

D = effective pool diameter (m)
A_f = surface area of the non-circular pool

As a pool of burning liquid is consumed, its depth decreases. This rate of burning is called the regression rate and is defined as, volumetric loss of liquid per unit surface area of the pool per unit time. The regression rate can be expressed as:

$$v = \frac{\dot{m}''}{\rho} \qquad (5)$$

where:

v = regression rate (m/sec)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

Table 3 provides the results of the calculation, HRR and burning duration of liquid spill in Fire Zone 98-J. Appendix A provides the detailed Microsoft Excel® worksheets to estimate HRR, flame height, and burning duration of the pool fire. (See Worksheets 1, 2, and 3 for calculations)

Table 3
Fire Characteristics of Lubricating Oil

Lubricating Oil Volume = 1 gallon (0.00378 m^3)
Lubricating Oil Burning Rate = 0.039 kg/m^2-sec (Babrauskas 1995)
Lubricating Oil Heat of Combustion = 46000 kJ/kg (Babrauskas 1995)
Lubricating Oil Heat of Density = 760 kg/m^3 (Babrauskas 1995)
Height of Cable Tray from Floor = 6 ft (1.82 m) (Cable are non-qualified IEEE-383)

Fuel Spill Area, A_f m² (ft²)	Liquid Spill Diameter, D m (ft)	Heat Release Rate, $\dot{Q}$ kW	Pool Fire Flame Height, H_f m (ft)	Flame Impingement to Cable Tray	Burning Duration, t_b min
0.072 (0.785) **Worksheet 1**	0.3048 (1.0)	131	1.34 (4.5)	No	17
0.164 (1.77) **Worksheet 2**	0.4572 (1.5)	295	1.82 (6)	Yes	7.5
0.291 (3.14) **Worksheet 3**	0.6096 (2.0)	524	2.25 (7.4)	Yes	4.2

The above calculation shows that the ignition of the cables insulation is possible in cases when lube oil spills and forms a pool fire with a diameter of approximately 1.5 ft. In this case flame will impinge to the cable insulation which are non-qualified IEEE-383 (the height of the lowest cable tray in the Emergency Diesel Generator Corridor is 6 ft (1.82 m) from the floor. This is based on the EPRI TR-105928 (page 4-27), which states, "*Direct Flame impingement for ten minutes is necessary to ignite and propagate a fire in* ***qualified cable***". All cables in Emergency Diesel Generator Corridor are IEEE-383 non-qualified (non-rated). Non-qualified IEEE-383 cables are typically thermoplastic construction which will lose electrical integrity at an early stage of the fire when compared to IEEE-383 qualified cables (typically thermoset material). Non-qualified cables will also ignite at lower heat flux in less time. Once the failure temperature of the cable is reached, a hot short can occur that could result in the actuation of circuit breakers and circuit failure.

In addition, EPRI TR-100370, Fire-Induced Vulnerability Evaluation (FIVE) Methodology provides damage threshold failure temperature and heat flux for IEEE-383 qualified and non-qualified cables for FHA and fire modeling evaluation. On page 10.4-7, EPRI TR-100370 states that, "*A damage threshold temperature of 700 °F (370 °C) and a critical heat flux of 1 Btu/ft²-sec (10 kW/m²) have been selected for qualified cables for screening purposes. A damage threshold temperature of 425 °F (218 °C) and a critical heat flux of 0.5 Btu/ft²-sec (5 kW/m²) have been selected for non-qualified cables for screening purposes*". Thus the 7.5 minute flame impingement could be capable of igniting the non-qualified IEEE-383 cables.

Testing of energized electrical unaged and aged cables has shown a significant levels of leakage current to occur when the cables reach their critical temperature (NUREG/CR-5546). Leakage current on the order of 15 mA was observed prior to the onset of cable failure. It was also observed that once failure occurred the arcing caused the initiation of intense, sustained, open flaming in the cable samples further spreading the fire. Therefore, direct flame impingement causes preheating and ignition of non-qualified IEEE-383 cables leading to cable failure in the Emergency Diesel Generator Corridor, and initiation of a secondary fire in the cable trays which further increases the total HRR in Fire Zone 99-M.

