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Tom Elicson
Jim Bouchard
Heather Lucek
Bentley Harwood

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CALCULATION OF FIRE SEVERITY FACTORS AND FIRE NON-SUPPRESSION PROBABILITIES FOR A DOE FACILITY FIRE PRA

Tom Elicson*
WorleyParsons Polestar, Inc.
103 Chadbourne Dr Hudson, OH 44236
elicson@roadrunner.com

Jim Bouchard and Heather Lucek
WorleyParsons Polestar, Inc.
901 Pier View Drive, Suite 203 Idaho Falls, ID 83402
Jim.Bouchard@WorleyParsons.com; Heather.Lucek@WorleyParsons.com

Bentley Harwood
Idaho National Laboratory, Battelle Energy Alliance, LLC
1955 N. Freemont Ave Idaho Falls, ID 83415
Bentley.Harwood@inl.gov

ABSTRACT

Over a 12 month period, a fire PRA was developed for a DOE facility using the NUREG/CR-6850 EPRI/NRC fire PRA methodology. The fire PRA modeling included calculation of fire severity factors (SFs) and fire non-suppression probabilities (PNS) for each safe shutdown (SSD) component considered in the fire PRA model. The SFs were developed by performing detailed fire modeling through a combination of CFAST fire zone model calculations and Latin Hypercube Sampling (LHS). Component damage times and automatic fire suppression system actuation times calculated in the CFAST LHS analyses were then input to a time-dependent model of fire non-suppression probability. The fire non-suppression probability model is based on the modeling approach outlined in NUREG/CR-6850 and is supplemented with plant specific data.

This paper presents the methodology used in the DOE facility fire PRA for modeling fire-induced SSD component failures and includes discussions of modeling techniques for:

- Development of time-dependent fire heat release rate profiles (required as input to CFAST),
- Calculation of fire severity factors based on CFAST detailed fire modeling, and
- Calculation of fire non-suppression probabilities.

Key Words: Fire PRA, CFAST, Severity Factor, Non-Suppression Probability

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1 INTRODUCTION

The EPRI/NRC fire PRA methodology, presented in NUREG/CR-6850 [1], includes Task 8: Scoping Fire Modeling and Task 11: Detailed Fire Modeling to determine fire severity factors (SFs) and fire-non suppression probabilities (PNS) through the conduct of fire detection and suppression analyses. The fire severity factor is defined in NUREG/CR-6850 as the conditional probability of component failure from a specified fire source while the non-suppression probability is defined as the probability that a fire will not be suppressed prior to target set damage.

For the DOE reactor facility fire PRA, unique PNS and SF values were calculated for each unscreened safe shutdown component (SSD) considered in the PRA model. Determination of the severity factors relied primarily on detailed fire modeling to produce estimates of target set mean time to failure (MTTF) and target set failure probabilities. The target set failure probabilities were then used as the component SFs and the MTTF was input into a time-dependent model for fire detection and suppression to determine the component PNS.

This approach relies on the CFAST computer program [2,3] to perform detailed calculations of fire area response to fires and accounts for uncertainty through use of Latin Hypercube Sampling (LHS) as described in Elicson (2008) [4].

A key component of the CFAST analysis is the fire heat release rate (HRR) profile for various ignition sources. Thus, significant effort as part of Task 11 was devoted to developing realistic HRR profiles.

The reminder of this paper discusses the use of CFAST and LHS to calculate the fire severity factors, presents the time dependent model for fire detection and suppression to calculate fire non-suppression probabilities, and provides examples of fire growth and propagation modeling to calculate realistic fire HRR profiles. The end result is the development of basic event failure probabilities used in the fire risk model.

These methods were successfully applied over the past 12 months during development of the DOER facility fire PRA and are an alternate to the severity factor determination method relying on predetermined heat release rate bins outlined in Appendix E of NUREG/CR-6850.

2 CALCULATION OF SEVERITY FACTORS THROUGH DETAILED FIRE MODELING

2.1 Overview of Severity Factor Calculation

A severity factor is the probability of a fire from a given ignition source causing damage to other components in the fire compartment and essentially represents the probability associated with a specific fire intensity. However, when considering a fire area with multiple components, or targets, the probability of target damage is also influenced by the location of the target with respect to the ignition source and the target type (qualified cable, unqualified cable, solid state component). For example, if two identical components are located in a fire area – one near the fire source and the other on the opposite side of the room – then a higher fire intensity would be required to fail the far target while a lower fire intensity would be required to fail the near target. Thus, while the EPRI/NRC fire PRA methodology discuses the assignment of a single severity factor to each ignition source, a detailed analysis would produce a separate severity factor for each target affected by a given ignition source.

