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Docket Nos. 50-282
and 50-306

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Mr. D. M. Musolf
Nuclear Support Services Department
Northern States Power Company
414 Nicollet Mall - 8th Floor
Minneapolis, Minnesota 55401

Dear Mr. Musolf:

The Commission has issued the enclosed Exemption (Enclosure 1) to certain requirements of 10 CFR 50 Appendix R Subsection III.G.2 in response to your letter of June 30, 1982 as supplemented by letter dated October 22, 1982 for the Prairie Island Nuclear Generating Plant Unit Nos. 1 & 2. Subsection III.G.2 specifies the separation, fire barrier, and suppression requirements where both trains of redundant safe shutdown components are located within the same fire area.

You requested exemptions from the requirements specified in Subsection III.G.2 in nine fire areas throughout the plant. In five fire areas we conclude that additional modifications would not enhance fire protection safety above that provided by existing and proposed alternatives for the facility and therefore exemptions from the requirements in III.G.2 is granted. These areas are as follows.

1. Train A Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Room (Fire Area 31).

2. Train B Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Room (Fire Area 32).

3. Normal Switchgear Room Unit 1 (Fire Area 37).

4. Auxiliary Building Operating Level Unit 1 (Fire Area 60).

5. Auxiliary Building Operating Level Unit 1 (Fire Area 75).

In four areas an unacceptable level of fire protection safety exists in that noncompliance with the requirements specified in Subsection III.G.2 has not been justified and therefore your exemption requests are denied. The bases for these findings are given in our Safety Evaluation, Enclosure 2. Areas for which the requests are denied are identified as follows.

1. Auxiliary Building Ground Floor Level Unit 1 (Fire Area 58).

2. Auxiliary Building Mezzanine Level Unit 1 (Fire Area 59).

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3. Auxiliary Building Ground Floor Level Unit 2 (Fire Area 73).

4. Auxiliary Building Mezzanine Level Unit 2 (Fire Area 74).

By letter dated June 30, 1982 you also requested an exemption from the schedular requirements of 10 CFR 50.48(c)(2) from nine months after June 1, 1982 to January 1, 1984. The purpose for this schedular exemption request is to allow additional time to complete modifications that stem from your exemption requests dealing with the provision of Appendix R, III.G.2. Schedular requirements for completing modifications pertaining to exemptions involving the provisions of Appendix R, III.G.2 fall under 10 CFR 50.48(c)(6) and not under (c)(2). This is to provide a schedular allowance for final Commission action on exemption requests dealing with the provisions of Appendix R. Therefore an exemption from schedular requirements of 10 CFR 50.48(c)(2) to complete modifications that deal with exemption requests involving the provisions of Appendix R is not necessary nor required.

By your letter dated February 17, 1983 you identified minor corrections to our draft safety evaluation on the Appendix R exemptions issued by our letter dated January 4, 1983. We have reviewed these minor corrections and conclude that they do not change the results of our technical evaluation pertaining to the exemption requests. With respect to followup actions regarding exemption denials, you have elected to propose other alternatives for these exemption requests. The criteria presented in your letter dated February 17, 1983 for the proposed alternatives were reviewed and found acceptable by the staff.

You must meet the implementation schedule specified in 10 CFR 50.48(c)(6) for all exemption requests and the tolling period is terminated by this action.

Sincerely,

Original signed by
C.M. Trammell
for Robert A. Clark, Chief
Operating Reactors Branch #3
Division of Licensing

Enclosures:
1. Exemption
2. Safety Evaluation

cc: See next page

AD:MCET:DE	OELD	D:DL
WJohnston	W.Shields	DGEisenhut
4/6/83	4/28/83	5/ /83

corrections 4/11/83

CMT 5/4/83

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DATE	3/18/83	3/25/83	3/25/83	3/31/83	3/31/83	4/4/83	4/4/83

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

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Docket No. 50-282/50-306

Docketing and Service Section
Office of the Secretary of the Commission

SUBJECT: NORTHERN STATES POWER COMPANY, Prairie Island Nuclear Generating Plant, Unit Nos. 1 and 2

Two signed originals of the Federal Register Notice identified below are enclosed for your transmittal to the Office of the Federal Register for publication. Additional conformed copies (12) of the Notice are enclosed for your use.

- ☐ Notice of Receipt of Application for Construction Permit(s) and Operating License(s).
- ☐ Notice of Receipt of Partial Application for Construction Permit(s) and Facility License(s): Time for Submission of Views on Antitrust Matters.
- ☐ Notice of Availability of Applicant's Environmental Report.
- ☐ Notice of Proposed Issuance of Amendment to Facility Operating License.
- ☐ Notice of Receipt of Application for Facility License(s); Notice of Availability of Applicant's Environmental Report; and Notice of Consideration of Issuance of Facility License(s) and Notice of Opportunity for Hearing.
- ☐ Notice of Availability of NRC Draft/Final Environmental Statement.
- ☐ Notice of Limited Work Authorization.
- ☐ Notice of Availability of Safety Evaluation Report.
- ☐ Notice of Issuance of Construction Permit(s).
- ☐ Notice of Issuance of Facility Operating License(s) or Amendment(s).
- ☒ Other: EXEMPTION - Appendix R Subsection III.G.2

Division of Licensing
Office of Nuclear Reactor Regulation

Enclosure:
As Stated

OFFICE→	ORB#3:DL					
SURNAME→	PMKreutzer/pn					
DATE→	5/6/83					

NRC FORM 102 7—79

Northern States Power Company

cc:

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

In the Matter of NORTHERN STATES POWER COMPANY (Prairie Island Nuclear Generating Plant Unit Nos. 1 and 2)	)))))))	Docket Nos. 50-282 and 50-306

EXEMPTION

I.

The Northern States Power Company (the licensee) is the holder of Facility Operating License Nos. DPR-42 and DPR-60 which authorize operation of the Prairie Island Nuclear Generating Plant, Unit Nos. 1 and 2. These licenses provide, among other things, that they are subject to all rules, regulations and Orders of the Commission now or hereafter in effect.

The facility comprises two pressurized water reactors at the licensee's site located in Goodhue County, Minnesota.

II.

On November 19, 1980, the Commission published a revised Section 10 CFR 50.48 and a new Appendix R to 10 CFR 50 regarding fire protection features of nuclear power plants (45 FR 76602). The revised Section 50.48 and Appendix R became effective on February 17, 1981. Section III. of Appendix R contains fifteen subsections, lettered A through O, each of which specifies requirements for a particular aspect of the fire protection features at a nuclear power plant. One of these fifteen subsections, III.G., is the subject of this exemption request. Specifically, Subsection III.G.2 requires that one train of cables and equipment necessary to achieve and maintain safe shutdown be maintained free of fire damage by one of the following means:

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a. Separation of cables and equipment and associated non-safety circuits of redundant trains by a fire barrier having a 3-hour rating. Structural steel forming a part of or supporting such fire barriers shall be protected to provide fire resistance equivalent to that required of the barrier;

b. Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area; or

c. Enclosure of cables and equipment and associated non-safety circuits of one redundant train in a fire barrier having a 1-hour rating. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area.

III.

By letter dated June 30, 1982 as supplemented by letter dated October 22, 1982, the licensee requested an exemption from the requirements of Subsection III.G.2 of Appendix R in nine (9) fire areas, as follows.

- Train A Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room, Fire Area 31

- Train B Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room, Fire Area 32

- Auxiliary Building Ground Floor Level Unit 1, Fire Area 58

- Auxiliary Building Ground Floor Level Unit 2, Fire Area 73
- Auxiliary Building Mezzanine Level Unit 2, Fire Area 74
- Unit 1 Normal Switchgear Room, Fire Area 37
- Auxiliary Building Operating Level Unit 1, Fire Area 60
- Auxiliary Building Operating Level Unit 2, Fire Area 75
- Auxiliary Building Mezzanine Level Unit 1, Fire Area 59

The acceptability of the exemption request for five of these fire areas is addressed below. More details are contained in the NRC staff's related Safety Evaluation (SE) dated May 4, 1983, which is included herein by reference.

IV.

<u>Train A Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room, Fire Area 31</u>

<u>Train B Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room, Fire Area 32</u>

The licensee requested an exemption from Subsection III.G.2 to the extent that these areas lack twenty feet separation free of intervening combustibles between components of redundant trains needed for safe shutdown or one hour fire rated enclosure of one of the redundant trains.

Fire Area 31 contains Motor Control Centers MCC-2A1 and 2A2, #12 (motor-driven Unit 1) and #22 (turbine-driven Unit 2) Auxiliary Feedwater Pumps, #123 Instrument Air Compressor with associated equipment, and "A" Train Hot Shutdown Panel for Units 1 and 2. One of the two motor control centers (either 2A1 or 2A2) is necessary for safe shutdown as are the auxiliary feedwater pumps. It should be noted, however, that opposite train pumps are located in Fire Area 32, thereby ensuring separation by 3-hour fire rated barriers. Of the three instrument air compressors, one is located in Fire Area 31, representing Division A. The other two compressors (Division B) are located in Fire Area 32, again providing separation by 3-hour fire rated barriers.

Fire Area 32 contains Motor Control Centers MCC-1A1 and MCC-1A2 (only one of which is necessary for safe shutdown), #11 (turbine driven, Unit 1) and #21 (motor driven, Unit 2) Auxiliary Feedwater Pumps, #121 and #122 Instrument Air Compressors with associated equipment, and "B" train Hot Shutdown Panel for Units 1 and 2.

The safe shutdown evaluation identified the coexistence of redundant power and control cables required for safe shutdown with less than twenty feet horizontal separation. The redundant cables are installed in open horizontal cable trays between 16 and 18 feet above the floor, and within 3 feet of the ceiling. The redundant cables cross over one another and are separated by approximately one foot at the crossover. The licensee proposes to install thermal barriers on the top and bottom of the Division B cable trays and wrap all Division B conduits in one-hour fire rated barriers. By letter dated October 22, 1982, the licensee proposed to modify the existing automatic sprinkler systems presently installed at the ceiling level, to also provide area sprinkler coverage in accordance with NFPA-13 below the cable trays and piping in the areas.

The combustibles in Fire Area 31 are lubricating oil and cable insulation. The combustibles comprise a fuel load of 10,714 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of 8 minutes on the ASTM E-119 standard time temperature curve.

The combustibles in Fire Area 32 are lubricating oil and cable insulation. The combustibles comprise a fuel load of 16,954 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of 12 minutes on the ASTM E-119 standard time temperature curve.