The flame height is high enough to potentially engulf the cables causing ignition and flame spread along the cable trays. It is considered that the burning durations of a single gallon pool fire are long enough for the cables to reach critical heat flux for ignition. Because failure of the unprotected safety-related cables would be likely with such a small quantity of combustible liquid as an ignition source, further detailed fire modeling analysis is not warranted. Likewise, a larger quantity of combustible/flammable liquid (e.g., 5 gallon of transient lube oil) could produce similar/worse exposure fires.

100 lb (45.5 kg) Transients Combustibles Burning in Fire Zone 99-M, North Electrical Switchgear Room

Based on the information provided by the licensee, 100 pounds (45.50 kg) combustible materials (transients) may be stored in the Fire Zone 99-M without administrative control. A review of the literature was made of experimental data concerned with the fire growth from 100 lb (45.5 kg) combustible materials (transients). It appears that there are no direct data available on the burning of these fuel packages at full or intermediate scale. However, there are full scale test results available for plant trash, approximately 68 lb (31 kg) fire (NUREG/CR-3192). These tests were sponsored by the U.S. Nuclear Regulatory Commission to examine the adequacy of the 20-foot separation requirement, one of the requirements set forth in Appendix R of 10 CFR 50.

In this test series, twelve experiments were conducted at the Sandia National Laboratories (SNL) fire test facility in an enclosure 7.6 m x 7.3 m x 5.5 m high (25 ft x 24 ft x 18 ft high), in which 6 different fuels were evaluated as the ignition sources (heptane pool fire and solid fuel trash fire). A wall 2.4 m (8 ft) wide by 3.7 m (12 ft) high was constructed on a mobile test platform located near the center of the fire test enclosure. The fires were instrumented to measure and record fire temperature, heat flux, and fuel mass loss. Fire temperature was measured with 10 thermocouples on the wall adjacent to the fire platform. Radiative heat flux was measured with five calorimeters (heat flux gauges) located to the front and to the side of the fire platform.

The fuel sources in experiments 4 and 11 was simulated plant trash. The trash consisted of 25 lb (11.4 kg of rags, 17 lb (7.7 kg) of paper, 13 lb (5.9 kg) of plastic products (gloves and tape), and 2 gallons (7.5 liters) (5.9 kg) of methyl alcohol evenly mixed and placed in two trash bags (approximately 50 gallon size) [total 68 lb (31 kg)]. Figure 2 shows the measured radiative heat flux as a function of time for different ignition sources and also the duration of the fire. The plant trash fire test (experiments 4 and 5) results shows that the solid trash experiments were still burning after 30 minutes when the experiments were terminated. The measured peak heat flux

