Journal of the Korean Nuclear Society
Volume 34, Number 3, pp.259~267, June, 2002

Review on the New Fire Protection Standard for Nuclear Power Plants and Investigation for the Applicability of the Performance-Based Fire Modeling

Moon-Hak Jee, Sung-Yull Hong, Chang-Kyung Sung, and In-Hwan Kim
Korea Electric Power Research Institute
103-16 Munji-dong, Yuseung-gu, Daejeon, 305-380, Korea
jmhak@kepri.re.kr

(Received October 24, 2001)

Abstract

NFPA-803 has been referred as the Fire Protection Standard at the Nuclear Power Plants of Pressurized Water Reactor. This Standard has been used as the fire protection regulation, containing prescriptive requirements with deterministic methodology. Recently, with cumulative efforts by the U.S. Nuclear Regulatory Commission and Utilities in America to establish a new Standard, including a quantitative evaluation methodology, NFPA-805, the Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants was issued and approved by the American National Standards Institute as an American National Standard with an effective date of February 9, 2001.

This paper presents an analysis result from the computer modeling for the fire simulation. In addition, it proposes the idea that this kind of analytic method can be available for the facilities design of fire prevention and protection fields, as well as an evaluation for the fire suppression system with a quantitative analysis for the thermal phenomena in fire compartments in Nuclear Power Plants.

Key Words : fire protection standard, NFPA-805, FAST[1], CFAST[2], FPEtool[3]

1. Introduction

The governing regulatory Guidance until 1975 for the fire protection in Nuclear Power Plants, has been the General Design Criteria 3 (GDC-3) to 10CFR50 Appendix A. This regulatory requirement has been applied to the design of structures, systems and components important for safety in accordance with NRC guidelines. In January 1975, the Nuclear Regulatory Commission inherited its regulatory roles from the Atomic Energy Commission. In March, NRC experienced the fire at Browns Ferry Nuclear Station, which caused damage to the electrical circuits including safety related cables. As a result, it threatened the safety capability for a significant period of time for the cold shutdown at the plant. On reflection of this accident, NRC asked all the new nuclear power plants as well as operating plants to investigate their fire protection program and protective facilities. Since 1976, NRC has led reinforced regulatory positions for the vulnerable parts in safety disciplines at Nuclear Power Plants.

Referring to the aspects of major regulatory documents and positions by NRC, Branch Technical Position (BTP) 9.5.1 was published in May 1976, and Appendix A to the BTP 9.5.1 was issued in August 1976. Appendix R to 10CFR50 addressing fire protection and 10CFR50.48 containing a fire protection plan and program were published with effectiveness in 1979. Continually, 10CFR50.12, 10CFR50.59, and a large number of Generic Letters[4] were issued with the purpose of prescriptive regulation on the deterministic concepts of engineering judgment and implementation of fire protection requirements.

Contrary to the passive accommodation of the rigorous requirements, a movement in Nuclear Utilities was started in the middle of the 1970s to forward an approach to fulfil compliances to licensing requirements, the achievement of a nuclear safety goal, and performance objectives. This approach was cooperatively processed with the same recognition and needs in Regulation and Utilities. In July 1992, the NRC opened its position at SECY 92-263[5]. Soon after in 1993, Regulatory Review Group (RRG) was formed to achieve a continuing regulatory improvement including a performance-based regulation. Later on, both SECY 94-090[6] and SECY 96-134[7] were published. In October 1996, the Commission recognized modifications and amendments in some parts of Appendix R for the regulatory improvement, and revision of 10CFR50.48 to accomodate the performance-based and risk-informed approach. SECY 97-127[8] issued in June 1997 accelerated its direction toward a new rulemaking plan.

With a multiple effort by NRC and Nuclear Utilities, in 1997, Task Force Team with the host role of Nuclear Energy Institute (NEI) was formulated to investigate and analyze the at-present situation of the fire protection plan and program in Nuclear Power Sites. It endeavored to develop guidelines and applicable methodologies with EPRI, and supported Nuclear Power Sites to introduce developed techniques and methodologies.

During the regulatory improvement activities, a number of fire tests, systematic analysis for the operating experience, pilot experiments and overall analysis for the IPEEE[9] result executed by individual Plant were implemented with the same intents and insights by Regulation, Utilities and Research Institutes.

