Enclosure 2

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Department of Nuclear Energy

December 3, 1982

Randall Eberly
U.S. Nuclear Regulatory Commission
Chemical Engineering Branch - Mail Stop P-302
Washington, D.C. 20555

Re: Fire & Probabilistic Model Reviews - FIN A-3703

Dear Randall:

Enclosed is our review of Wisconsin Electric Power Company's (WEP) fire modeling and analyses used to justify exemption requests of their Point Beach facility to 10 CFR 50, Appendix R.

If you have any questions regarding this subject matter or our previous four reviews, please feel free to call either me or Drs. Charles Ruger (FTS 666-2107).

Yours truly,

John Boccio

John L. Boccio, Group Leader
Reliability & Physical Analysis

JLB/sm
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EVALUATION OF THE ANALYTICAL FIRE MODELING
BY THE WISCONSIN ELECTRIC POWER COMPANY (WEP)
IN THEIR JUNE 1982 REPORT
"POINT BEACH NUCLEAR PLANT, UNITS 1&2, RESPONSE TO 10 CFR 50, APPENDIX R FIRE PROTECTION OF SAFE SHUTDOWN CAPABILITY"

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1. INTRODUCTION

This report contains our evaluation of the fire-modeling methodology employed by the Wisconsin Electric Power Company (WEP) in their June 1982 report, "Point Beach Nuclear Plant, Units 1&2, Response to 10 CFR 50, Appendix R Fire Protection of Safe Shutdown Capability." As an alternative to the requirements specified in Section III.G of Appendix R to 10CFR50, WEP 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 minimum amount of combustibles that would be necessary 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 WEP 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 WEP. This is followed by some of our general thoughts on the complexity of the fire-phenomena modeling and some key items we consider as forming the foundation of our appraisal. Sections 4 & 5 give our overall evaluation of the WEP approach based upon a detailed critique, which is provided.

2. SUMMARY OF THE WEP FIRE MODELING PROCESS

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

(1) Identify the electrical cables of interest, 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.8 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, a method for determining the size of thermal shields, a heat conduction model, a model for heat transfer inside a cabinet, and a switch radiation model. Section 4 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 5 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.

3. 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 burning rate 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 more sound 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) is 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, is provided in Appendix A.

4. SUMMARY EVALUATION OF THE WEP APPROACH

As a concept, the overall 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, 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:

- pool-fire plume model
- pool-fire induced stratification model
- pool-fire radiation model
- fire-induced electrical cable damage criterion
- thermal shield analysis
- finite element heat conduction model
- thermal analysis of cabinet/panel internals
- panel switch radiation model

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. However we question 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 is not uniformly valid when cables, either in the fire plume or in the stratified layer, are in the process of burning, thereby adding thermal energy to the enclosure.

To be consistent with the experiments conducted to establish the stratification 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 valid within the time frame.

On the other hand, when the damaged cables are completely enclosed in conduit, the electrical damage criterion may be sufficient.

(2) The above observation notwithstanding, the electrical failure tests that form the basis for the 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, 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 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, has not been investigated.

(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.

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

(8) 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 appraisal.

(9) The Rayleigh numbers of the postulated fires are far beyond the range for which the plume impingement model is valid.

(10) An error has 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.

(11) It is not clear which radiation heat transfer model is used in the analysis or from where the configuration factor is obtained.

5. DETAILED EVALUATION OF THE WEP APPROACH

The basic fire models are presented in Appendices A.1 to A.8 of the submittal. These appendices include data on heat release rates and models for ceiling layer heat flux, buoyant diffusion plumes, thermal radiation, a method for determining the size of thermal shields, heat conduction, internal cabinet heat transfer, and cabinet switch radiation. Section 4 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 5 of the submittal. These sections are now discussed further with regard to modeling, assumption uncertainties, and application of the methodology.

5.1 Review of Appendix A.1

Appendix A.1 of the submittal describes a basis for selecting liquid hydrocarbon heat release rates, based on the current state of knowledge in fire sciences. Values of the heat of combustion, vaporization rate, and heat release rate, are given for acetone, lubricating oil and heptane. 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 generated, actual heat of combustion data by Tewarson is also conservative since the most efficient combustion achievable in the laboratory is employed in the analysis.