In the CFAST analysis, all SSDs in a fire area are modeled as thermal targets for which CFAST calculates a time-dependent target temperature. The LHS analysis randomly generates fire heat release rate profiles (i.e., the fire intensities) for the selected ignition source according to the ignition source uncertainty parameters and one CFAST case is run for each HRR (i.e., each LHS trial). Results for all CFAST trials are analyzed to determine which target temperatures exceed their prescribed failure temperatures and the time at which the failure temperature was exceeded. The target failure information is tabulated and the severity factor is then the probability of target failure calculated as the number of trials leading to target failure divided by the total number of trials.

With this approach, one LHS analysis is performed for each ignition source in the fire area and the result is one severity factor for each target for each ignition source. The LHS and CFAST calculations also produce a mean time to failure (MTTF) for each target which is used to evaluate the non-suppression probability. Thus, one non-suppression probability is calculated for each target for each ignition source in a fire area.

2.2 Latin Hypercube Sampling Methodology

The analytical method used for detailed fire modeling relies on Latin Hypercube Sampling (LHS) to drive scenario definitions for use with the CFAST computer program.

An early application of LHS with the CFAST computer program is documented by Notarianni (2000) [5]. Notarianni states that "… only parameters or combinations of parameters with uncertainty great enough to change decisions regarding the final design are treated as uncertain. These are referred to as the crucial variables." Notarianni used 500 CFAST runs in a sample calculation and suggests a confidence metric to determine the relationship between the number of LHS runs and the statistical significance of the results.

More recently, Hostikka and Keski-Rahkonen (2003) [6] used CFAST in a Monte Carlo analysis of a postulated nuclear power plant cable tunnel fire to determine the failure probability of cables located in the same tunnel with the fire. The analysis used classic Monte Carlo sampling with 1000 calculations and demonstrated the ability of Monte Carlo techniques to address fire modeling uncertainty issues.

The basis for LHS is to use a constrained Monte Carlo sampling scheme [7]. Classic Monte Carlo sampling simply selects one value at random from a probability density function for each of the k variables (X1 , X2 , … Xk) considered for each calculation in the analysis. LHS sampling first divides the range of values for each variable into n non-overlapping intervals, or strata, with each stratum having equal probability. Then, for each of the k variables, one value from each stratum is selected at random based on the probability density for that stratum. The n values selected for variable X1 are paired in a random manner with the n values of variable X2 and these pairs are then combined in a random manner with the n values of variable X3, and so on until the n values of variable Xk are randomly combined to form n k-tuplets. These n k-tuplets are the Latin hypercube sample.

The current analysis uses an LHS sample size of n=10 strata with each stratum corresponding to a 10% probability. The use of 10 strata yields meaningful results with as little as 200 – 300 calculations [4].

2.3 Uncertainty Parameters

Parametric uncertainties are accounted for by random sampling of selected variables in the LHS analysis. To perform random sampling, the uncertainty parameters (e.g., mean and standard deviation for a normal distribution or □and □ for a gamma distribution) must first be specified for each uncertainty parameter.

Sampling used in the fire PRA was designed to satisfy the detailed fire modeling requirements contained in NFPA 805 [8]. NFPA-805 lists the following characteristics of a fire scenario that are considered in the analysis:

1. Combustible materials: type, quantity, location
2. Combustion characteristics: fire growth rate, heat release rate, radiant heat flux
3. Ignition sources: transient or in situ
4. Ventilation effects: natural and forced ventilation effects
5. Personnel actions
6. Fire protection systems
7. Plant area configuration

To establish baseline failure times, personnel actions and fire protection systems used to mitigate fire damage (items 5 and 6) are not considered in the CFAST analysis. Rather, these uncertainties are addressed in the fire detection and suppression model discussed below. The plant area configuration is well known, is subject to very little uncertainty, and is modeled based on the current plant conditions. Uncertainty in combustible material properties is addressed by selecting the most limiting material type for electrical components (i.e., PVC rather than XLPE cable types) and selecting a bounding failure temperature. Ventilation is modeled using the expected plant configuration for fires (i.e., normal ventilation is adjusted based on fire damper actuation). Characteristics for items 2 and 3 contain inherent uncertainty and these are the focus of the uncertainty modeling.

