Enclosure 2

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Department of Nuclear Energy

October 21, 1982

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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.

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 feedwate 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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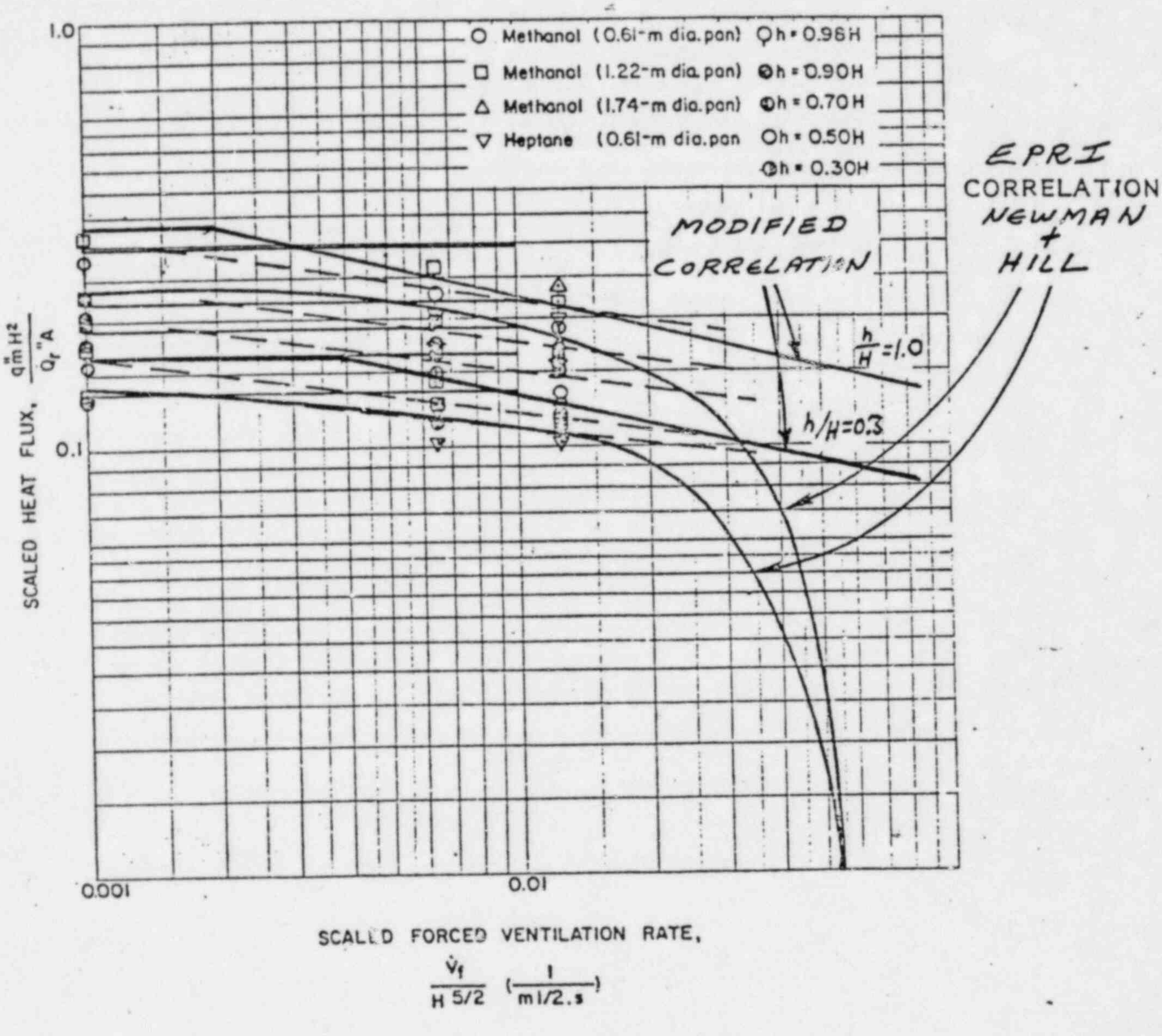


Figure 1. Scaled Heat Flux versus Scaled Forced Ventilation Rate

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

REFERENCES

1. 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.

2. Alpert, R.L., "Calculation of Response Time of Ceiling-Mounted Fire Detectors", Fire Technology, Vol. 8, 1972, pp. 181-195.

3. Alpert, R.L., "Turbulent Ceiling Jet Induced by Large-Scale Fires", Combustion Science and Technology, Vol. 11, 1975, pp. 197-213.

4. You, H.Z. and Faeth, G.M., "Ceiling Heat Transfer During Fire Plume and Fire Impingement", Fire and Materials, Vol. 3, No. 3, 1979, pp. 140-147.