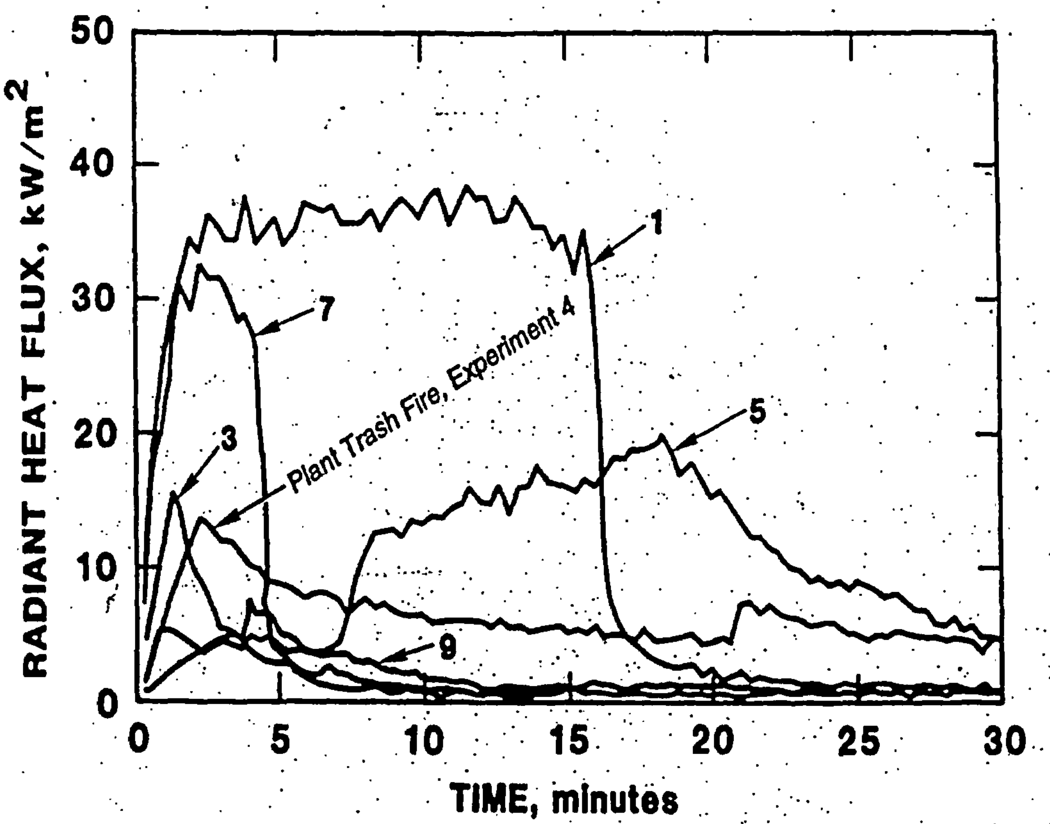


Figure 2 Fire Heat Flux Measurements for Heptane Pool Fire and Solid Fuel Trash Fire
Plant Trash Fire (Experiment 4) - 26 lb rags + 17 lb paper towels + 13 lb of plastic products (gloves and tape) + 2 gallon of methyl alcohol. Evenly mixed and placed in two plastic trash bags (approximately 40 gallon size)
(NUREG/CR-3192, "Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R")

for plant (experiment 4) trash fire was approximately 15 kW/m^2 at approximately 3 minutes in to the fire and 8 kW/m^2 steady-state at the end of experiment (30 minutes).

NUREG/CR-3192, experiment 4, 68 lb (31 kg) plant trash fire data was reviewed, and the peak radiant heat flux of 15 kW/m^2 was selected to analyzed fire damaged in the Fire Zone 98-M. The peak heat flux of 15 kW/m^2 was measured for plant trash 68 lb (31 kg), therefore fire from the burning of 100 lb (45.5 kg) transients should be considered more intense and yield a higher radiant heat flux.

The corresponding temperature from radiant heat flux data (experiment 4) can be estimated from the following equation. For explicit reradiation calculations a surface emissivity value of one is assumed (Quintiere 1997):

$$\dot{q}''_{crit} = \sigma\left(T_{ig}^4 - T_\infty^4\right) + h\left(T_{ig} - T_\infty\right) \qquad (6)$$

where:

$\dot{q}''_{crit}$ = critical incident heat flux (kW/m^2)
σ = Stenfan-Boltzman constant [5.67 x 10^{-11} kW/(m^2-K^4)]
T_{ig} = ignition temperature (°C or K)
T_∞ = ambient temperature (20 °C + 273 = 293 K)
h = convective heat transfer coefficient (0.01 kW/m^2-K)

Table 4 provides the results of the calculations using Equation 6.

Table 4
Ignition Temperatures based on the Measured Radiative Heat Flux from Transient Fire

Measured Radiative Heat Flux, $\dot{q}''_{crit}$ (Experiment 4, NUREG/CR-3192) kW/m^2	Ignition Temperature, T_{ig} °C (°F)
15	401 (758)
8	292 (558)

Estimating Potential Fire Exposure in Fire Zone 99-M, North Electrical Switchgear Room

The potential for ignition and fire spread exists in the Fire Zone 99-M due to radiative heat flux from the burning of less than 68 lb (31 kg) transient combustibles. This emitted radiant energy (flame heat transfer) from the flame could be sufficient to ignite open safety-related cables or equipment of redundant trains of systems for safe shutdown and impact surrounding equipments.

Typically, piloted ignition temperatures for solid combustible materials range from 250 °C to 450 °C (482 °F to 842 °F) (Fire Dynamic Course Guide, May 1995). This would corresponds to a minimum or critical incident heat flux (the heat flux required to just the surface temperature to the ignition temperature is known as the critical incident heat flux) for ignition using Equation 6 of approximately 6.15 to 19.40 kW/m^2. Below these heat fluxes an object will typically not ignite while above these heat fluxes the time to ignition will decrease with the increasing heat flux. Based on this, safety-related equipment of redundant trains and electrical cabinets in this Fire Zone will be damage due to a fire of the transient combustibles allowed.