Failure and ignition temperatures are taken from NUREG/CR-6850 and represent the lower end of the experimentally observed failure/ignition spectrum. These thresholds are considered "sufficiently bounding" as defined in the CFAST Code Application Guidance [9, Section 4.4]:

> "The SFPE Engineering Guide to Performance-Based Fire Protection (SFPE, 2000) recommends that the term sufficiently bounding may be used 'when all but one parameter used for an analysis are set to best-estimate values, and the one extreme parameter is set as follows:
>
> Scientific input values (e.g., [failure thresholds] and flashover temperature) should be taken at 95 percent coverage.'"

Since the failure/ignition criteria in the current analysis are already "sufficiently bounding" no further parametric variation of the failure thresholds are considered in the LHS analysis.

The NUREG/CR-6850 target damage and ignition criteria are based on either surface heat flux or temperature. However, the CFAST Code Guidance notes that "Unless specific test data is available that is consistent with the modeled problem, the heat flux criterion for ignition should not be used." This is because while most heat flux tests measure the incident heat flux, the tests have little or no convective heat transfer. In addition, the test data ignore reflected radiation. In contrast, the target heat flux calculated by CFAST is a net value which includes incident heat flux due to convection and radiation less any reflected radiation flux. Thus comparing CFAST heat flux calculations to failure criteria based on heat flux tests is "…usually not appropriate." So, for the CFAST LHS analysis, all target failures and secondary ignitions rely on temperature criteria. Table I summarizes the failure and ignition criteria used for various target types

Table I. Component Failure Criteria from NUREG/CR-6850 [1, p. 8-10]

Component Type	Failure Temperature, °C	Failure Heat Flux, kW/m2	Ignition Temperature, °C
Thermoplastic (unqualified cable)	205	6	205
Thermoset (qualified cable)	330	11	330
Solid State Components	65	3	205

The remaining crucial variables are all represented by parameters found in the CFAST fire object files. In CFAST, a separate fire object file is used for each ignition source and one unique fire object file is generated for each LHS trial. Thus, if the LHS analysis consists of 300 trials, then 300 fire object files would be generated with random variations in the crucial variables based on the fire object uncertainty distributions. Table II summarizes the fire object crucial variables and their associated uncertainty parameters used to define the CFAST fire scenarios for a subset of the ignition sources. Overall, the analysis considered 66 different fire objects, although many objects, such as those for electrical cabinets, were used for multiple ignition sources.

As shown in Table II, ignition sources that are characterized by burning cables (e.g., electrical cabinets, pumps, motors, cables in trays) share many of the same combustion properties. The only notable difference between the different cabling sources is the HRR profile which is characterized by fire growth, steady burning, and decay times, and a peak HRR value. Other ignition sources, such as the cotton clothing storage rack shown in Table II or hydrocarbon fuels, plastic storage containers, wood scaffolding, or paper products (not shown) have varied combustion properties. The parameters listed in Table II plus the parameters used to develop the fire heat release rate profiles (discussed below) form the basis of the LHS uncertainty analysis.

2.4 Fire Growth and Propagation

Tests typically show three distinct phases of a fire: fire growth, steady burning, and decay. These three fire phases are evident in Fig. 1 which displays CAROLFIRE cable tray fire test date [10]. For fire modeling purposes, an idealized 4-point curve is used to represent the HRR profile, as demonstrated in (Fig. 2).

Three broad categories of combustibles are considered in the fire PRA: electrical components such as cabinets and motors, cables in trays, and transient combustibles. Fire growth in electrical components used the HRR information from NUREG/CR-6850 Table E-1 with fire growth, steady burning, and decay times based on results of the CAROLFIRE test series [10]. For cable trays, the analysis used the cable tray fire growth model from NUREG/CR-6850, Appendix R and developed a generic methodology to construct HRR profiles for stacks of trays.