In this sequence, the performance-based fire protection Standard for the Light Water Reactor came to be published and promulgated as an American National Standard on February 9, 2001. While US NRC did not disclose its official position to endorse NFPA-805 up to the present, the Standard as an output of improved regulation for performance-based approach describes the methodology for applying performance-based requirements, fundamental fire protection program design, determination of fire protection systems and features, and fire protection during decommissioning and permanent shutdown. It is surely expected that in a very near future, NRC will adopt NFPA-805 and will provide an implementation guide for its application at the Nuclear Power Sites.

2. Investigation for Fire Modeling Applicability at Nuclear Power Plants

2.1. the Number of the Exemptions for the Fire Protection Requirements

Since the comprehensive regulatory document

Table 1. The Number of the Exemptions Approved for Appendix R

Section	Technical Area	Number of Approved Exemptions
Ⅲ.	Specific Requirements	-
Ⅲ. A	Water Supplies	1
Ⅲ. E	Hose Testing	1
Ⅲ. F	Automatic Fire Detection	14
Ⅲ. G	Safe - Shutdown Capability	780
Ⅲ. H	Fire Brigade	1
Ⅲ. J	Emergency Lighting	39
Ⅲ. L	Alternative and Dedicated Shutdown Capability	36
Ⅲ. M	Penetration Seals	4
Ⅲ. O	Reactor Coolant Pump Oil Collection	24
	Total Number	900

Appendix R to 10CFR50 has been applied from 1980, Nuclear Utilities requested a number of exemptions for the safety requirements in fire protection fields. NRC granted their request as an exemption if they could provide alternatives or an equivalency to the prescriptive requirements of Appendix R. During this process of exemption, the justification and technical background presented by the licensees were submitted primarily with the qualitative analysis based on the engineering judgment, whereas there were only a few items that were approached with the quantitative analysis, such a way using a fire modeling.

According to the NUREG report published in 1998, the number of exemptions and deviations approved by NRC reached 1,351 items. Most of the approved request as the exemption for Appendix R requirements attributes to Section Ⅲ.G, designated as Safe Shutdown Capability, and the classification for the exemption is shown on the table 1 above.

2.2. The Approach to the Computer Simulated Fire Modeling

The data at table 1 explains a meaningful transition that the exemption items were requested merely with the qualitative analysis and engineering judgment by licensees, while NRC approved the request after the detail review and conservative evaluation. Most of the exemptions approved by NRC were related to the highly important areas such as safety shutdown capability. In this sense, it is assumed that if a quantitative approach or a performance-base analysis had been used, the justification could be presented more extensively and distinctively. Now, the performance-based approach can be applied to the design process of the new power plant or the refurbishing stage of the operating power plants. The computer simulated fire modeling can be also available to the analysis and verification of the existing fire protection facilities and their features, and a fire hazard analysis after the facility alteration and improvement. It can be a tool to judge the excessive regulation and intrinsic design defects and the current abilities of fire protection facilities.

In this context, we look over the characteristics of the fire model code for the FPEtool(Version 3.2) and FAST(Version 3.1.6) that were developed with some updates by the National Institute of

Standard and Technology (NIST), and that are being effectively utilized at the Nuclear Power Plants as well as in the fields of industry. In addition, we want to review and confirm the applicability of the performance-based fire modeling by comparing the quantitative fire hazard analysis[10] methodology by EPRI and the fire simulation result from the fire modeling.

2.3. The Synopsis of FPEtool and FAST Program

FPEtool can separate the fire area into two or three zones, simulate the thermal circumstances, and calculate the numerical engineering output for the steady-state fire phenomena. This program disregards the heat loss through the fire compartment barrier and any additional consecutive combustion of other materials. It can not interpret human behavior and residence reliability accrued from a fire, but it can evaluate the smoke layer development with the time elapse and can estimate the human viability resulting from the smoke toxicity and temperature. It can also predict the thermal response of a detector or sprinkler from fire, the development of smoke height, the variation of gas concentration, heat release rate, mass flow and so forth on a time-dependent basis. FPEtool is composed of five main programs that are Fireform, Makefire, Fire Simulator, Corridor, and Third Room, all of which hold several sub-modules correlatively or independently.