5. Alpert, R.L. and Ward, E.J., "Evaluating Unsprinklered Fire Hazards", FMRC J.I. No. 01836.20, Factory Mutual Research Corporation, Norwood, Ma., August 1982.

6. Stavrianidis, P., "The Behavior of Plumes Above Pool Fires", a Thesis presented to the Faculty of the Department of Mechanical Engineering of Northeastern University, Boston, Ma., August 1980.

7. Steward, F.R., "Prediction of the Height of Turbulent Diffusion Buoyant Flames", Combustion and Science Technology, Vol. 2, 1970, pp. 203-212.

8. Hottel, H.C. and Sarofim, A.F., "Radiative Transfer", McGraw-Hill Book Company, New York, 1967.

9. Orloff, L., "Lip Effects in Pool Fires", Paper No. 33, Canadian Section of the Combustion Institute, Kingston, Ontario, May 1979.

10. Schlichting, "Boundary Layer Theory", Seventh Edition, McGraw-Hill Book Company, New York, 1979.

11. Modak, A.T., "Ignitability of High-Fire-Point Liquid Spills", EPRI NP-1731, Electric Power Research Institute, Palo Alto, Ca., March 1981.

12. Tewarson, A., Lee, J.L. and Pion, R.F., "Categorization of Cable Flammability Part 1: Laboratory Evaluation of Cable Flammability Parameters", EPRI NP-1200, Electric Power Research Institute, Palo Alto, Ca., October 1979.

13. Lee, J.L., "A Study of Damageability of Electrical Cables in Simulated Fire Environments", EPRI NP-1761, Electric Power Research Institute, Palo Alto, Ca., March 1981.

14. Tewarson, A., "Damageability and Combustibility of Electric Cables", paper presented at FMRC/EPRI Seminar, Factory Mutual Conference Center, Norwood, Ma., December 9-11, 1981.

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

- h → target height (m)
- $\dot{V}_f$ → ventilation rate (m^3/sec)
- $\dot{Q}''_T$ → heat release rate (kW/m^2) of exposure fire
- H → room height (m)

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

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

- E_{ef} → effective energy of electrical failure (kJ/m^2)
- $\dot{q}''_{ef}$ → minimum effective flux of electrical failure (kW/m^2)
- $\dot{q}''_e$ → external heat flux (kW/m^2)
- $(t)_{EF}$ → time to electrical failure (sec)

For a particular electrical cable material, E_{ef} and $\dot{q}''_{ef}$ are known. Then by considering $\dot{q}''_{ss} \equiv \dot{q}''_e$, 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, $\dot{m}''_b$, as constant, the total mass of fuel can be approximated by

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

- $\dot{m}''_b$ → mass burning rate (gr/m^2 sec)