5.2 Review of Appendix A.2

Appendix A.2 of the submittal 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. However, in re-examination of Figure 7 of Reference 4, the heat flux appears to have a radial dependency to the -1.25 power. This is shown in Figure 1 provided herein. To further check this difference, we utilized the heat transfer coefficient parameter, h_c, presented by Veldman, et al (Reference 15) in their Figure 14. This shows a radial dependency for this parameter to the -0.6 power which, when applied to the -2/3 power correlation presented by Alpert in Reference 2 for the maximum plume temperature difference, ΔT, yields in concert a radial power law dependency of approximately (-1.27), which is in close agreement with the -1.25 power indicated in Fig. 1.

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. This also tends to show no benefit to horizontal cable separation for radial distances closer than 20% of the ceiling height.

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 fires 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 2 (attached) with the modified correlation on page A.2-4 included. The correlation is not valid if secondary fires occur, or if excess pyrolyzates burn in the stratified layer.

5.3 Review of Appendix A.3

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 correlations are valid), and virtual source height. The heat flux correlations of You and Faeth[4] for the stagnation region ($r/H < 0.2$) and the ceiling jet are also presented. The correlations are for Rayleigh numbers of 10^9 to 10^{14}, whereas the fires discussed in Section 5 of the submittal have Rayleigh numbers of about 10^{17}. There should be some defense of this extension.

These represent state-of-the-art 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 pages 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.3-8 and A.3-9 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 radial dependence in the correlation should be to the -1.25 power as explained in the review of Appendix A.2.

5.4 Review of Appendix A.4

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 1255° K is assumed based on the work of Stavrianidis[6]. 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 the 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. The equation on page A.4-7 contains this factor but no mention is made as to what values are used or from where they are obtained.

5.5 Review of Appendix A.5

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 stream 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.

5.6 Review of Appendix A.6

Appendix A.6 discusses the solution of the two dimensional heat conduction equation on page A.6-5 for transient heat conduction in a solid by means of the finite element method. The accuracy of this method depends upon a judicious choice by the analyst of element shape, nodal positions, interpolating function, and also a final judgement as to the acceptability of the temperature profiles. There is no discussion of boundary conditions (e.g., how are the radiative and convective boundary conditions on both the heated surface and back face applied), the effect of neglecting the third spatial dimension, or the acceptance of the analyst's judgement. However, the issue is not how to solve the equation, but rather, how WEP should demonstrate that the complex heat conduction processes taking place during a fire can be adequately modeled by the equation. It is stated on page A.6-8 that a switch and an undervoltage relay might be representative of a broader class of the many different types of components that may be found mounted in electrical switchgear and cabinets in a nuclear power plant. No evidence is given in support of this judgement.

5.7 Review of Appendix A.7

This appendix contains a brief discussion of a one-dimensional heat transfer model for computing temperatures of objects inside a cabinet or panel. Again we feel that WEP should discuss the limitations of the model. For example, the back wall in Figure A.7-1 appears to be exposed to a constant ambient temperature during the fire. This may not be valid in general.

There are some typographical errors. Part of a heat radiation term is missing from Eqn. 1 on page A.7-2; the numbers at the bottom of page A.7-3 are for the product of density and heat capacity (ρc in the model and not c as in the text); and the units in parenthesis should be BTU/in^3-R for both steel and air.

5.8 Review of Appendix A.8

This appendix contains a model for thin-wall temperature response. Under the thin wall condition, there are no body temperature gradients and heat received diffuses instantaneously through the material. This simplifies the mathematics of heat conduction and also affords treatment of more complex systems. As a practical measure, a plate is considered thermally thin if the temperature difference across its thickness at a given instant is less than some prescribed value. However, the thin-wall approximation may possibly not be valid for bakelite since its thermal conductivity is much less than that for steel. The model calculates the response of a thin plate exposed to a radiant heat input while reradiating to a constant sink environment. The equation is solved by a commonly used fourth-order Runge-Kutta method.

5.9 Review of Chapter 4

Chapter 4 of the submittal outlines in very general terms the methodology used in the fire hazards analysis of Chapter 5. 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 results in conservative estimates of the heat release rates. Also conservatism is imparted in the analysis as a result of the neglect of attenuation of radiant energy due to smoke. However, nowhere is 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 4.3.2 on 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 4-1 and 4-2 of the submittal. In Table 4-1, 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 4-1 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 4-2. We calculate based upon the correct data the following which should be compared with Table 4-2 on page 4-18 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.

5.10 Review of Chapter 5

The fire hazards analysis of individual fire areas is discussed in Section 5. This section also addresses specific assumptions which are very important to the analysis, such as the cable damage criterion, and the non-ignitability of lubricating oil.