Table II. Ignition Source Uncertainty Parameters for Select Sources				
	Ignition Source			
Property	**Vertical cab, unqualified cable, fire in multiple bundles, doors closed**	**Motors**	**Cables in trays (Unqualified)**	**Cotton clothing in a storage rack**
Radiative Fraction				
Distribution Type	Gamma	Gamma	Gamma	Gamma
Alpha, min, mean	25.46	25.46	25.46	11.2
Beta, max, std dev	0.0197	0.0197	0.0197	0.0242
Default value (75th or mean)	0.5	0.5	0.5	0.27
Peak Heat Release Rate, W				
Distribution Type	Gamma	Gamma	Gamma	Gamma
Alpha, min, mean	3.6	2	Scenario specific	Scenario specific
Beta, max, std dev	67800	11700		
Default value (75th or mean)	232000	32000		
Fire Growth Time, sec				
Distribution Type	Gamma	Gamma	Normal	Normal
Alpha, min, mean	11.9	11.9	Scenario specific	Scenario specific
Beta, max, std dev	63.6	63.6		
Default value (75th or mean)	754	754		
Fire Steady Burning Time, sec				
Distribution Type	Gamma	Gamma	Normal	Normal
Alpha, min, mean	0.7	0.7	Scenario specific	Scenario specific
Beta, max, std dev	528.6	528.6		
Default value (75th or mean)	368.4	368.4		
Fire Decay Time, sec				
Distribution Type	Gamma	Gamma	Normal	Normal
Alpha, min, mean	10.13	10.13	Scenario specific	Scenario specific
Beta, max, std dev	111	111		
Default value (75th or mean)	2244	2244		
Soot Yield (C/CO2)				
Distribution Type	Gamma	Gamma	Gamma	Gamma
Alpha, min, mean	2.375	2.375	2.375	0.7325
Beta, max, std dev	0.047	0.047	0.047	0.0899
Default value (75th or mean)	0.1116	0.1116	0.1116	0.0659

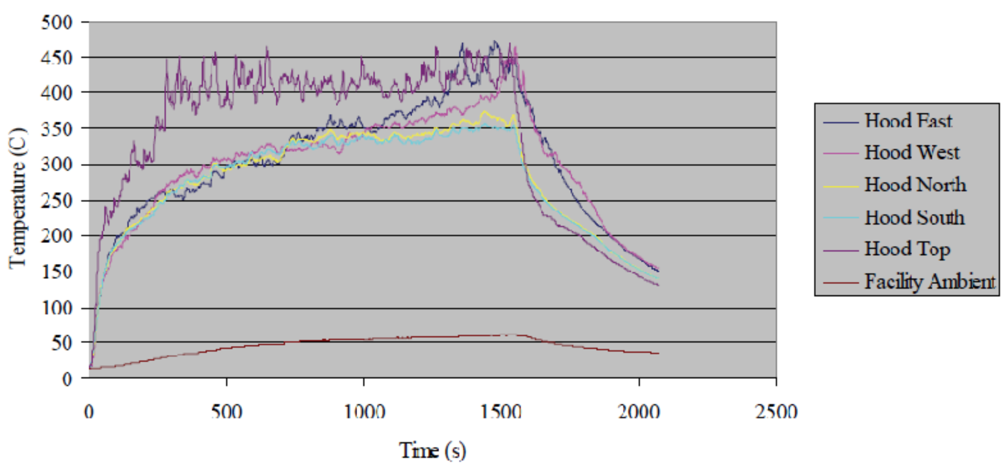


Figure 1. Temperature measurements from CAROLFIRE Test IT-5 [10, Fig. 6.40].

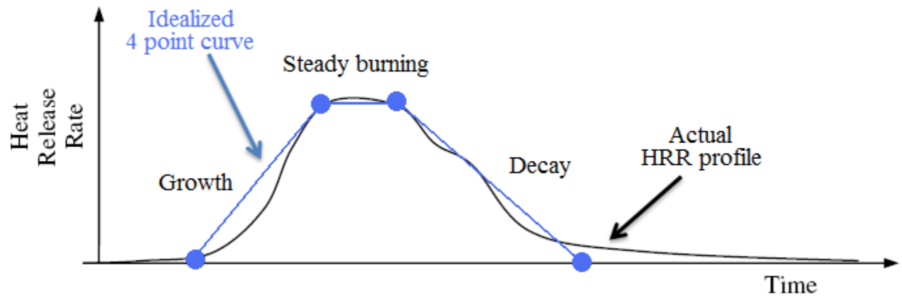
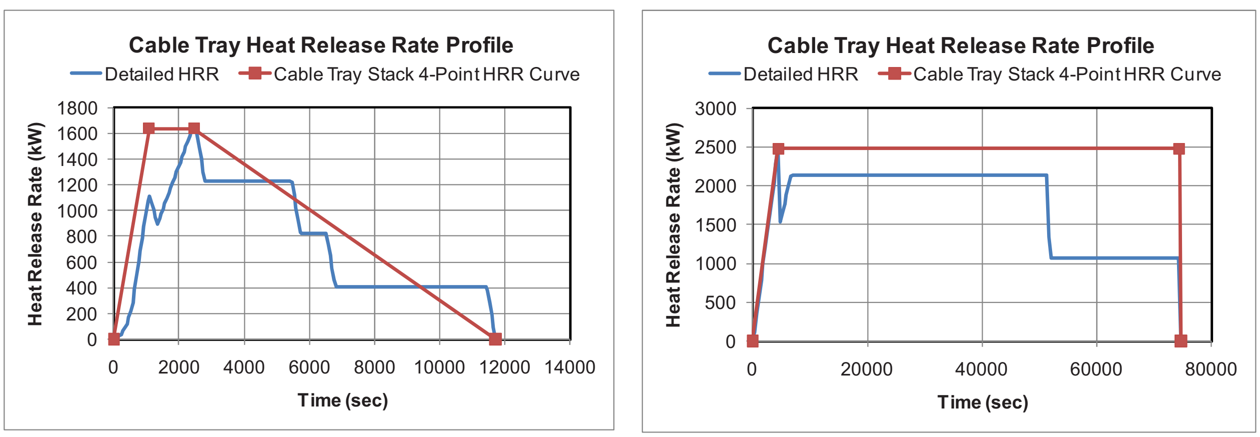