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

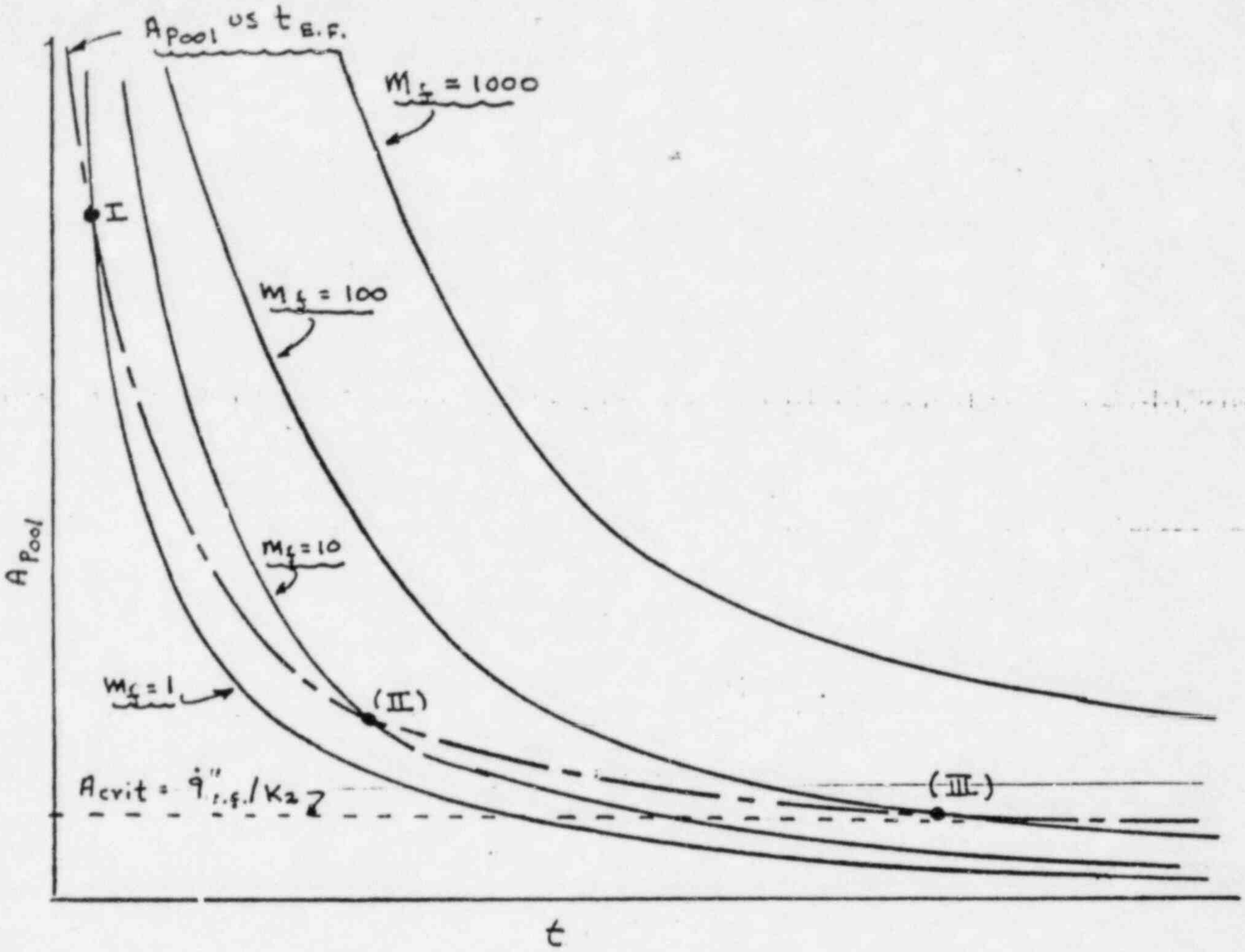
$$A_{Pool} = K_1 m_f/t_b \quad m_f = m_{f,1};\ m_{f,2};\ m_{f,3} \qquad (5)$$

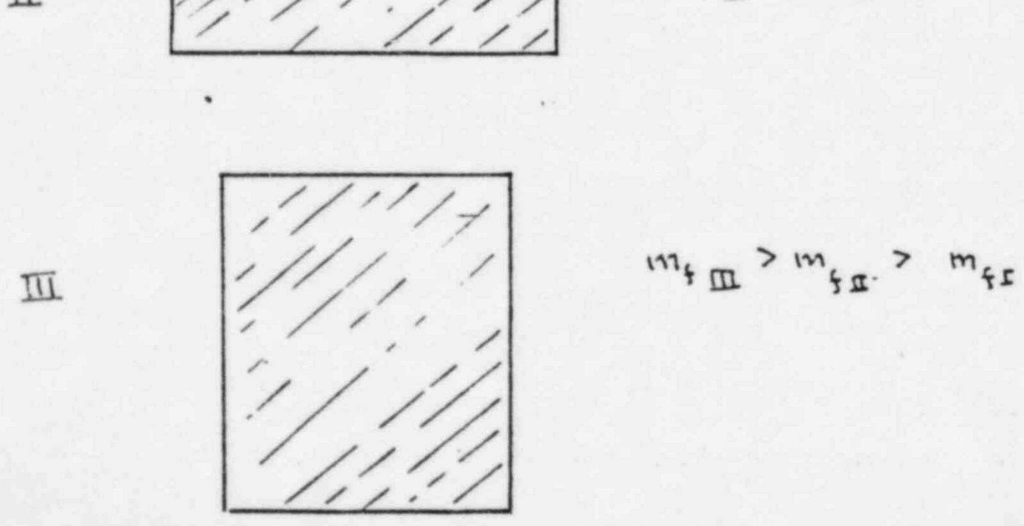
which is also shown superimposed in the accompanying figure. The intersection of Eqn. (5) with Eqn. (3) gives a focus of points allowing one to pick a value of m_f required, burning in a pool of size A_{Pool}, to cause cable electrical damage in time, t_{EF}. Also note that by eliminating t between Eqns.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


A_{pool} vs $t_{s.f.}$
$m_f = 1000$
$m_f = 100$
$m_f = 10$
$m_f = 1$
I
(II)
(III)
$A_{crit} = \dot{q}''_{r.f.}/K_2$
A_{pool}
t


I
$m_{f\,I}$
II
$m_{f\,II} > m_{f\,I}$
III
$m_{f\,III} > m_{f\,II} > m_{f\,I}$