The safety injection, containment spray, and emergency feedwater pumps 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 4-2, (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.

One should consider the potential of the combustibility of the products of pyrolysis of the cables. For instance, the PE/PVC cable has carbon monoxide and gaseous hydrocarbon yields 17% and 4% 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. On the other hand, if the cables are completely enclosed in conduit, these combustion products need not be considered.

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. Also, page 4-3 of the submittal orders the stages of fire damage as offgassing, electrical failure, then ignition. There should be some explanation of this ordering.

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.

We note that Lee[13] tested two types of PE/PVC cables, designated by him as Samples 5 and 6. The electrical failure indices used by WEP are those associated with the latter sample due to the fact that it exhibits a larger slope, which is a measure of the critical energy, than the former sample. However, referring to Fig. 3-15 of Reference 13, it should be noted that for external heat fluxes of 70 kW/m^2 or less, the trend of the data indicates that Sample 5 exhibits earlier electrical failure than that shown for Sample 6 for the same incident heat flux. Accordingly, the use of Sample 6 as the referenced cable would yield non-conservative estimates within the aforenoted heat flux range.

The point we are making here is that one should be careful in the choice of referenced cable utilized in the analyses due to the fact that the data can exhibit crossover for the same insulation/jacket material.

However, it appears likely that WEP is making an unstated assumption, which would result in the cable with the largest slope in Figure 3-15 of Reference 13 being the most easily damaged. This assumption is that cables are damaged at all heat fluxes, not just at heat fluxes above the critical heat flux as indicated in Reference 13. This would result in all curves of Figure 3-15 of Reference 13 being shifted so as to pass through the origin. The cable with the largest slope would then be damaged at an earlier time for the same incident flux. This neglect of the critical flux is conservative, but it is inconsistent with the data obtained in Reference 13.

Another factor in applying the methodology is the assumption of instantly achieving a steady-state, over-ventilated combustion condition. Assuming steady-state conditions are reached immediately conservatively maximizes the heat release from the exposure fire.

We now discuss the application of the unit models given in the Appendices to the specific fire areas. The submittal states that a "back calculation" approach is used which calculates the smallest quantity of fuel to cause both redundant divisions to just exceed the damage criteria. It is stated that "classical optimization techniques for non-linear 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 should at least state the heat flux that each mechanism (plume impingement, stratification, radiation) delivers to the cable. Suffice it to say that for Fire Zones wherein cables of concern are routed in conduit, the electrical failure criteria may be appropriate if indeed there are no other intervening combustibles within the area in question.

The stratified ceiling layer heat flux model has been discussed in Section 5.2, which reviews Appendix A.2. It appears that the submittal uses a method which considers the transient heat flux model and ignores the critical heat flux aspect of the damage criterion. This conclusion is based purely on the results of various calculations since no description of the details or method are given in the submittal. The assumption of cable damage occuring below the critical heat flux is extremely conservative when the critical heat flux is a substantial percentage of the maximum, steady-state heat flux.

The stagnation plume impingement model on page A.3-8 is discussed next. Calculations for configurations representative of those in the submittal yield rather low values of heat flux. The reasons for these low values are now given.

The Rayleigh number for the plume impingement model is about 10^{17}, which is far beyond the range of correlation ($10^9 < R_a < 10^{14}$) given in Appendix A.3. The question remains as to why the plume impingement model yields such a low value for stagnation point heat flux. Responding to this query required an in-depth examination of the relevant reference, viz., Reference 4. We have already alluded to some concerns regarding the use of the correlations presented in this reference in our critique of Appendix A.3. To re-emphasize, we feel that the heat flux parameter behaves like $(r/H)^{-1.25}$ rather than like $(r/H)^{-1/3}$. What concerns us here is that the experimental data used to obtain the correlations needed in the plume-impingement model are based upon tests performed with a sub-scaled apparatus. One is therefore resorting to correlations based upon experiments performed at a maximum height on the order of 1 meter and applying these laws in areas where the ceiling heights could be an order of magnitude larger. Also, the experiments considered flame heat release rates up to 3500 W, while the present fires have heat release rates of about a factor of 10^3 larger. Under these circumstances, the similitude in the turbulent length scales, which phenomonologically describe the diffusion processes of mass momentum, and energy, are markedly different. This precludes the "universiality" of the correlations employed.

Because of this factor, we suggest the use of the correlation presented by Alpert and Ward[5]. Basically their correlation, for stagnation point heat flux agrees with that of Reference 4 once the Rayleigh number dependency is removed, and also agrees with the heat-flux parameter given by Newman and Hill[1] in the limit of zero ventilation rate.