Effects of Heat and Smoke on Electrical Equipment

Recent studies suggest an accidental fire is a significant risk factor in the safe operation of a NPP. In addition to the local destructive effect the fire may cause, further damage may occur far from the spread of smoke. As a toxic mixture of combustion products, smoke hinders working in the area by reducing the visibility and creating a potential lethal environment for plant personnel. Further, the probability of failures in the electrical components increases when the temperatures and smoke concentration of the surroundings increase.

Sensitivity studies have shown that prolonged fire-fighting response times can lead to noticeable increase in fire risk. Smoke, identified as one of the major contributors to prolonged response times, can also cause misdirected suppression efforts, hamper operators' ability to safely shutdown the plant, initiate automatic suppression systems in areas away from the fire, and fail electrical equipment. The results of a sensitivity study indicated that the smoke could typically result in core damage frequencies (CDFs) in the range from 1.4×10^{-6}/year to 3.8×10^{-5}/year (Singh 1999). In addition, the impact of misdirected suppression efforts because of smoke (or the effects of smoke directly if the equipment is susceptible) could be substantial, i.e., a CDF on the order of 10^{-3}/year, if no credit for fire suppression efforts is given (Singh 1999). In actual NPP experience, fire fighters often have difficulty in locating the fire source because of smoke and equipment is known to have failed in smoke-filled environments, as demonstrated by the fires at the Browns Ferry Nuclear Plant (BFNP) Unit 1, March 1975, Waterford Unit 3, June 1995, and San Onofre Nuclear Generating Station (SONGS) Unit 3, February 2001.

Manual fire-fighting involving large amounts of cables is a considerable challenge even to the most well trained and equipped fire brigade. Further, the pant fire brigade may never have actually experienced this type of situation. Factory Mutual Data Sheet 5-31, states the following which supports this view, "Smoke is a major factor in the ability of manual fire-fighting response to control a cable fire". Large cable fire tests were conducted at the Factory Mutual Research Corporation (FMRC) Test Center for the Electric Power Research Institute (EPRI). A short time after the start of each test the building filled with smoke making it difficult to find the fire. The test center is a large building similar in size to a small aircraft hanger approximately 63,757 m^3 (2,250,000 ft^3).

Empirical data indicate that a nuclear facility will experience more frequent event precursors (in this case, smaller fires that have no impact on nuclear safety) than actual fire occurrences affecting nuclear safety equipment, such as the BFNP Unit 1 fire. Many argue that no fire in a NPP is without nuclear safety implications because every fire is a threat to safety, through its effects on either equipment or personnel operating the facility. Nevertheless, a NPP is expected to experience a fire that affects nuclear safety equipment every 6 to 10 years (Ramsey and Modarres, 1998). The initial probabilistic risk assessments (PRAs) conducted at 12 U.S. NPPs showed that fire represented 60% of the core melt probability. This was determined to occur primarily because fire can result in loss of an otherwise highly reliable redundant safety capability. The loss of this redundant safety capability defeats success paths and leads to core melt (Ramsey and Modarres, 1998).

Conclusion

The following conclusion are based on the analysis documented in this report:

(1) The effects of fire in Fire Zone 98-J has been analyzed using the HRR from the fuel spill of one gallon of lubricating oil onto the Emergency Diesel Generator Corridor floor. Turbulent diffusion flame from the pool fire will impinge the non-qualified IEEE-383 cables resulting in potential ignition and flame spread along the cable trays.

(2) The fire detection system in the Fire Zone 98-J will not actuate the fire suppression system until it has received a signal from a spot-type ceiling-mounted smoke detector and a signal from a detector wire. For a floor-based fire, a hot gas layer would develop causing the ceiling-mounted detectors to send a signal to the suppression control system. Sprinkler heads would also begin opening. However, because the detector wires are on top of cables and therefore shielded by the cables trays, there would be significant delay in the actuation of the fire suppression system resulting in damage to cables.