The fire protection in these areas consists of automatic sprinklers, ionization smoke detectors, nearby standpipe hose stations that could service both fire areas and portable fire extinguishers. Other features in these areas offering compensation for the lack of 20 feet separation or one hour barriers are the thermal shield installed on both the top and bottom of the Division B cable trays. The thermal shields are not considered equivalent to a one-hour fire rated barrier, as they may only inhibit fire damage for several minutes. However because of the low in-situ combustible fuel loads, we find for anticipated transient combustible exposure fires the thermal shields will protect the Division B cable trays from direct flame impingement or a descending hot layer for a reasonable time period until the automatic sprinklers installed at the ceiling level and below the cable trays are activated to mitigate the effects of the fire.

In addition, the low in-situ fuel load in conjunction with the proposed thermal shields provides reasonable assurance that the automatic detection and sprinkler systems will be activated before the redundant cables are damaged.

Based on our evaluation, we conclude that with the modifications proposed by the licensee and the existing level of safety in the Train A and Train B Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Rooms (Fire Areas 31 and 32) are equivalent to the requirements specified in Subsection III.G.2 of Appendix R and therefore the licensee's exemption request is granted for these fire areas.

Unit 1 Normal Switchgear Room, Fire Area 37; Auxiliary Building Operating Level Unit 1, Fire Area 60; Auxiliary Building Operating Level Unit 2, Fire Area 75

These areas do not comply with Subsection III.G.2 because they do not have an automatic fire suppression system. There is no alternative shutdown capability independent of these areas. Fire protection in these areas consists of ionization smoke detectors standpipe hose stations, and portable fire extinguishers. In addition all redundant motor control centers and associated cables entering and leaving these areas are horizontally separated by at least 20 feet or more.

The licensee justifies the request for the exemption from Subsection III.G.2 on the basis of (1) all cables are qualified to IEE-383, (2) the in-situ combustible loadings are light, and (3) ionization smoke detection is provided in each area.

We agree with the licensee that, because there are negligible in-situ combustibles in these areas, any postulated fire would be limited to transient combustible material. Hazardous quantities of transient combustibles would not be expected in these fire areas for several reasons. First, the areas are not adjacent to or near any major plant traffic route. Second, maintenance and operations in these areas do not involve the use of combustible materials. Third, accessibility to these areas is restricted to personnel performing essential duties in the areas because of potential radiation hazards. On this basis, we agree with the licensee that any fires in these areas resulting from transient combustibles would be of limited severity and duration. The installed early warning detection system would be able to promptly detect incipient fire conditions, and the separation between redundant trains in each area will maintain the integrity of the cables and equipment until the fire brigade is able to respond and to extinguish the fire. The fire brigade should be capable of reaching each of these areas within a few minutes after an alarm is received in the control room. It is out opinion that this combination of protective features provides reasonable assurance that one train of equipment necessary for safe shutdown will be maintained free of fire damage.

Based on our evaluation, the level of existing protection for Fire Areas 37 Unit 1 Normal Switchgear Room, Fire Area 60 Auxiliary Building Operating Level, Unit 1 and Fire Area 75 Auxiliary Building Operating Level, Unit 1 provides a level of fire protection equivalent to the requirements specified in Subsection III.G.2 of Appendix R. Therefore, the exemption from the requirements specified in Subsection III.G.2 for these fire areas is granted.

V.

Accordingly, the Commission has determined that, pursuant to 10 CFR 50.12, an exemption is authorized by law and will not endanger life or property or common defense and security and is otherwise in the public interest and hereby grants an exemption from the requirements of Subsection III.G.2 of Appendix R to 10 CFR 50 to the extent discussed in Section IV above.

The NRC staff has determined that the granting of this Exemption will not result in any significant environmental impact and that pursuant to 10 CFR 51.5(d)(4) an environmental impact statement or negative declaration and environmental impact appraisal need not be prepared in connection with this action.

FOR THE NUCLEAR REGULATORY COMMISSION

Darrell G. Eisenhut

Darrell G. Eisenhut, Director
Division of Licensing
Office of Nuclear Reactor Regulation

Dated at Bethesda, Maryland
this 4th day of May, 1983.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO EXEMPTIONS FROM 10 CFR 50, APPENDIX R

NORTHERN STATES POWER COMPANY

PRAIRIE ISLAND NUCLEAR GENERATING PLANT UNITS 1 AND 2

DOCKET NOS. 50-282 AND 50-306

1.0 Introduction

By letter dated June 30, 1982 the licensee requested exemptions from Section III.G of Appendix R within nine plant fire areas. By letter dated October 22, 1982, the licensee provided additional information.

Section III.G.2 requires that one train of cables and equipment necessary to achieve and maintain safe shutdown be maintained free of fire damage by one of the following means:

a. Separation of cables and equipment and associated non-safety circuits of redundant trains by a fire barrier having a 3-hour rating. Structural steel forming a part of or supporting such fire barriers shall be protected to provide fire resistance equivalent to that required of the barrier;

b. Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustibles or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area; or

c. Enclosure of cables and equipment and associated non-safety circuits of one redundant train in a fire barrier having a 1-hour rating. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area.

If these conditions are not met, Section III.G.3 requires alternative shutdown capability independent of the fire area of concern. It also requires a fixed suppression system in the fire area of concern if it contains a large concentration of cables or other combustibles.

These alternative requirements are not deemed to be equivalent for all configurations, however, they provide equivalent protection for those configurations in which they are accepted.

Because it is not possible to predict the specific conditions under which fires may occur and propagate, the design basis protective features are specified in the rule rather than the design basis fire. Plant specific features may require protection different than the measures specified in Section III.G. In such a case, the licensee must demonstrate, by means of a detailed fire hazards analysis, that existing protection or existing protection in conjunction with proposed modifications will provide a level of safety equivalent to the technical requirements of Section III.G of Appendix R.

In summary, Section III.G is related to fire protection features for ensuring that systems and associated circuits used to achieve and maintain safe shutdown are free of fire damage. Fire protection configurations must either meet the specific requirements of Section III.G or alternative fire protection configurations must be justified by a fire hazard analysis.

Our general criteria for accepting alternative fire protection configurations are the following:

- The alternative assures that one train of equipment necessary to achieve hot shutdown from either the control room or emergency control stations is free of fire damage.

. The alternative assures that fire damage to at least one train of equipment necessary to achieve cold shutdown is limited such that it can be repaired within a reasonable time (minor repairs with components stored on-site).

. Modifications required to meet Section III.G would not enhance fire protection safety above that provided by either existing or proposed alternatives.

. Modifications required to meet Section III.G would be detrimental to overall facility safety.

2.0 Analytical Method

The licensee employed an analytical method to demonstrate the inherent protection afforded to existing safe shutdown systems. The intent of this method was to provide common parameters by which individual fire areas could be judged, to demonstrate that verbatim compliance with Section III.G of Appendix R would not enhance the fire protection for safe shutdown.

The method can be summarized as follows:

- The redundant cables and components of concern are identified.

- Their geometry and configuration within the fire area are described.

- The type of cable insulation and failure criteria are specified.

- The minimum quantity of flammable liquid needed to produce sufficient heat flux and heat energy to damage the cables is calculated, considering several heat transfer modes, i.e. radiation, plume impingement, and stratification.

- The analysis determines the heat flux into the room needed to cause electrical failure of redundant cables. This heat flux is converted to a quantity of flammable liquid, usually acetone, of approximately 10 to 20 gallons, in a circular pool configuration.

We and our contractor Brookhaven National Laboratory have reviewed the analytical method. A copy of their report is attached. We have determined that the results of the methodology, as applied, do not demonstrate the equivalence of the protection provided for safe shutdown to the specific alternatives set forth in Section III.G of Appendix R. For example:

. The method does not consider the heat released to the room by secondary fires involving in-situ combustibles. The method uses an electrical failure criteria with the thermal energy release to the room by a single exposure fire. When the cables of concern are at the conditions of electrical failure, other cables within the enclosure are burning and also releasing energy to the room.

. The method does not consider the increased heat release rate of a given fire when it occurs against a wall or in a corner; the method considers only the heat release of a fire as it occurs in an open area.

. The method does not consider the effects of excess pyrolyzate resulting from the degradation of plastics burning in the stratified layer.

. The method does not consider all of the alternatives set forth in Section III.G; i.e., 3-hour fire barrier, 1-hour fire barrier with suppression system, twenty-feet separation free of combustibles with automatic suppression and alternate or dedicated shutdown capability independent of the area. The method considers only separation without automatic suppression and uses a stratification model which does not include the effects of separation.

The licensee has not used the results of this analysis to compare the protection provided with that specified in Section III.G. The licensee has stated that only the accumulation of the calculated quantity of flammable liquids in the required configuration is an unrealistic condition, and will be prevented by administrative controls. We do not deem this to be a valid argument because there is no positive means of preventing the accumulation of transient materials in individual plant areas. As documented in Inspection ahd Enforcement Branch Reports, recent inspections at plants such as Davis Besse (50-346/82-03, April 1, 1982), Duane Arnold (50-331/81-25, January 11, 1982), D. C. Cook (50-315/82-11, December 31, 1981), and Nine Mile Point (50-220/82-09), have demonstrated that substantial quantities of hazardous substances such as 55 gallon drums of waste oil are located in even highly restricted and controlled entry areas.

We have not relied upon the results of the licensee's analysis in our evaluation. We have evaluated each exemption request using our standard method of review:

a) Review the information submitted and that existing in the docket file to determine the configuration of the redundant components,

b) Evaluate the existing fire protection, proposed modifications, and other compensating features or mitigating factors to determine the overall level of fire protection in the area of concern, and

c) Determine if the overall level of safety is equivalent to that provided by Section III.G of Appendix R.

3.0 Fire Area 31: "A" Train Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room and Fire Area 32: "B" Train Hot Shutdown Panel; Instrument Air Room and Auxiliary Feedwater Pump Room

3.1 Exemption Requested

The licensee requests exemptions from Section III.G.2 to the extent that it requires 20 feet of separation without intervening combustibles between redundant trains.