It is not clear what radiation model is being used in the exposure fire effects calculation. Is it the classical model with a total emissivity of 0.3 as mentioned on page 5.8, or is it the model on page A.4-7 in which the gaseous emissivity is represented as a function of fire diameter. Note the comments on the definition of this diameter in Section 5.4. In any case, both models require an expression for the configuration factor which is not discussed in the submittal. We suggest a configuration factor such as that given in Reference 16 for a cylinder radiating to a plane surface with a normal perpendicular to the axis of the cylinder.

Another comment relates to larger size radiation fires. For large fires in an enclosure, consideration must be given to the radiant heat flux from the stratified smoke layer to the target below. Such a model is discussed in Reference 17.

Summarizing this aspect of our review, we are still unsure as to the analytical procedures used by the utility in the back-calculation approach.

Much credit is taken for thermal shields located beneath cable trays. However, no analysis is described for determining the heat flux to the cables. The analysis in Appendix A.5 for determining shield width is a phenomenological model based on analysis including small scale turbulence. However, fires differentiate themselves by large scale turbulence, resulting in convoluted flows not accounted for in this analysis.

Also, fire position is an important consideration. If a fire is not located directly beneath a tray or there are adjacent banks of trays, the fire plume may cause damage by radiation to the top or sides of the tray or by convective heat transfer as the shield-disturbed plume courses its way through the banks of trays.

In Fire Zone 8, a calculation is mentioned which results in a tray surface temperature of 188°F, which is below ignition temperature. The compatability of using ignition temperature in lieu of the damage criteria, previously defined, has not been substantiated in the submittal.

Therefore, since little detail of the shield analysis is given, and due to errors pointed out in Section 5.5 and considerations mentioned here, the credit taken for the fire protection of thermal shields should be further scrutinized by WEP and elaborated upon by analysis.

Also, in Fire Zone 8, where 4.4 gallons of acetone was found to damage a single cable, credit is taken for the mitigating effects of closed-box cable trays and Kaowool blankets in contradiction to the analysis basic assumptions. This would require a heat conduction analysis through the box using a convective heat flux coefficient for the outer boundary condition. This analysis could, in principle, be done if detailed information regarding box geometry and thermal properties were given. Neither was this information detailed in the submittal, nor was there any discussion pertaining to a heat-conduction analysis.

For Fire Areas 6 and 8, WEP attempts to show that the electrical panels and cabinets used house relays and other electromechanical equipment also provide some level of fire propagation retardancy. They also take credit for rapid fire detection and response, which is in contradiction to the premise of Chapter 4 that no credit will be given to fire protection mitigating systems. Nevertheless, WEP considers a 30-second exposure fire (cabinet panel is immersed in flames) using the "Hotbox" model of Appendix A.7, and a 30 second exposure fire using the heat conduction model of Appendix A.6. We question the application of these models in relation to Appendix R exemptions since they give only a general understanding of thermal lag and panel fire resistance, and there is no clear discussion of boundary conditions. Also, there could be a loss of functionability due to thermal stresses induced by the highly transient thermal environment, (the table on page 5-96 shows large temperature gradients) and additional heating through ventilation ducts.

6. CONCLUSIONS

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, WEP? as such, cannot be completely judged. We, however, do give credit to CPL 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 WEP, 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.

7. ACKNOWLEDGEMENT

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[illegible] in [illegible]

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)

. Fire Dynamics [illegible] 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

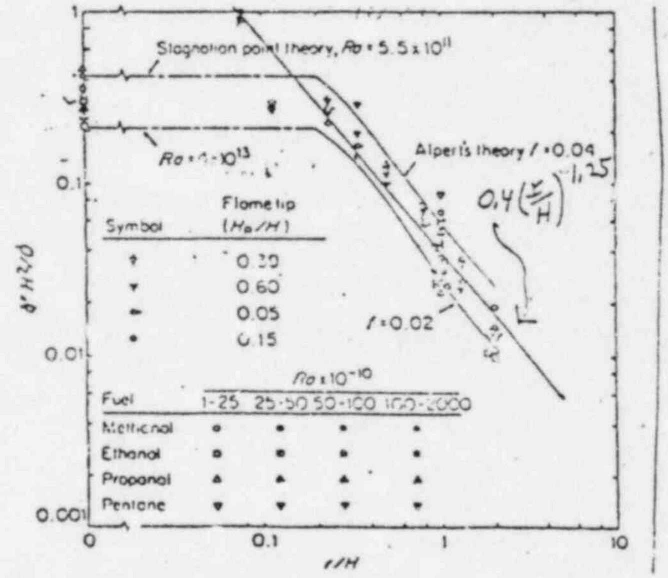

Figure 1. Heat flux as a function of position for plume impingement on an unconfined ceiling. (From Figure 7 of Reference 4)