FAST keeps the technical cores of Hazard I for the fire hazard analysis and FASTLite for the analysis of fire phenomenon developed by NIST. This program comprises the integrated fire modeling tools underlying the latest version of fire model CFAST in GUI and the routines of FIREFORM. It also provides an engineering analysis and results of fire behavior in fire compartments. The main characteristics of CFAST predict the change of enthalpy and mass flowrate for each finite time interval after a fire, calculate the diffusion and development of the smoke layer, show the concentration of smoke gas with time and estimate the temperature, pressure and other variables in fire compartment and zones. Particularly, the program can evaluate the output resulted from the intentional variable input by user such as heat release rate, mass flowrate, toxicity, and so on. The sub-modules of FAST are identical with the Fireform of FPEtool in respect to the engineering concept and algorithm. As a consequence, the output is same with that in the Fireform.

2.4. The Comparison Between the Fire Scenario Output and Experimental Data

1) Case 1 : Fire Analysis in Closed Compartment with Mechanical Ventilation

Thermal and Environmental Condition for this case is as follows:

- Room Size : $18.3^L * 12.2^W * 6.1^H$ [m]
- Fire Location : Center on Floor (Correction Factor = 1.0)
- Ventilation type : mechanical ventilation with a draw-through type
- Number of Ventilation : 10 times/hour
- Nominal Fire Heat Release Rate : 2,000kW
- Combustion Condition : Steady-state Combustion for 10 minutes
- Atmospheric Condition : 20℃ and 101.3 KPa
- Experimental Data : FM/SNL Test Series (referred to NUREG/CR-4681, CR-5384)
- Comparison between analysis result from EPRI FHA and experimental data is performed:
- Determination for the Confined / Unconfined condition

-L/W = 18.3/12.2 = 1.5 > 1/2, H/W =

Table 2. Result for Mechanical Ventilation with HRR of 2,000kW

r/H	ΔT_{avg}(K)	$\Delta T_{ceiling\ jet}$(K)	T(K)	FM/SNL Test (#3)
0	132	195	620	Peak Value
0.5	132	93	518	: 641 K
1.0	132	59	484	- Temperature Difference : 21K
1.5	132	45	470	- Ambient(initial)
2.0	132	37	462	Temperature : 293K

Table 3. Comparison for Mechanical Ventilation with HRR of 2,000kW

r/H	$T_{ceiling\ jet}$(K):FPEtool	$T_{ceiling\ jet}$(K) : EPRI	Reference
0	598	620	Peak Value at
0.5	509	518	FM/SNL Test
1.0	478	484	(Serial #3)
1.5	466	470	: 641K
2.0	458	462	

6.1/12.2 = 0.5 < 2.5

- as a result, it is confirmed as an Unconfined condition

• Ventilation Rate : 3.8m³/sec

• Ventilation incurred from Gas Expansion

- $V')\text{expansion} = \dfrac{Q'_{net}}{\dfrac{Q_0}{V}} = \dfrac{(1 - 0.7) * 2000}{353} = 1.7\text{m}^3/\text{sec}$

(here, $Q'_{net} = (1\text{-}x_l)Q'$ and xl is heat loss factor of 0.7 with nominal HRR, $Q' = 2000$. Q_o/V represents the ambient HRR at unit volume, that is, $\rho_o C_p T_o$ with 353Kj/m³)

- Mechanical ventilation exceeds the incurred ventilation from gas expansion
- as a result, it is justified for the closed compartment referring to the EPRI TR-100443

• $\Delta T_{avg} = Q'_{net}/(\rho V'\ C_p) = 132$ K

• $\Delta T_{plume} = 25(Q'^{2/3}/ Z^{5/3}) = 195$ K

• $\Delta T_{ceiling\ jet} = \Delta T_{plume} \dfrac{0.3}{(\frac{r}{H})^{2/3}} = \dfrac{58.5}{(\frac{r}{H})^{2/3}}$

(here, V' : ventilation rate(3.8m³/sec), Q' : nominal HRR, Z or H : height of purpose)

• Result based on EPRI FHA Method (reference : FM/SNL test) is presented at Table 2.

While there are minor differences in the program characteristics of FPEtool and FAST, equations for the engineering calculation are the same in view of the conservation principles of energy, mass, and momentum. The equation for the plume temperature and the ceiling jet temperature has identical variables, and as such the constant values become equal.