3.2 Discussion

Fire Areas 31 and 32 are located on the ground floor safeguard corridor of the Turbine Building at elevation 695 ft. The area is completely enclosed by 3-hour-rated fire walls with 3-hour-rated fire seals provided for combustible pathway penetrations. Fire Area 31 is separated from Fire Area 32 by a 3-hour-rated fusible linked sliding door which closes to isolate Fire Area 31 from Fire Area 32 in the event of a fire. The fire protection in these areas consists of automatic sprinklers, ionization smoke detectors, and portable fire extinguishers. The standpipe hose stations and fire extinguishers that are located immediately outside the controlled access doors on the west and east side of Fire Area 31 and 32 can provide service to Fire Areas 31 and 32.

Fire Area 31 contains Motor Control Centers MCC-2A1 and 2A2, #12 (motor-driven Unit 1) and #22 (turbine-driven Unit 2) Auxiliary Feedwater Pumps, #123 Instrument Air Compressor with associated equipment, and "A" Train Hot Shutdown Panel for Units 1 and 2. One of the two motor control centers (either 2A1 or 2A2) is necessary for safe shutdown as are the auxiliary feedwater pumps. It should be noted, however, that opposite train pumps are located in Fire Area 32, thereby ensuring separation by 3-hour fire rated barriers. Of the three instrument air compressors, one is located in Fire Area 31, representing Division A. The other two compressors (Division B) are located in Fire Area 32, again providing separation by 3-hour fire rated barriers.

Fire Area 32 contains Motor Control Centers MCC-1A1 and MCC-1A2 (for which only one is necessary for safe shutdown), #11 (turbine driven, Unit 1) and #21 (motor driven, Unit 2) Auxiliary Feedwater Pumps, #121 and #122 Instrument Air Compressors with associated equipment, and "B" train Hot Shutdown Panel for Units 1 and 2.

The safe shutdown evaluation identified the coexistence of redundant power and control cables required for safe shutdown with less than twenty feet horizontal separation. The redundant cables are installed in open horizontal cable trays between 16 and 18 feet above the floor, and within 3 feet of the ceiling. The redundant cables cross over one another and are separated by approximately one foot at the crossover. The licensee proposes to install thermal barriers on the top and bottom of the Division B cable trays and wrap all Division B conduits in one-hour fire rated barriers. By letter dated October 22, 1982, the licensee also proposes to modify the existing automatic sprinkler systems presently installed at the ceiling level to also provide area sprinkler coverage in accordance with NFPA-13 below the cable trays and piping in the areas.

The combustibles in Fire Area 31 are lubricating oil and cable insulation. The combustibles comprise a fuel load of 10,714 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of 8 minutes on the ASTM E-119 standard time temperature curve.

The combustibles in Fire Area 32 are lubricating oil and cable insulation. The combustibles comprise a fuel load of 16,954 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of 12 minutes on the ASTM E-119 standard time temperature curve.

3.3 Evaluation

These areas do not comply with Section III.G because they do not have twenty feet of separation free of intervening combustibles or one hour fire rated barriers. There is no alternative shutdown capability independent of this area.

The features in this area which are offered as compensation for the lack of 20 feet separation or one hour barriers are the thermal shield installed on both the top and bottom of the Division B cable trays. The thermal shields cannot be considered equivalent to a one-hour fire rated barrier, as they may only inhibit fire damage for several minutes. However because of the low in-situ combustible fuel loads, we find for anticipated transient combustible exposure fires the thermal shields will protect the Division B cable trays from direct flame impingement or a descending hot layer for a reasonable period of time until the automatic sprinklers installed at the ceiling level and below the cable trays are activated to mitigate the effects of the fire.

The low in-situ fuel load in conjunction with the proposed thermal shields provide reasonable assurance that the automatic detection and sprinkler systems will be activated before the redundant cables are damaged.

3.4 Conclusion

Based on our evaluation, we conclude that with the proposed modifications, the level of safety provided in the Train A and Train B Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Rooms (Fire Areas 31 and 32) will be equivalent to the technical requirements of Section III.G of Appendix R and therefore the licensee's requests should be granted.

4.0 Fire Area 58: Auxiliary Building Ground Floor Level Unit 1
Fire Area 73: Auxiliary Building Ground Floor Unit 2
Fire Area 74: Auxiliary Building Mezzanine Level Unit 2

4.1 Exemption Requested

The licensee requests exemptions from Section III.G.2 to the extent that it requires 20 feet of separation without intervening combustibles between redundant trains and the installation of an automatic fire suppression system.

4.2 Discussion

Fire Area 58

Fire Area 58 is located on the ground floor immediately northwest of the containment building for Unit 1, at the 695 ft. elevation. The fire area is enclosed by 3-hour-rated walls on all but the west side, with 3-hour-rated fire seals provided for combustible pathway penetrations. The west side of Fire Area 58 is separated from the nearest area of concern in Fire Area 73 by approximately 100 ft of horizontal separation. The height of the ceiling in the area is 19 ft. The fire protection in the area consists of smoke detectors, standpipe hose stations and portable fire extinguishers.

Fire Area 58 contains motor control centers MCC-1K1, 1K2, and 1KA2; #11 and #21 Component Cooling Water Pumps; #11 and #12 Residual Heat Removal Pumps, located in separate pits; and #12 Charging Pump and #12 Safety Injection Pump, each located in separate compartments in separate pits. Either MCC-1K1 or MCC-1K2 must be available for safe shutdown. MCC-1KA2 is fed from MCC-1K2 while the redundant motor control center to MCC-1KA2 is located in another fire area. The component cooling water pumps each have the redundant division pump (#12 and #22) also located in another fire area. Also, the residual heat removal pump and the Chemical Volume Control System pumps (Charging Pump Division A and Safety Injection Pump Division B) are physically located in separate rooms.

The safe shutdown evaluation identified the co-existence of power and control cables required for redundant safe shutdown with less than twenty feet horizontal separation. The redundant cables are installed in open horizontal cable trays between 11 and 18 feet above the floor. Each division is separated by 8 feet and installed within 3 feet of the ceiling.

The combustible in the area is cable insulation, comprising a fuel load of 9,990 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of approximately 7.5 minutes on the ASTM E-119 standard time temperature curve.

The licensee proposes to install thermal shields on the bottom of the Division B cable trays. By letter dated October 22, 1982, the licensee has also proposed to provide thermal shields on the top of some Division B cable trays where practical.

Fire Area 73

Fire Area 73 is identical to Fire Area 58, but is located in Unit 2.

The safe shutdown evaluation identified the co-existence of redundant power and control cables required for safe shutdown with less than twenty feet horizontal separation. The redundant cables are installed in open horizontal and vertical cable trays installed between 13 and 16 feet above the floor. Each division is separated by approximately 5 feet horizontally and installed within 3 feet of the ceiling.

The combustible in the area is cable insulation. The cable insulation comprises a fuel load of 7,810 BTU/sq. ft. which if totally consumed, would correspond to a fire severity of approximately 6 minutes on the ASTM E-119 standard time temperature curve.

The licensee proposes to install thermal shields on the bottom of the Division B cable trays. By letter dated October 22, 1982, the licensee has also proposed to provide thermal shields on the top of some Division B cable trays where practical.

Fire Area 74

Fire Area 74 is located on the mezzanine level immediately north of, and adjacent to, the Containment Building for Unit 2, directly above Fire Area 73 at an elevation of 715 ft. The room is enclosed by 3-hour-rated fire walls on all but the east side with 3-hour rated fire seals provided for combustible pathway penetrations. The east side of Fire Area 74 is separated from the nearest area of concern in Fire Area 59 by approximately 100 ft. The height of the ceiling in the area is 19 ft. Fire protection in the area consists of smoke detectors, standpipe hose stations and portable fire extinguishers.

Fire Area 74 contains cable and conduit needed for safe shutdown. The safe shutdown evaluation identified the coexistence of redundant cables required for safe shutdown with less than twenty feet horizontal separation. The redundant cables are installed in horizontal cable trays between 12 and 19 feet above the floor. Each division is separated by approximately 8 feet and installed within 3 feet of the ceiling.

The combustible in the area is cable insulation comprising a fuel load of 14,700 BTU/sq. ft. which if totally consumed, would correspond to a fire severity of approximately 11 minutes on the ASTM E-119 standard time temperature curve.

By letter dated October 22, 1982, the licensee proposes to install fire stops in non-safety trays to prevent the possibility of propagating fires from one division to another.

The licensee justifies these alternatives on the basis of (1) all cables are qualified to IEEE Std-383 (2) the in-situ combustible loadings are light, (3) smoke detection is provided and (4) an analytical model was employed to show that the magnitude of an exposure fire needed to damage redundant components is significantly higher than reasonably expected.

4.3 Evaluation

These areas do not comply with Section III.G because they do not have automatic fire suppression systems and twenty feet of separation free of intervening combustibles or one-hour fire rated barriers. There is no alternative shutdown capability independent of these areas.

There are generally two mechanisms by which fire damage is propagated; either (1) an exposure fire in close proximity to the redundant equipment or (2) an exposure fire at any point in the room of sufficient magnitude to form a stratified layer of hot gases at the ceiling level, which descends to the floor level at a rate correlated to the room volume, the burning time and fuel quantity. In the case of a fire which produces a stratified layer of hot gases at the ceiling level, the most severe damage will occur to cables and equipment located within several feet of the ceiling. The redundant cables in each fire area are installed within three feet of the ceiling. This configuration does not provide reasonable protection from a hot gas layer. A local exposure fire could also cause damage to the redundant cables if they are exposed to a heat flux of sufficient intensity.

The features in the fire areas which are offered as compensation for the lack of Section III.G required protective features are the proposed thermal shields and that all cables are qualified to IEEE-383. Neither of these can be considered equivalent to a one-hour fire rated barrier, as they may only inhibit fire damage for several minutes. The fire areas do not present any other features that would compensate for the lack of protective features specified by Section III.G.

Because of the close proximity of redundant safe shutdown cables that are not protected by an automatic suppression system, an exposure fire in any of the fire areas could damage both trains prior to the response of the fire brigade. There will be a time lag between the ignition of the fire, detector response, and the arrival of the fire brigade. The existing protection does not provide reasonable assurance that redundant cables of both trains will not be damaged in this time interval.

The existing protection in each of these fire areas does not provide a level of fire protection equivalent to Section III.G. Modifications such as the installation of an automatic sprinkler system and one-hour fire rated barriers would provide the requisite levels of safety.