(3) Fire Zone 99-M is protected with only a detection system, i.e., no automatic fire suppression systems is provided. This room contains the green train switchgear; however, cables associated with red train safe shutdown equipment traverse through this room. These red train cables are not protected with 1-hour rated fire barrier and not separated from red train redundant cables by a minimum 20 feet distance free of intervening combustibles and as such could be damaged from the floor based fire. Heat flux from a fire of transient combustibles could also be intense enough to ignite safety-related cables.

(4) A fire from burning of less than 100 lb (45.5 kg) of transient combustibles allowed by plant procedures in Fire Zone 99-M would damage the nearby safety-related equipment of redundant trains and electrical cabinets. Without automatic fire suppression protection, hazardous condition are expected to occur in a relatively short period of time. Under these conditions a fire could damage the alternate shutdown panel. Thermal damage and soot deposition will, in general manifest itself quickly. Corrosion damage could occur in a longer time frame, while particulate damage may occur almost immediately.

(5) Smoke and heat effects from a fire in Fire Zone 98-J and Fire Zone 99-M could cause damage to the electrical and electronic components. The main cause of the failures were (a) smoke damage due to soot deposition (b) heat damage due to high temperature and (c) corrosion damage due to hydrochloric acid (HCl).

(6) Smoke increases conductance and can cause failures in energized electronic equipment through shorts and arcs. Smoke-induced leakage currents are highest during a fire when smoke is in the air.

(7) The results obtained in the NRC sponsored studies (NUREG/CR-5904, NUREG/CR-6406, NUREG/CR-6543, NUREG/CR-6476, and NUREG/CR4596) on effects of smoke on electrical and electronic components indicate that (a) particulate deposition as noted as a failure mode for switches, uncovered relays and meters (b) corrosion as well as

particulate deposition was noted as a possible failure mode for meters relative to sticking or jamming of indicators (c) penetration of particulate or corrosive vapors into components may substantially effect the response, for example relay enclosures, and (d) electronic counter failures were caused by corrosion induced leakage paths on circuit boards. Note that these failures occurred after the fire tests were completed.

(8) In the event of an exposure fire involving transient combustible material, there will be a time lag between the ignition of fire, detection and alarm, and fire brigade response. The existing configuration of safety-related cables, with partial protection of suppression in Fire Zone 98-J and with no automatic fire suppression protection in Fire Zone 99-M, provides no protection against the radiative heat flux of an exposure fire.

(9) Based on the results of this FHA, the postulated fire in Fire Zone 98-J and Fire Zone 99-M could damage the unprotected safety-related cables and alternate control panel before the completion of numerous manual actions to operate components of redundant trains of equipments necessary to achieve and maintain safe shutdown.

(10) The fire modeling performed by the licensee does not provide reasonable assurance that one train of safe shutdown cables will be maintained free of fire damage. This is because the HRR data used in the fire modeling for the source fires (electrical cabinets) is based on the combustion of cable insulation only and neglects the large energy release due to energetic electrical faults.

(11) The staff concludes that the level of existing protection for the Fire Zone 98-J and Fire Zone 99-M does not provide a level of fire protection equivalent to 10 CFR Part 50, Appendix R, Section III.G.2 and does not meet 10 CFR Part 50 §50.48 (a)(2)(iii) in that means have not been provided to limit fire damage to structures, systems, or components important to safety so that the capability to shutdown the plant safely is ensured.

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Appendix - A

Fire Dynamics Microsoft Excel® Worksheets
Flammable Liquid Lubricating Oil Spill in Fire Zone 98-J,
Emergency Diesel Generator Corridor

Heat Release Rate, Flame Height, and Burning Duration Calculations

Worksheet -1

ESTIMATING POOL FIRE BURNING DURATION

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-197)

ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Fire Zone 99-J, North Electrical Switchgear Room

Arkansas Nuclear One, Unit 1

The following calculations estimate the heat release rate, burning duration and flame height for liquid pool fire.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent values are calculated by the spreadsheet and based on values specified in the input parameters.