• Result of FPEtool and Estimation from EPRI FHA (reference : FM/SNL test) is shown on Table 3 above:

2) Case 2 : Fire Analysis in Closed Compartment with Natural Ventilation

Thermal and Environmental Conditions are identical with case 1 except the following:

• Ventilation Type : Mechanical ventilation with a draw-through configuration

• Number of Ventilation : 1 time/hour

• Nominal Fire Heat Release Rate : 1,000kW

Comparison between analysis result from EPRI

Table 4. Result for Natural Ventilation with HRR of 1,000kW

r/H	ΔT_{avg}(K)	$\Delta T_{ceiling\ jet}$(K)	T(K)	FM/SNL Test (#8)
0	97	123	513	Peak Temperature: 566 K - Differential Temperature : 53K - Ambient(initial) Temperature : 293K
0.5	97	58	448	
1.0	97	37	427	
1.5	97	28	418	
2.0	97	23	413	

Table 5. Comparison for Natural Ventilation with HRR of 1,000kW

r/H	$T_{ceilingjet}$(K) : FPEtool	$T_{ceilingjet}$(K) : EPRI	Reference
0	500	513	Peak Value of FM/SNL Test (Serial #8) : 566K
0.5	444	448	
1.0	424	427	
1.5	417	418	
2.0	412	413	

FHA and experimental data is evaluated:

- Unconfined condition
- Mechanical Ventilation : $0.38m^3/sec$
- Ventilation incurred from Gas Expansion : $0.85m^3/sec$
  - as a result, it is reasonable to analyze as an unventilated space
- $\Delta T_{avg} = 293[\exp(\frac{Q_{net}}{Q_o}) - 1] = 98K$
  - Qnet : 138.3MJ (Heat loss factor 0.7, combustion efficiency 0.77 were applied)
  - $Qo = 353KJ/m^3 \times 1{,}362m^3 = 480.7MJ$
- $\Delta T_{plume} = 25(Q'^{2/3}/Z^{5/3}) = 123\ K$
- $\Delta T_{ceiling\ jet} = \Delta T_{plume} \dfrac{0.3}{(\frac{r}{H})^{2/3}} = \dfrac{36.9}{(\frac{r}{H})^{2/3}}$
- Result by EPRI FHA (reference : FM/SNL test) is shown on Table 4

Result of FPEtool and Estimation from EPRI FHA(reference : FM/SNL test) is given on the Table 5, Comparison for Natural Ventilation with 1,000 kW HRR.

2.5. Analysis for the Result

The equation for the calculation of the plume and ceiling jet temperature is confined at Table 6 for each program, EPRI and FPEtool or FAST.

Here, the temperature profile for the plume and ceiling jet temperature is illustrated for the convenience of understanding.

Referring to the results from the comparison speculated above and the temperature profile at Figure 1, we can arrive at somewhat meaningful insights based on the following reviews.

The first insight is the justification for the setting of the room temperature, which is not the value at an initial condition but the one at the condition of the thermal steady state of the fire compartment. The temperature of the ceiling jet at the region of r/H=0.2 should be regarded on the following engineering judgment:

As this interfacing boundary of r/H=0.2 corresponds to the plume region as well as the ceiling jet region, the value of $T_{ceiling\ jet}$ and T_{plume} must

Table 6. Applied Equation for Each Program

	EPRI	FPEtool/FAST	Reference
Plume Temperature	$\Delta T_{plume} = 25\frac{(Q')^{2/3}}{H^{5/3}}$	$T_{plume} = T_{\infty} + 22.2\frac{(Q')^{2/3}}{H^{5/3}}$	r/H ≤ 0.2
Ceiling Temperature	$\Delta T_{ceiling} = \Delta T_{plume}\frac{0.3}{(r/H)^{2/3}} = 7.5\frac{(Q'/r)^{2/3}}{H}$	$T_{ceiling} = T_{\infty} + 6.81\frac{(Q'/r)^{2/3}}{H}$	r/H ⟩ 0.2