4.4 Conclusion

Based on our evaluation, the level of existing protection for Fire Area 58 Auxiliary Building Ground Floor Level Unit 1, Fire Area 73 Auxiliary Building Ground Floor Unit 2 and Fire Area 74 Auxiliary Building Mezzanine Level Unit 2 does not provide a level of fire protection equivalent to the technical requirements of Section III.G of Appendix R. Therefore, the exemptions should be denied.

5.0 Fire Area 37: Unit 1 Normal Switchgear Room
Fire Area 60: Auxiliary Building Operating Level, Unit 1
Fire Area 75: Auxiliary Building Operating Level, Unit 2

5.1 Exemption Requested

The licensee requests exemptions from Section III.G.2 to the extent it requires the installation of an automatic fire suppression system.

5.2 Discussions

Fire Area 37

Fire Area 37 is located on the ground level of the turbine building safeguard corridor at an elevation of 695 ft. The area is enclosed by 3-hour-rated fire walls on all sides with 3-hour-rated fire seals provided for combustible pathway penetrations. The height of the ceiling in the area is 19 ft. Fire protection in the area consists of detectors and portable fire extinguishers. The standpipe hose stations and fire extinguishers are located outside the access door and are available for servicing these fire areas.

This fire area contains emergency diesel generator power cables of redundant divisions from which one train is necessary for safe shutdown. Both division cables are routed in conduit through the area. The existing horizontal separation between the redundant emergency diesel generator power supplies is greater than twenty feet.

The combustible in the area is cable insulation comprising a fuel load of 11,727 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of approximately 9 minutes on the ASTM E-119 standard time temperature curve.

Fire Area 60

Fire Area 60 is located on the operating level of the Auxiliary Building immediately north and west of the Unit 1 containment building at an elevation of 735 ft. The area is enclosed by 3-hour-rated fire walls on all sides, with 3-hour-rated fire seals provided for combustible pathway penetrations. The height of the ceiling in the area is 19 ft. Fire protection in the area consists of ionization smoke detectors, standpipe hose stations and portable fire extinguishers.

This fire area contains Motor Control Centers MCC-1LA1 and MCC-1LA2, one of which is required for safe shutdown. Loss of MCC-1LA1 and MCC-1LA2 due to fire will not result in the loss of the following critical functions required for safe shutdown because:

1. Valve and the breaker for Unit 1 redundant steam supply to the turbine driven auxiliary feedwater pump are locked open.
2. Redundant RHR suction valves are closed and the breaker locked open.

The motor control centers and associated cable entering and leaving the motor control centers are horizontally separated by 22 feet. The fuel load in the area is negligible.

Fire Area 75

Fire Area 75 is located on the operating level of the Auxiliary Building immediately north and east of the Unit 2 containment building at an elevation of 735 ft. The area is enclosed by 3-hour-rated fire walls on all sides with 3-hour-rated fire seals provided for combustible pathway penetrations. The height of the ceiling in the area is 19 ft. Fire protection in the area consists of ionization smoke detectors, standpipe hose stations and portable fire extinguishers.

Fire Area 75 contains two safeguard Motor Control Centers, MCC-2LA1 and MCC-2LA2, one of which is required for safe shutdown. Loss of MCC-2LA1 and MCC-2LA2 due to a fire will not result in the loss of the following critical functions required for safe shutdown.

1. Valve and breaker for Unit 2 redundant steam supply to the turbine driven auxiliary feedwater pump are locked open.
2. Redundant RHR suction valves are closed and the breaker locked open.

The motor control centers and associated cable entering and leaving the motor control centers are horizontally separated by 22 feet. The fuel load in the area is negligible.

The licensee justifies these alternatives on the basis of (1) all cables are qualified to IEEE-383 (2) the in-situ combustible loadings are light, and (3) ionization smoke detection is provided in each area.

5.3 Evaluation

These areas do not comply with Section III.G because they do not have an automatic fire suppression system. There is no alternative shutdown capability independent of these areas.

Because there are negligible in-situ combustibles in there areas, and postulated fire would involve transient combustible materials. Hazardous quantities of transient combustibles would not be expected in these fire areas for several reasons. First, the areas are not adjacent to or near any major plant traffic route. Second, maintenance and operations in these areas do not involve the use of combustible materials. Third, accessibility to these areas is restricted to personnel performing essential duties in the areas because of potential radiation hazards. On this basis, we agree with the licensee that any fires in these areas resulting from transient combustibles would be of limited severity and duration. The installed early warning detection system would be able to promptly detect incipient fire conditions, and the separation between redundant trains in each area will maintain the integrity of the cables and equipment until the fire brigade is able to respond and to extinguish the fire. The fire brigade should be capable of reaching each of these areas within a few minutes after an alarm is received in the control room. It is our opinion that this combination of protective features provides reasonable assurance that one train of equipment necessary for safe shutdown will be maintained free of fire damage.

5.4 Conclusion

Based on our evaluation, the level of existing protection for Fire Areas 37 Unit 1 Normal Switchgear Room, Fire Area 60 Auxiliary Building Operating Level, Unit 1 and Fire Area 75 Auxiliary Building Operating Level, Unit 1 provides a level of fire protection equivalent to the technical requirements of Section III.G of Appendix R. Therefore, the exemptions should be granted.

6.0 Fire Area 59: Auxiliary Building Mezzanine Level Unit 1

6.1 Exemption Requested

The licensee requests an exemption from Section III.G.2 of Appendix R to the extent that it requires one-hour fire rated barriers or 20 feet of horizontal separation free of intervening combustibles to separate redundant divisions and a total area automatic fire suppression system.

6.2 Discussion

Fire Area 59 is located on the mezzanine level in the immediate northwest corner of Unit 1 containment, directly above Fire Area 58 at an elevation of 715 ft. The fire area is enclosed by 3-hour-rated fire walls on all but the west side, with 3-hour-rated fire seals provided for combustible pathway penetrations. The west side of Fire Area 59 is separated from the nearest area of concern in Fire Area 74 by approximately 100 ft. of horizontal separation. The height of the ceiling in the area is 19 ft. Fire protection in the area consists of smoke detectors, standpipe hose stations and portable fire extinguishers, and a wet pipe sprinkler system which provides spot area coverage only around trays.

This fire area contains two Motor Control Centers, MCC-1L1 and MCC-1L2, and redundant division cables for safe shutdown equipment. One of the motor control centers is required for safe shutdown. The redundant cables are installed in open horizontal trays between 13 and 19 feet above the floor. The cables are separated by approximately 4 feet 6 inches and installed within 3 feet of the ceiling.

The combustible in the area is cable insulation comprising a fuel load of 25,000 BTU/sq. ft., which if totally consumed, would correspond to a fire severity of 19 minutes on the ASTM E-119 standard time temperature curve.

The licensee proposes to install fire stops in non-safety cable trays to prevent the possibility of propagating fires between redundant divisions.

The licensee justifies this alternative on the basis of (1) all cables are qualified to IEEE-383, (2) partial area sprinkler protection has been provided, (3) the in-situ combustible loading is light, (4) smoke detection is provided and (5) an analytical model was employed to show that the magnitude of an exposure fire needed to damage redundant components is significantly higher than reasonably expected.

6.3 Evaluation

This area does not comply with Section III.G.2 because it does not have a total area automatic suppression system and twenty feet of separation free of intervening combustibles or one-hour fire rated barriers. There is no alternative shutdown capability independent of this area.

The features in this area which are offered as compensation for the lack of Section III.G protective features are the proposed fire stops and that all cables are qualified to IEEE-383 Std. Neither of these can be considered equivalent to a one-hour fire rated barrier, as they may only inhibit fire damage for several minutes.

The lack of separation between redundant cable trays represents a significant threat to safe shutdown capability. A fire involving combustible materials located in the proximity of the redundant shutdown systems may cause failure of those systems prior to fire suppression action by the fire brigade or the fixed fire suppression system.

The automatic sprinkler systems will mitigate the fire hazard but may not provide fast total coverage of cabling and/or the floor area. Without the required separation distance, or the installation of a one-hour fire rated barrier, as required by Section III.G.2, we do not have reasonable assurance that damage to redundant trains would not occur pending activation of the suppression system.

The existing protection in this fire area does not provide a level of fire protection equivalent to Section III.G. Modifications such as the installation of one-hour fire rated barriers would provide the requisite level of safety.

6.4 Conclusion

Based on our evaluation, the level of existing protection for Fire Area 59 Auxiliary Building Mezzanine Level Unit 1 does not provide a level of fire protection equivalent to the technical requirements of Section III.G of Appendix R. Therefore, the exemption should be denied.

Summary

Based on our evaluation, we conclude that the licensee's proposals for the following four areas do not represent an acceptable level of safety to that which would be achieved with compliance with the requirements of Section III.G of Appendix R to 10 CFR 50:

1. Auxiliary Building Ground Floor Level Unit 1 (Fire Area 58)
2. Auxiliary Building Mezzanine Level Unit 1 (Fire Area 59)
3. Auxiliary Building Ground Floor Level Unit 2 (Fire Area 73)
4. Auxiliary Building Mezzanine Level Unit 2 (Fire Area 74)

Therefore, the licensee's request for exemptions for these areas should be denied.

In five areas of the plant, we agree with the licensee that modifications required to meet Section III.G would not enhance fire safety above that provided by existing and proposed alternatives. Therefore, the licensee's request for exemptions for the following areas should be granted:

1. Train A Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Room (Fire Area 31).

2. Train B Hot Shutdown Panel, Instrument Air and Auxiliary Feedwater Pump Room (Fire Area 32)

3. Normal Switchgear Room Unit 1 (Fire Area 37)

4. Auxiliary Building Operating Level Unit 1 (Fire Area 60)

5. Auxiliary Building Operating Level Unit 1 (Fire Area 75)

Principal Contributor:
John Stang, DE

Attachment: BNL letter report
dated October 27, 1982

Attachment 2

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Department of Nuclear Energy

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October 21, 1982

Mr. Robert L. Ferguson
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Mail Stop P-302
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Re: Evaluation of Analytical Fire Modeling in Northern States Power Company's NSPFHA02, Final Report, June 30, 1982 "Fire Protection Safe Shutdown Analysis Compliance with 10 CFR Part 50, Appendix R, Section III.G and Substantive Basis for Exemption Requests", for Prairie Island Nuclear Generating Plant.

Dear Bob:

This letter report contains our evaluation of the fire-modeling methodology employed by Northern States Power Company (NSP) in their fire-hazards analysis for the Prairie Island facility. As an alternative to the requirements specified in Section III.G. of Appendix R to 10 CFR 50, NSP purports to provide analyses that justify exemption from these requirements in particular plant fire areas.