Pool Fire Diameter Calculation

$D = \sqrt{(4A/\pi)}$

D = 0.305 m

INPUT PARAMETERS

Calculation for Regression Rate

$v = m''/\rho$

Fuel Spill Volume (V)	1.00	gallons	0.0038 m^3
Fuel Spill Area or Dike Area (A_{dike})	0.79	ft^2	0.073 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	

Where m" = mass burning rate of fuel (kg/m^2-sec), ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Lube Oil

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b = 1011.49 sec 16.86 minutes ANSWER

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate	Heat of Combustion	Density ρ (kg/m^3)
[illegible]	[illegible]	[illegible]	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
[illegible]	[illegible]	[illegible]	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	[illegible]	26,200	1035
Diethy Ether	[illegible]	34,200	714
Benzine	0.048	44,700	740
Gasoline	[illegible]	43,700	740
Kerosine	0.039	43,200	820
[illegible]	[illegible]	[illegible]	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810

ESTIMATING POOL FIRE FLAME HEIGHT

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 2-10)

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)

Q = pool fire heat release rate (kW)

D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f = 1.340 m 4.40 ft ANSWER

NOTE

The above calculations are based on principles developed in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering 2nd Edition 1995. Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-4)

$Q = m'' \Delta H_{c,eff} A_f$

Where Q = pool fire heat release rate (kW)

m" = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

Heat Release Rate Calculation (Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

$Q = m'' \Delta H_c A_f$

Q = 130.83 kW 124.01 BTU/sec ANSWER

ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT
Fire Zone 99-J, North Electrical Switchgear Room
Arkansas Nuclear One, Unit 1

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent values are calculated by the spreadsheet and based on values specified in the input parameters.

INPUT PARAMETERS

Fuel Spill Volume (V)	1.00	gallons	0.0038 m^3
Fuel Spill Area or Dike Area (A_{dike})	1.77	ft^2	0.164 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	

Lube Oil

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydrocarbon	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Referenc: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-4)

$Q = m"\Delta H_{c,eff} A_f$

Where Q = pool fire heat release rate (kW)

m" = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

Works t-2

Heat Release Rate Calculation (Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

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$Q = m"\Delta H_c A_f$

Q = 294.52 kW 279.15 BTU/sec ANSWER

ESTIMATING POOL FIRE BURNING DURATION

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-197)

$t_b = 4V/\pi D^2 v$

Where t_b = burning duration of pool fire (sec)
V = Volume of liquid (m^3)
D = pool diameter (m)
v = regression rate (m/sec)

Pool Fire Diameter Calculation

$A_f = \pi D^2/4$

$D = (4A_f/\pi)^{1/2}$

$D =$ 0.457 m

Calculation for Regression Rate

$v = m''/\rho$

Where m'' = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

$v =$ 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

$t_b =$ 449.34 sec 7.49 minutes **ANSWER**

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 2-10)

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where H_f = pool fire flame height (m)
Q = pool fire heat release rate (kW)
D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

$H_f =$ 1.818 m 5.96 ft **ANSWER**

NOTE

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ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Fire Zone 99-J, North Electrical Switchgear Room
Arkansas Nuclear One, Unit 1

The following calculations estimate the heat release rate, burning duration, and flame height for a liquid pool fire.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent values are calculated by the spreadsheet and based on values specified in the input parameters.

INPUT PARAMETERS

Fuel Spill Volume (V)	1.00	gallons	0.0038 m^3
Fuel Spill Area or Dike Area (A_{dike})	3.142	ft^2	0.292 m^2
Mass Burning Rate of Fuel (m'')	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	

Lube Oil

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydrocarbon	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-4)

$Q = m''\Delta H_{c,eff} A_f$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

Heat Release Rate Calculation (Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

$Q = m''\Delta H_c A_f$

Q = 523.60 kW 496.28 BTU/sec **ANSWER**

ESTIMATING POOL FIRE BURNING DURATION

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-197)

$t_b = 4V/\pi D^2 v$

Where t_b = burning duration of pool fire (sec)
V = Volume of liquid (m^3)
D = pool diameter (m)
v = regression rate (m/sec)

Pool Fire Diameter Calculation

$A_f = \pi D^2/4$

$D = (4A_f/\pi)^{1/2}$

D = 0.610 m

Calculation for Regression Rate

$v = m''/\rho$

Where m'' = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b = 252.74 sec 4.21 minutes ANSWER

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 2-10)

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)
Q = pool fire heat release rate (kW)
D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f = 2.253 m 7.39 ft ANSWER

NOTE

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