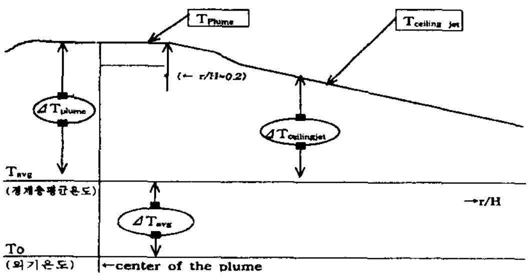

Fig.1. Temperature Profile and Interface Layer from the Flame Center Line

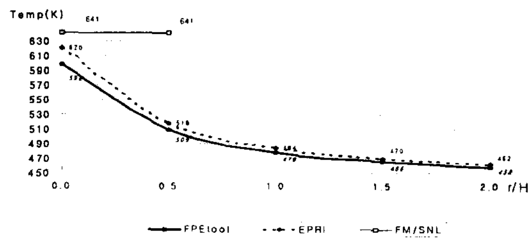

Fig. 2. Temperature Distribution at the HRR of 2,000kW and Forced Ventilation

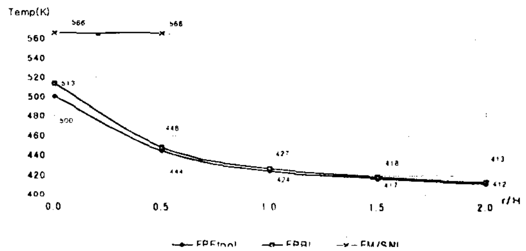

Fig. 3. Temperature Distribution at the HRR of 1,000kW and Natural Ventilation

be equal. However, if T_{∞} is set to 293°K(20℃) when referred to the Technical Reference Guide 3.5 of FPEtool or as a room (ambient) temperature requested at the computer program, the plume temperature shall be 466°K(193℃) and the ceiling jet temperature is calculated as a different value of 448°K(175℃) at the heat release rate of 2,000kW. In addition, if we review the applied equation at table 6, both formulas of EPRI and FPEtool/FAST are analogous except the constant variable of the equation. It means that at the steady-state of the fire compartment T_{∞} should not be the initial room temperature or the ambient temperature, whereas it should be the mean temperature of interface layer as shown on the Figure 1 when referring to the equation of EPRI FHA, $\Delta T_{plume} = 25\frac{(Q')^{2/3}}{H^{5/3}}$ and considering the continuity of the temperature curve of the plume and ceiling jet region. In this rationale, the room temperature after a certain elapse of time after a fire should be expressed as T_{∞} = To + ΔTavg. Consequently, in Case 1 of HRR, 2,000kW, we obtain T_{∞} = To + ΔTavg = 293 + 132 = 425°K. In Case 2 of HRR, 1,000kW, T_{∞} = To + ΔTavg = 293 + 98 = 391°K. In the region of

$r/H \leq 0.2$, temperature is calculated to be 598°K and 500°K respectively at each HRR.

The second meaning of this study can be derived from the temperature values at each fire region and their distribution, shown on Figures 2 and 3, at the different HRR and Ventilation conditions by use of FPEtool, EPRI FHA and FM/SNL experiment data:

In the tendency of plume temperature, the experimental data of FM/SNL is relatively high. That is, about 6.3% more than the value achieved from EPRI FHA and almost 9.2% more than that of FPEtool estimation. It can be concluded however, that the FM/SNL data is too much conservative and also overestimated. The basic screening procedure that was used in FM/SNL test series can yield either overly conservative predictions or nonphysical predictions if extended significantly beyond the actual conditions. The overestimation of the FM/SNL data was confirmed by the computation of the ASHTBX module in FPEtool. That is to say, when using the ASHTBX simulation to reach at 598°K of the plume temperature, heat release rate should be reached at 7,463kW with the heat loss factor of 0.7. When the heat loss factor was assumed to be 0.8, heat should be provided up to 9,942kW. This simulation explicitly proves that the plume temperature of 598°K is much exaggerated under the condition of 2,000kW HRR.

On the other aspect, when the results of FPEtool and EPRI FHA are compared, which represents a slight difference less than 1.3%, the applicability of the computer simulated fire modeling such as FPEtool or FAST is recognized as a significant tool to fulfill its objectives. On the graph above, the temperature change in each region can be seen. It should be noted that the value of the FM/SNL data should be a dot at the figure representing the center line temperature of the plume, that is 641°K at 2,000kW and 566°K at 1,000kW, but the point was extended to compare with ease to other data.