Briefly, the general approach taken by the licensee in this regard is to calculate the energy needed to damage redundant cables in a given plant area employing conservative assumptions in the attendant model and then to calculate the amount of combustibles that would be necesary to provide such energy also employing in the analysis a set of conservative assumptions. The underlying thesis is to demonstrate that, regardless of what administrative controls are assumed, the amount and type of combustibles, as determined via analysis and/or heuristic arguments, that are necessary to damage the requisite cables will simply not be found in the plant area under investigation.

A more detailed description of the NSP approach is contained herein. In this connection, the overall scope of our evaluation is to assess that (1) the method employed is technically sound; (2) the overall approach will yield realistic or conservative results; and (3) the end use of the results is valid.

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We start our detailed review of the reference submittal by first describing in more depth than above the fire modeling process employed by NSP. This is followed by some of our general thoughts on the complexity of the fire-phenomena modeling and some key items we have considered as forming the foundation of our appraisal. The last two sections give our overall evaluation of the NSP approach based upon a detailed critique which is provided in the last section.

A. SUMMARY OF THE NSP FIRE MODELING PROCESS

The general approach taken by NSP is to identify the minimum quantity and geometry of liquid hydrocarbon spill which would exceed the damage criteria for the electrical cables of interst. This is accomplished in the following manner:

(1) Identify the electrical cables of interst, their specifications, geometry, and the dimensions of the plant area.

(2) Identify the fixed and transient liquid hydrocarbon materials of concern.

(3) Calculate the minimum quantity of the fuels of interest and the associated fire geometry (location, area, and depth) necessary to exceed the damageability criteria for the identified electrical cable through the following mechanisms:

a) Stratification

b) Radiation

c) Buoyant diffusion plume impingement

For the purposes of analysis, the effects of actual room geometry, floor slope, and equipment layout are ignored and the presence of a perfectly horizontal floor free of fire inhibiting equipment is assumed. Also, the effects of pipes and ventilation systems in diverting the flow of hot gases, absorbing incident heat flux or blocking the free passage of radiation to the cables of interest is ignored.

The objective of the analysis is to demonstrate the equivalent protection of plant passive fire protection measures alone to that protection afforded by Appendix R. Thus, wherever possible, the process so described ignores assumptions regarding "credible" quantities of transient combustibles or the value of administrative controls and attempts to present fire protection in terms of quantities of different fluids.

The basic fire models used are presented in Appendices A.1 to A.5 of the submittal. Included therein are data on heat release rates and descriptions of the mathematical models employed for calculating the ceiling layer heat flux, buoyant diffusion plume growth, thermal radiative heat flux, and an analysis for determining the size of a thermal shield needed to protect cable trays from the convective heat fluxes produced by exposure fires. Section 5 of the submittal provides a general discussion of the methodology used to support the exemption request. For each fire area, identified as not being in compliance with Section III.G.2 of Appendix R, a fire hazards analysis is contained in Section 6 of the submittal. The discussions provided in these two sections, along with each of the appendices, comprises the scope of our review. The following section describes the BNL review philosophy.

B. BASIC BNL REVIEW PHILOSOPHY

For our appraisal, some general thoughts are deemed warranted on the complexity of fire phenomena and the state of fire science with regard to enclosure fire development.

Computer models of enclosure fire development appear capable of predicting quantities of practical importance to fire safety, provided the model is supplied with the fire initiating item's empirical rate of fire growth and the effect of external-radiation on this rate. As a science, however, we cannot predict the initiating item's growth rate due to relatively poor understanding of basic combustion mechanisms. Questions and doubts have even been raised regarding the ability to predict the rate of burning of a non-spreading, hazardous scale, fire in terms of basic measurable fuel properties. However, while awaiting development of meaningful standard flammability tests and/or sounder scientific predictions, realistic "standardized" fire test procedures should continue to be formulated for empirically measuring the rate of growth of isolated initiating items, the attendant fire plume, its development within an enclosure, and the convective and radiative heat loads to "target" combustibles. Thus, in lieu of large scale computer codes to assess the fire hazard in an enclosure, we define "state-of-the-art" for the purposes of this evaluation as one which incorporates a unit-problem approach to seven general components of the fire considered relevant in understanding, at least on heuristic principles and pragmatic efforts, the phenomena of fire. The following list may be obvious, but, in the framework of this unit-problem approach, how one considers the complex heat flux and material flux interactions within the fire-modeling methodology forms the general basis for our appraisal.

The seven components and the various important interactions are:

- The burning object receives radiative and convective heat from the combusting plume and radiative heat from the hot ceiling layer and possibly the ceiling.

- The combusting plume (or flame) receives volatile species from the burning object. It receives air (which may be preheated and vitiated in oxygen) from the cold layer. When the upper point of the flame extends into the hot layer, overall burning may be modified. Room geometry, non-combusting obstacles, and burning object location influence plume development.

- The hot layer will be influenced by natural and forced ventilation, by the heat and gas combustion products, produced by the flame, and by heat losses to the enclosure walls, ceiling, and other objects. Also transient combustion within the hot, ceiling layer has been observed and may be considered an interaction with the flame. Transient combustion in the hot layer could be due to excess pyrolyzate from the burning object (both solid firebrands and gaseous incomplete products of combustion).

- The cold layer is influenced by the natural and forced ventilation, the hot layer, and obstacles within the enclosure.

- The targets are heated by radiation (and also convection for an upward spreading fire), coming from the combusting plume, the hot layer, and possibly the ceiling (if the hot layer is transparent to radiation). Ignition of a target increases the overall thermal energy content within the enclosure.

- The enclosure geometry (ceiling and walls) are heated by convection and radiation from all burning objects, and the hot ceiling layer.

- The vents influence the mass flow rate of oxidizer and the radiative and convective components of thermal energy loss.

Positive feedback is a critical part of the fire growth phenomenon and its accountability within the licensee's submittal has also been a factor in our evaluation. (Granted, each form of interaction has a characteristic time or physical dimension associated with it, which would provide a measure of its relative importance.) A matrix of the more important items which we feel are crucial for subsequent discussion in the licensee submittal are provided in Enclosure A.

C. SUMMARY EVALUATION OF THE NSP APPROACH

Conceptually, the methodology represents, in part, a technically sound and conservative technique for assessing the potential hazard presented by exposure fires to electrical cables.

The modeling tools used in assessing the relative value of existing separation that is afforded by the plant configuration in passively protecting plant safe shutdown systems from the effects of exposure fires consists in employing the following unit-models:

- fire plume model
- pool-fire induced stratification model
- pool-fire radiation model
- shield analysis
- fire-induced electrical cable damage criterion

The unit-problem approach employed, together with the correlations and electrical cable damage criterion, can be classified as most current and methodologically consistent with what is being suggested in the open literature as a viable approach for assessing the fire hazard potential associated with cable tray fires.

Thus, in most respects, we find the method employed to be technically sound and the overall approach, if applied properly (as described subsequently) could yield realistic and conservative results for asessing the thermal environment in the fire area. We question, however, the validity of the concept, as applied, in demonstrating the equivalence of the protection provided with the requirements of Appendix R, Section III.G.2.

This is based upon the following general observations:

(1) The use of an electrical damage criterion, in conjunction with the stratification model described, is not valid because the model provides a correlation that is based only on the consideration of the effect of a single exposure fire on the ensuing thermal energy content within the enclosure. Accordingly, the model/damage criterion are not uniformly valid when cables, either in the fire plume or in the stratified layer, are in the process of burning, and thereby adding thermal energy to the enclosure.

To be consistent with the experiments conducted to establish the stratifiction model, the model/damage criterion could only be considered valid when piloted-ignition, in lieu of electrical failure damage criteria is employed. Establishing a time for piloted ignition would be such that the additional heat released by the onset of cable ignition would be small compared to the exposure fire thereby making the stratification model, within the time-frame, valid.

(2) Notwithstanding the above observation, the electrical failure tests that form the basis for damage criterion employed were obtained from test observations on the short circuiting of a 70V signal. Voltages in plant cables could be much higher than this and could conceivably cause earlier damage than indicated by the experimental tests.

(3) An intrinsic limitation of the stratification model, in attempting to show equivalency in protection provided, is the independency of the correlation to lateral separation distance. In effect, the model would show that the local thermal environment to redundant horizontal cable trays situated within the stratified layer at the same height above the floor would be identical, regardless of the horizontal separation between each tray with all other pertinent data being equal.

(4) Neither the models employed nor the methodology used consider the increased heat flux that exposure fires can generate when located near walls and corners.

(5) Only liquid pool spills are considered. The possibility has not been investigated of excess pyrolyzate, resulting from insulation degradation or from initiating fires resulting from the burning of solid combustibles, which could enter into and subsequently burn within the stratified layer.

(6) Errors in the data listed, needed in establishing the hazards associated with high fire-point liquid hydrocarbons, provides significant doubts when used with the analyses described, as to conclusions drawn that such liquid spills do not present a significant fire hazard when spilled on concrete. This error is especially relevant when one has to consider the hazard associated with auxiliary feedwater pump and air compressor lubricating oil spills.

(7) Fires initiated at locations, other than on the floor, have not been addressed.

(8) An error has also been found on the thermal shield analysis, which, if corrected, would alter the limits placed on the wake velocity and temperature defects incorporated in establishing the size of shield required for protecting cables immersed within the fire plume.

(9) The non-linear optimization methodology used to determine the minimum amount of liquid fuel required to cause electrical damage to both redundant and safe shutdown systems is not presented in sufficient detail to allow for audit calculations or in-depth appraisal.

D. DETAILED EVALUATION OF THE NSP APPROACH

The basic fire models are presented in Appendices A.1 to A.5 of the submittal. These appendices include data on heat release rates and models for ceiling layer heat flux, buoyant diffusion plumes, thermal radiation and a cable failure criteria. Section 5 of the submittal provides a general discussion of the methodology used for the exposure fire analyses, which support the exemption requests. The fire hazards analysis of each fire area identified as not being in compliance with Section III.G.2 of Appendix R is contained in Section 6 of the submittal. These sections are now discussed further with regard to modeling and assumption uncertainties and application of the methodology.