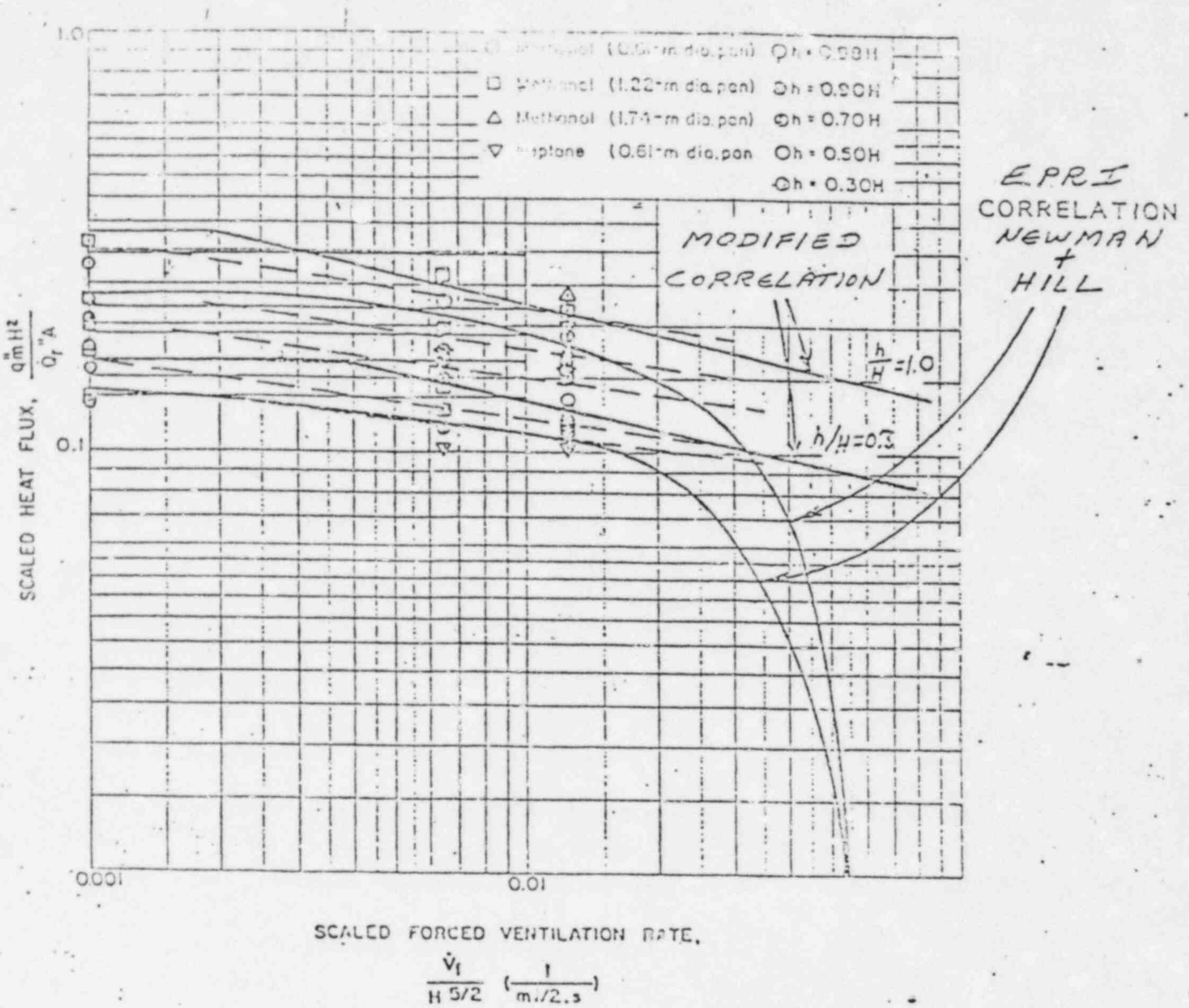

Figure 2. Scaled heat flux versus scaled forced ventilation rate. (From Figure 1 of Reference 1)