3. Conclusions

The existing Fire Protection Standard in the PWR, NFPA-803, came to be replaced with NFPA805 which is the Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants. The new Standard was publicized on January 13, 2001 and became valid as an American National Standard with an effective date of February 9, 2001. It is explicitly expected that the performance-based fire protection methodology will be introduced to the design of fire protection facilities and features, the evaluation of effective utilization of fire protection systems, and the analysis of the dynamic and thermal phenomena in fire compartments or fire zones with the quantitative and engineering approach.

With this in mind, we evaluated the computer simulated fire modeling suggested in the Performance-Based Fire Protection Standard by simulation of a fire scenario to estimate the tendency of temperature change in a fire compartment and finally compared and verified with the results of the EPRI FHA methodology and the FM/SNL experimental data.

Finally, we reached the conclusion that the evaluation method by virtue of the fire modeling could be applicable to the design of fire protection equipment. It was verified in their effectiveness for the fire suppression system design, as well as the engineering evaluation and physical phenomena in fire compartments. Also, it was assumed that the evaluation result and the quantitative analysis could be used as technical background to support a new method of design improvement, and be available to the fire hazard analysis related with the defense-in-depth Power Operation in Nuclear Sites.

Whereas, it should be noted that there are some operational routines and engineering disciplines to be modified and reinforced for the near-term application with the verification and validity in fields such as reliability evaluation for the input data and variables, uncertainty analysis, implementation guide or manual for the program, and correlation with the existing analysis methodologies like Probability Risk Assessment.

References

1. NFPA 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants. (2001 Edition)
2. NFPA 803, Standard for Fire Protection for Light Water Nuclear Power Plants. ('93 edition)
3. NISTIR 5486-1, "Technical Reference Guide for FPEtool Version 3.2", U.S. Department of Commerce, Technology Administration, NIST
4. "A User' s Guide for FAST : Engineering Tools for Estimating Fire Growth and Smoke Transport('20 edition)", U.S. Department of Commerce, Technology Administration, NIST
5. NUREG-1521, "Technical Review of Risk-Informed, Performance-Based Methods for Nuclear Power Plant Fire Protection Analysis(Draft for Comment)
6. Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decision on Plant-Specific Changes to the Licensing Basis"
7. Regulatory Guide 1.189, "Fire Protection for Operating Nuclear Power Plants", April, 2001
8. SRP 9.5-1 ; Standard Review Plan(NUREG-0800)
9. Appendix A to BTP 9.5-1 ; Branch Technical Position APCSB 9.5-1 "Guidelines for fire protection for nuclear power plants docketed prior to July 1, (1976).
10. Appendix R to 10 CFR 50 ; Fire Protection Program for Nuclear Power Facilities Operating Prior to Jan. 1, (1979).
11. 10 CFR 50.48 ; Fire Protection
12. EPRI TR-108799, "Planning for Risk-Informed and Performance-Based Fire Protection at Nuclear Power Plant", Final Report, December, (1997).
13. EPRI TR-105928, "Fire PRA Implementation Guide", Final Report, December, (1995).
14. EPRI TR-100443, "Methods of Quantitative Fire Hazard Analysis", Final Report, May, (1992).

Footnotes

1. FAST stands for Fire Growth and Smoke Transport.
2. CFAST means the Consolidated Model of Fire Growth and Smoke Transport.
3. FPEtool is a collection of computer simulated procedures providing numerical engineering calculations of fire phenomena.
4. GL81-12, GL82-21, GL83-33, GL85-01, GL86-10, Supplement 1 of GL86-10, GL88-20, Supplement 1, 2, 3, 4 and 5 of GL86-20, GL89-13 and GL92-08 and so on.
5. Staff Plans for Elimination of Requirements Marginal to Safety.
6. Institutionalization of Continuing Program for Regulatory Improvement.
7. Options for Pursuing Regulatory Improvement in Fire Protection Regulation for Nuclear Power Plants.
8. Development to a Risk-Informed, Performance-Based Regulation for Fire Protection at Nuclear Power Plants.
9. IPEEE : Individual Plant Examination for External Event.
10. Appendix D, "Methods of Quantitative Fire Hazard Analysis" of EPRI.