Stratification

Appendix A.1 of the submittal describes a basis for selecting liquid hydrocarbon heat release rates which is based on current state of knowledge in fire sciences. The assumption that ventilation is always sufficient to provide ideal fuel-oxygen ratios leads to the use of a conservative upper bound for the heat release rate. Also conservative asymptotic values (large scale fires) for steady state mass loss rate per unit area are used, i.e., the fire is assumed to reach steady state conditions immediately. The use of laboratory scale, actual heat of combustion data of Tewarson is also conservative by assuming the most efficient combustion achievable in the laboratory.

Appendix A.2 of the submittal describing the stratification model is based on the correlation of Newman and Hill[1] for the convective and radiative heat flux in the stratified ceiling hot gas layer developed by a pool fire within an enclosure. The heat flux is related to the room's dimensions, the target height above the floor, the fuel's flammability parameters and the room ventilation rate.

This correlation should be adequate for evaluating the heat flux due to pool exposure fires. However, it should be pointed out that one conclusion reached from the data in reference 1 and carried over into the correlation, namely that horizontal heat flux variations are minimal, is not in agreement with some other authors[2-5]. In these references, data[4] and theory[2,3] show that, for radial distances from the fire plume axis greater than 20% of the ceiling height, the heat flux decreases with radial distance to the -1/3 power. These works consider a quiescent enclosure while Newman and Hill include forced ventilation in most of their tests. However, since Newman and Hill's heat flux data for no ventilation fall in the center of You and Faeth's data[4] for radial distances closer than 20% of the ceiling height (no radial dependence), the neglect of the decrease in heat flux with radial distance by Newman and Hill should yield a conservative result.

On the other hand, references 3 and 5 show that if the exposure fire is near a wall or in a corner, the ceiling temperatures increase as if the fire heat release rate is increased by a factor of 2 and 4 respectively. Therefore, care must be taken in applying the Newman and Hill correlation for exposure firs in the vicinity of walls or corners so that non-conservative results are not obtained.

The submittal does not use the Newman and Hill correlation exactly as presented in reference 1. Instead a modified form as given on page A.2-4 is used. Apparently, this was done to extend the correlation at ventilation rates greater than those for which measurements were taken in reference 1. This fact, coupled with the unrealistic cooling behavior of the original Newman and Hill correlation at higher ventilation rates as shown in Figure A.2-2 leads to the need for the modified correlation, which continues the data trend to higher values of ventilation. This modified correlation is more conservative than the original. Since the labeling of Figure A.2-2 is somewhat confusing, it is replotted as Figure 1 (attached) with the modified correlation on page A.2-4 included.

Several questions are therefore raised in applying the Newman-Hill correlation in the context of a stratification model, viz.,

- How can one judge the benefits of horizontal separation between redundant divisions with a correlation law that is independent of the lateral dimension?

- How valid would the correlation be in accounting for the effects of exposure fires situated in closer proximity to walls and corners than those analyzed by Newman and Hill?

- If one presupposes the likelihood of secondary fires within the enclosure, how valid then is the use of the stratification model?

In this connection, one must, therefore, recognize the utility of such a correlation commensurate with its implicit limitations.

Diffusion Plumes

Appendix A.3 of the submittal describes a turbulent, buoyant diffusion plume model, which is essentially the classical Morton-Taylor model. The experiments of Stavrianidis[6] are considered along with his correlations for critical height, (height to which plume correlation is valid), and virtual source height. The heat flux correlations of You and Faeth for the stagnation region ($r/H < 0.2$) and the ceiling jet are also presented.

These represent the more recent correlations for hydrocarbon pool-fire plumes. However, there are several errors, most likely typographical, which should be corrected. First, the exponent of the factor F_a in the buoyancy expressions on page A.3-2 and A.3-3 should be 2/3 rather than 1/3. A review of You and Faeth's work yields the following comments concerning the heat flux correlation on pages A.3-9 and A.3-10 of the submittal:

- The Greek symbol ν appearing in the Rayleigh number is defined as the kinematic viscosity not the radial velocity.
- The heat flux correlation appearing on the bottom of page A.3-9 is valid in the ceiling jet, outside the stagnation region ($r/H > 0.2$), for free flame height to ceiling height ratios up to 2.5 as evidenced by the data in Figure 7 of Reference 4.
- The range of the Rayleigh number dependency, namely, $10^9 < R_a < 10^{14}$, in the stagnation point heat flux parameter (see page A.3-8) leaves one to doubt the use of this correlation for ceiling heights an order of magnitude larger than the experimental apparatus used in deriving said correlation.

Radiation

The radiant heat transfer from a high temperature turbulent, buoyant diffusion plume is discussed in Appendix A.4 of the submittal. A classical approach based on the Stefan-Boltzmann law is used. A uniform gaseous temperature of 1200° K is assumed based on the work of Stavrianidis. It is not clear which correlation for flame height is used, although Stavrianidis has a correlation for hydrocarbon which is consistent with data. However, passing mention of Steward's[7] work is all that is found in this appendix. Effective values for gaseous and soot emissivities are used, with a value of 0.1 being taken for soot. An expression for the gaseous emissivity which is dependent on the gaseous temperature, the partial pressure of CO_2 (a combustion product) and the mean beam length is presented. These classical expressions and assumptions are acceptable as present state of knowledge in radiant heat transfer.

However, there is some confusion about the definition of mean beam length on pages A.4-5 and A.4-7, where it is defined as a fraction of the electrical cable diameter. The mean beam length cannot be a function of the target receiving the radiation, but must be a geometric property of the flame producing the radiation. Hottel and Sarofim[8] have shown that the average mean beam length for a target at the flame boundary (very conservative) is well approximated by

$$L_m = 3.5V_f/A_f$$

where V_f is the flame volume and A_f the flame bounding area. Less conservatively, for targets far removed from the flame, a somewhat better approximation[9] for L_m is 0.9 times the ratio of the effective flame volume to the flame area projected on a vertical plane. It is not clear if this expression was used in the determination of the needed gaseous emissivity in the calculation of radiant heat transfer, or whether a value of 0.2 was used as mentioned in the main body of the submittal. Also, calculations for a cylindrical flame, using the above mean beam length, give approximately the same heat flux results as the expression on page A.4-7, with D equal to the fire diameter. Therefore, the use of cable diameter in the submittal may only be a documentation error. A typographical error does exist on page A.4-6, where both the factors 0.131 and 0.94D should be raised to the 0.412 power.

Also in need of clarification is the nature of the configuration factor used to obtain the fraction of the heat flux delivered to a target point by the assumed radiant right cylinder.

Thermal Shields

In Appendix A.5 of the submittal, an analysis is presented which is used to provide a basis for determining the required size of baffles used to protect a vertical stack of trays from convective heating due to direct impingement of an exposure fire plume. A data correlation[10] based on the turbulent wake behind a blunt body is used to obtain an expression for the required baffle width in terms of the downstream extent of the zone to be protected. The condition that the velocity be reduced to 20 percent of the free steam value was used as a protected zone boundary definition. However, it is then implied that the temperature reduction (defect) in the wake is linearly proportional to the velocity defect. A closer review of reference 10 indicates that experimental data and theoretical results based on Taylor's assumption of turbulence, rather than Prandtl's theory of free turbulence, results in the wake temperature defect being equal to the square root of the velocity defect. Therefore, a shield which limits the velocity to 20% of the free stream velocity, will only reduce the temperature to 45% of its free stream value. This is less conservative than implied in Appendix A.5.

Analytical Methods

Chapter 5 of the submittal outlines in very general terms the methodology used in the fire hazards analysis of Chapter 6. Due to this generality, only two comments are made here, viz, 1) the ventilation assumption and 2) the ignitability of high fire point hydrocarbon spills.

The assumption is made that there is always sufficient ventilation to support an optimum stoichiometric fuel/air ratio and to maintain the compartment desmoked. This assumption will result in conservative estimates of the heat release rates, due to optimum burning conditions, and conservative estimates on radiation effects due to the neglect of attenuation due to smoke. However, nowhere is there due consideration given for the possibility of secondary fires stemming from the ignition of the products of incomplete combustion, elsewhere in the enclosure.

The analysis in Section 5.3.2 of the combustibility of high fire point liquid hydrocarbons based on the work of Modak[11] is significant for evaluating the magnitude and duration of the external heat source necesary for ignition of postulated spills in the plant. Note that the expression in the submittal (T on the right hand side represents time; on the left hand side T represents temperature) is only the leading term of Modak's expressions. For thick spills this term is the classical solution for a non-transparent medium, with the additional terms necessary for semi-transparent oils. For thin spills, the leading term represents the condition where the spill depth approaches zero.

There are some serious errors in Tables 5-1 and 5-2 of the submittal. In Table 5-1, the values of thermal conductivity and volumetric heat capacity listed for concrete are actually the values for copper given in reference 11. Additionally, the units of thermal conductivity have been interpreted incorrectly from reference 11. Table 5-1 should read:

	λ_i (kW/m·K)	$\rho_i C_i$ (kJ/m^3· K)
Concrete (273° K)	1.8×10^{-3}	2.10×10^{3}
Liquid Hydrocarbon (300°-600°K)	1.25×10^{-4}	1.90×10^{3}

This is an error of 10^9 in λ_i of the hydrocarbon. Whether this erroneous value was actually used in calculations is not clear.

The use of the correct parameters in the leading term of Modak's relationships for a 10-minute exposure duration results in external heat fluxes considerably lower than presented in Table 5-2. We calculate based upon the correct data the following which should be compared with Table 5-2 on page 5-19 of the submittal.

	Thin Spill	Thick Spill
Lubricating Oil-Flash point (489°K) (Pennzoil 30-40)	20.56 kW/m^2	5.15kW/m^2
-Ignition Temperature (650°K)	37.98 "	9.52 "
Heptane-Ignition Temperature (487°K)	20.41 "	5.11 "

Comparing the values in these two tables leads one to believe that the conclusion in the submittal, namely "that high fire point liquid hydrocarbons are, in actuality, not significant fire hazards when spilled on concrete" should be reconsidered in light of these corrected heat flux values.

Analysis and Exemption Requests

The fire hazards analysis of the individual fire areas is discussed in Section 6. This section also discussed many specific assumptions such as cable-damage criteria, intervening cables not being a source of combustibles, non-ignitability of lubricating oil, etc., which are very important to the analysis. These assumptions will be addressed before discussing any particular fire area calculations.

The auxiliary feedwater pump and air compressor lubricating oil is not considered as a source of combustibles in the analysis. In light of the lower revised values of required heat flux in Table 5-2, (a thick spill of oil with a flash point of 450°F would only require an external flux of about 5.3kW/m^2 for 10 minutes to ignite), this assumption should be reconsidered.

All electrical cables are assumed flame retardant and are therefore not considered as intervening combustible material. This is based on the low heat release rate and low propagation potential of these cables. However, one should still consider the potential of the combustibility of the products of pyrolysis of the cables. For instance, the EPR/Hypalon cable has carbon monoxide and gaseous hydrocarbon yields of 7% and 1% of the mass loss rate, respectively. These products can collect in the ceiling layer and result in a secondary fire. However, the stratification model is not valid for such secondary fires.

The next consideration is the important one of selection of a cable damage criterion. The analysis focuses on the minimum conditions necessary to cause a loss of cable function through piloted electrical failure as defined by Lee[13]. The choice of the electrical failure appears to be somewhat less conservative for two reasons.

First, as stated by Tewarson[14], cable damage first appears as insulation/jacket degradation, then piloted ignition and then electrical failure. Since Appendix R states that cables should be free from fire damage, it would be more conservative to use the insulation/jacket degradation failure mode as a cable damageability criterion.

Secondly, the electrical failure tests of Lee were based on short circuiting a 70V signal. However, voltages in plant cables are usually much higher than this and could conceivably cause earlier damage than the tests indicated.

Another point concerns the particular EPR/Hypalon cables chosen as a failure criteria out of the two tested by Lee (see Fig. 3-15 of reference 13). Sample 8 was chosen since it has the largest slope, i.e., the smallest critical energy of the two cables. However, for external heat flux less than about 50 kW/m^2, where the smaller fires considered in the fire hazards analysis should fall, cable sample 11 would actually give a shorter time to failure. This then would be a more conservative failure criteria choice in this range of heat flux. This difference looks small on the curve, but for an external heat flux of 25 kW/m^2, the difference in time to failure is about 6 minutes.

Another assumption made in applying the methodology is the instantaneous achievement of steady-state, overventilated combustion. Assuming steady-state conditions are reached immediately, conservatively maximizes the heat release from the exposure fire.

In the analysis non-combustible thermal shields are placed beneath cable trays to protect them from failure due to direct plume impingement. However, since little detail of these shields is given and, as mentioned earlier with regard to Appendix A.5, there is an error in the shield analysis which, when corrected, would not yield as conservative a result as implied, the design of the thermal shields should be further scrutinized.

With this as background information, the actual calculations for specific fire areas are now discussed. The submittal states that a "back calculation" approach is used that calculates the smallest quantity of fuel which causes both redundant divisions to just exceed the damage criteria. It is stated that "classical optimization techniques for nonlinear functions" are used. However, this methodology is not explained sufficiently to be reproducible. The methodology description does not state which equations and minimization techniques are used. Each result does not state the heat flux that each mechanism (plume impingement, stratification, radiation) delivers to the cable.

Some direct calculations were attempted using the submittal results for Fire Area 31. These results assume that one cable tray is protected from direct plume impingement by a non-combustible thermal shield. Then it would seem that the problem reduces to calculating the heat flux received by these cables from the thermal mechanisms within a stratified ceiling layer. Therefore, calculations were made using the stratification model of Appendix A.2. It should be noted that the tests of Newman and Hill also include the effects of pool fire radiation (which are small). Therefore, this correlation should give the heat flux received by the shielded cables.

Using a constant external heat flux value of 17 kW/m^2 (which we calculate using the same input as in the submittal) the electrical failure curve, Figure 3-15 of reference 13, for sample 8 gives a time of failure of about 5400 seconds. This is much larger than the stated 880 seconds - a time which would require an external flux of about 33 kW/m^2 as indicated from the failure curve. Therefore, the submittal analysis needs to be further clarified to resolve this discrepancy.

Another point which requires clarification arises from a comparison of the minimum fuel quantity results and the forced ventilation rates for each fire area. As shown in the table, certain fire areas have exactly the same fuel requirements even though their ventilation rates differ.

As an exercise, the plume stagnation heat flux expression of Appendix A.3 was used to calculate the heat flux impressed to a cable tray 17'6" above the fire as postulated for Area 31. This results in a heat flux of approximately 12 kW/m^2, a value less than the critical heat flux required to damage the cable. Therefore, the methodology used for the plume impingement mechanism in the submittal also needs clarification. We believe that the plume impingement model is not applicable because the Rayleigh number is outside the range where the correlation applies.

To complete the analytical appraisal (as far as we could go), the radiant heat flux from the fire postulated for Fire Area 31 was obtained using the equations documented in Appendix A.4. Three calculations were performed. The first uses the equation on page A.4-7, except that the diameter D is taken as the fire diameter as mentioned previously and not cable diameter as indicated in the Appendix. The second considers a fixed value of 0.2 for gaseous emissivity. The third computes the gaseous emissivity from the equation on page A.4-5, but with the mean beam length calculated from the correlation[8] mentioned earlier. With the configuration factor taken as unity, all three calculations yield a heat flux of about 42 kW/m^2. Of course, the configuration factor can be a number much less than unity depending on the exact geometry, but this calculation shows the similarity of the methods. If we had the exact value for the configuration factor, we could then possibly discuss the differences between the BNL result of 17 kW/m^2 for external heat flux and the BNL-inferred value of 33 kW/m^2.

E. CONCLUDING REMARKS

In our appraisal and review process, we have considered the following attributes: accuracy, completeness, applicability, and traceability. Of the four, we found traceability, especially in the exemption request and in the optimization technique, to be the most wanting. Next in the decreasing hierarchal order is completeness, mainly manifested by the lack of due consideration of other types and locations of exposure fire. For applicability, we mainly question the use of the cable damageability index employed. Accuracy, in a sense, is linked to the overall traceability of the analysis and, as such, cannot be completely judged. We, however, do give credit to NSP for utilizing state-of-the-art modeling techniques (as we have defined); we give credit for their use of reasonable physical data and, in some respects, the degree of conservatism employed. To editorialize for the moment, we feel hard-pressed to judge the overall conservatism. In some fire phenomena factors, the models and assumptions lead to over-conservatism; in others, non-conservatism prevails.

We think the approach taken by NSP, employing a unit-problem methodology, is technically sound in assessing the impact of liquid pool spill fires, albeit incomplete in appraising the overall fire hazard within an area. Also, in our estimation, the analysis, its limitations, and the lack of traceability of the submittal, precludes one from demonstrating equivalency between proposed fire protection features and requirements stipulated in Section III.G.2 of Appendix R to 10 CFR 50.

We recommend, however, that analyses such as that presented by NSP should continue with more depth in the realm of fire phenomena modeling and consistency in the overall approach by taking into account the limitations implicit in the various models employed.

In summary, this report represents the combined efforts of Dr. John Boccio and myself in evaluating the fire-modeling methodology employed by NSP in their fire-hazards analysis of the Prairie Island facility.

Yours truly,

John Boccio for

Charles J. Ruger
Reliability & Physical Analysis Group

CJR/sm
Enclosures
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W. Kato

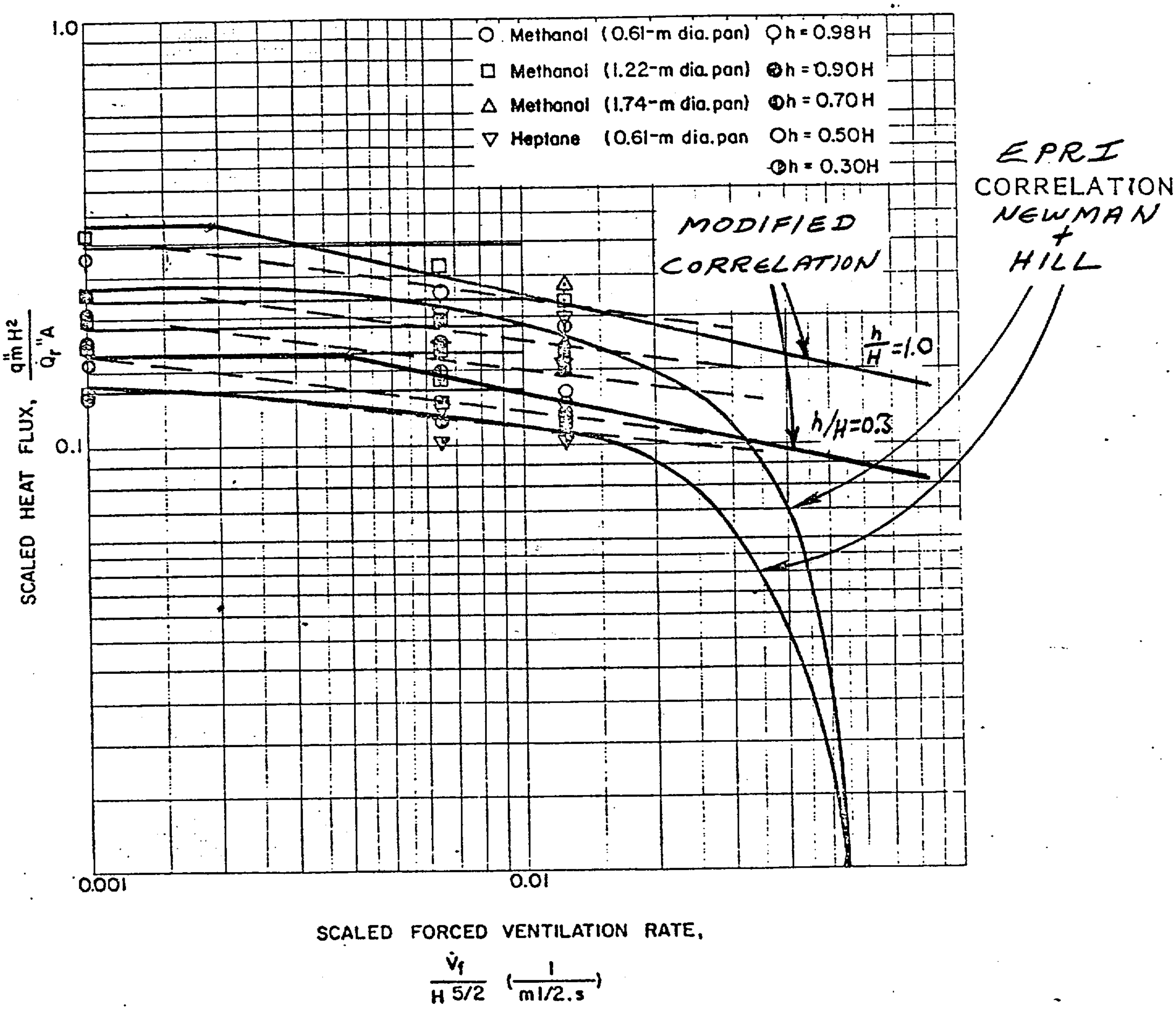

Figure 1. Scaled Heat Flux versus Scaled Forced Ventilation Rate

Reproduced from Newman, J.S. and Hill, J.P., "Assessment of Exposure Fire Hazards to Cable Trays", EPRI-NP-1675, Electric Power Research Institute, Palo Alto, CA, January 1981

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ENCLOSURE A

Factors Considered in the Evaluation

1. Initiating Fire

    1.1 Type of combustible (liquid and/or solid)
    1.2 Amount of combustible
    1.3 Combustible geometry/orientation

        1.3.1 pool spill (confined or unconfined)
        1.3.2 solid fuel (vertical/horizontal)

2. Initiating Fire Location

    2.1 Relative to "target(s)"
    2.2 Relative to room geometry

        2.2.1 centrally located
        2.2.2 wall
        2.2.3 corner
        2.2.4 non-burning obstacles
        2.2.5 height

3. Combustion/Pyrolysis Properties

    3.1 Initiating combustible/target combustible (transient and/or fixed)

        3.1.1 ignition sensitivity
        3.1.2 mass loss rate in pyrolysis
        3.1.3 mass loss rate in combustion
        3.1.4 heat flux to surface (radiative & convective & losses)
        3.1.5 excess pyrolyzate
        3.1.6 fuel stoichiometry
        3.1.7 heat release rate
        3.1.8 product generation rate

4. Target Damageability Criteria

    4.1 Solid combustibles (cables)

        4.1.1 insulation/jacket degradation
        4.1.2 ignition (piloted and auto ignition)
        4.1.3 electrical integrity failure

    4.2 Equipment (safety related)

        4.2.1 radiation heat flux
        4.2.2 convective heat flux
        4.2.3 chemical degradation (from products of combustion)

5. Fire Dynamics/Room Geometry

  5.1 Ventilation

    5.1.1 forced
    5.1.2 normal

  5.2 Obstacles
  5.3 Ceiling

    5.3.1 smooth
    5.3.2 beamed

6. Fire Dynamics Models

  6.1 Combusting Plume

    6.1.1 flame height/diffusion
    6.1.2 ceiling heat transfer
    6.1.3 radiative heat transfer

  6.2 Hot Layer

    6.2.1 thickness
    6.2.2 heat content
    6.2.3 convective heat transfer
    6.2.4 radiative heat transfer
    6.2.5 transient combustion

  6.3 Target(s)

    6.3.1 horizontal
    6.3.2 vertical (wall-plume; wall-wake)

7. Protection Measures

  7.1 Barriers
  7.2 Detection
  7.3 Suppression
  7.4 Administrative Controls

ENCLOSURE B

Some Thoughts on the Stratification/Cable Damageability Model

Given the geometry of the enclosure, the height of the "target" combustible, the forced ventilation rate, and the type of exposure fire combustible, the stratification model states that the maximum external heat flux to the target is

$$\dot{q}''_{ss} = K_2 \, A_{Pool} \tag{1}$$

where $K_2 = K_2 \, (H, \dot{Q}''_T, \dot{V}_f, h)$

target height (m)

ventilation rate (m^3/sec)

heat release rate (kW/m^2) of exposure fire

room height (m)

Considering electrical failure of the target combustible, the damageability model states that the electrical failure index (EFI) is given by

$$EFI = (1/t)_{EF} = (\dot{q}''_e - \dot{q}''_{ef})/E_{ef} \tag{2}$$

effective energy of electrical failure (kJ/m^2)

minimum effective flux of electrical failure (kW/m^2)

external heat flux (kW/m^2)

time to electrical failure (sec)

For a particular electrical cable material, E_{ef} and $\dot{q}''_{ef}$ are known. Then by considering $\dot{q}''_{ss} \doteq \dot{q}''_e$, Eqns. (1) and (2) give

$$K_2 A_{Pool} (t)_{EF} - K_3 (t)_{EF} = K_4 \tag{3}$$

which for given values of A_{Pool} one can calculate the effective time to failure. This variation is shown in the accompanying figure. Now considering the mass burning rate of the liquid pool, m''_b, as constant, the total mass of fuel can be approximated by

$$m_f = \dot{m}''_b \, A_{Pool} \, t_b \tag{4}$$

mass burning rate (gr/m^2 sec)

Specifying values of m_f and with $\dot{m}''_b$ known

$$A_{Pool} = K_1 \, m_f / t_b \qquad m_f = m_{f,1};\ m_{f,2};\ m_{f,3} \tag{5}$$

which is also shown superimposed in the accompanying figure. The intersection of Eqn. (5) with Eqn. (3) gives a focus of points allowing one to pick a value of m_f required, burning in a pool of size A_{Pool}, to cause cable electrical damage in time, t_{EF}. Also note that by eliminating t between Eqns. (3) and (4) yields

$$\frac{dm_f}{dA} = - K_4 \, K_3 \; / \; K_1 \; [K_2 \; A-K_3]^2$$

$$= - \dot{m}''_b \, E_{ef}\dot{q}''_{ef} \; / \; [K_2A-\dot{q}''_{ef}]^2$$

which shows that $dm_f/dA < 0$ implying that as the area of the pool increases the amount of fuel required to cause damage decreases.

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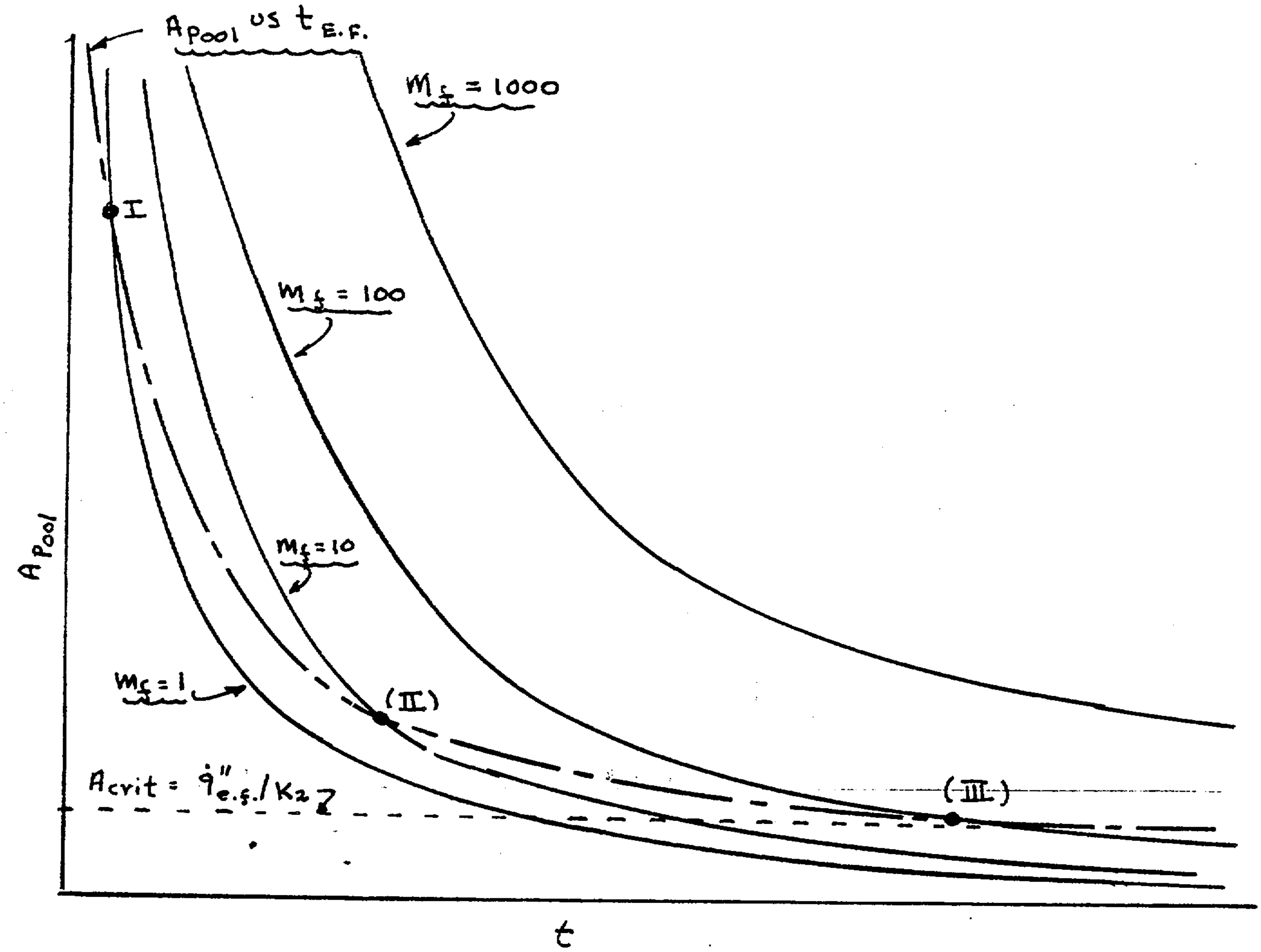
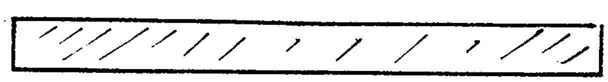
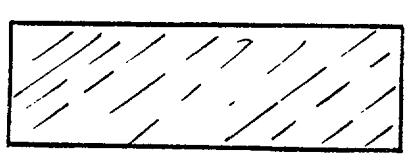
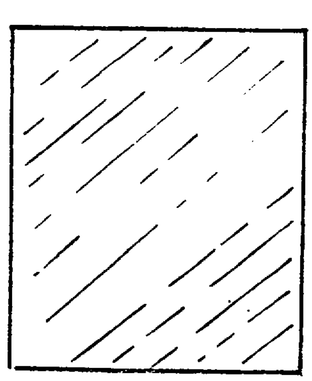


I  m_{f_I}

II  $m_{f_{II}} > m_{f_I}$

III  $m_{f_{III}} > m_{f_{II}} > m_{f_I}$