Figure 2. Idealized 4 point curve superimposed on a hypothetical heat release rate profile taken from NUREG/CR-6850 Fig. G-1 [1]

To construct a cable tray HRR profile, the cable tray section and loading are first extracted from the fire PRA database. The total HRR profile is the sum of the HRRs for each tray in the stack and an idealized 4 point HRR curve is then superimposed over the detailed HRR profile. For the fire PRA, the entire process was automated in a macro-enabled spreadsheet. As an example, Fig. 3 presents HRR profiles for two different cable trays. Overall, HRR profiles were developed for 41 separate cable tray sections in the fire PRA.

A somewhat different methodology is necessary fire growth in transient combustibles. Ignition source walkdowns identified a number of transient combustibles including wood and paper products, cotton clothing, trash cans, and maintenance equipment. For these miscellaneous ignition sources, the peak HRR was obtained from Table G-1 of NUREG/CR-6850 or from the open literature while the duration of the fire used a t-squared squared (t2) model for fire growth and then held the HRR at its maximum value until all fuel material was consumed.



a. Typical cable tray HRR profile **b. Cable tray HRR profile for sample fire scenario**

Figure 3. Sample cable tray HRR profiles

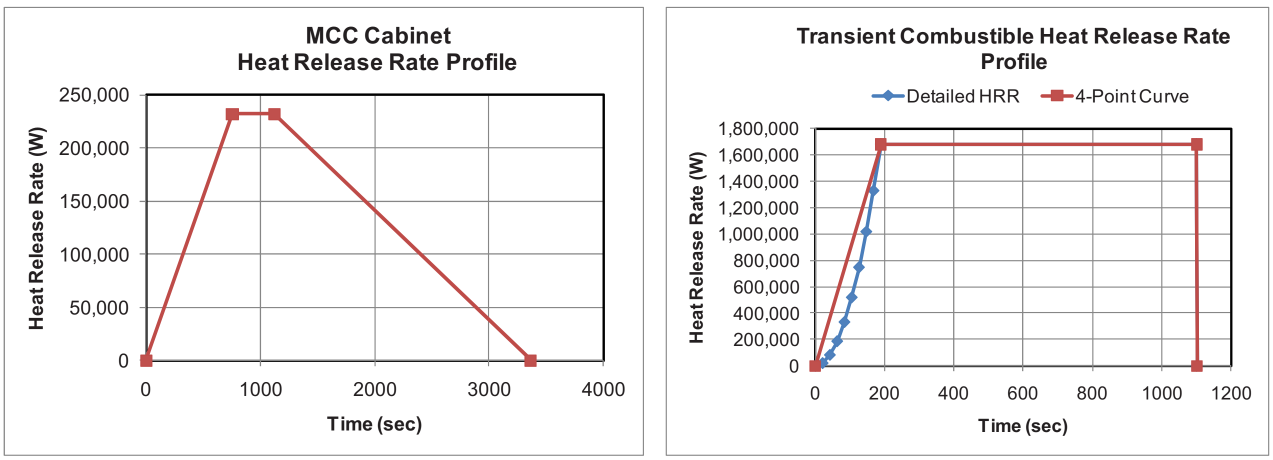
The t-squared model [11, Sect. B.1] can be arranged to yield the time at which steady burning begins (i.e., the time at which the peak HRR is reached):

$$t = (Q / Q_0)^{1/2} * t_0 \quad (1)$$

where,

t_0 = Fire growth time constant, 75 sec for ultra-fast fire growth, 150 sec for fast fire growth, 300 sec for medium fire growth, and 600 sec for slow fire growth.
Q_0 = Normalizing factor, 1.055 MW (1000 Btu/sec)
Q = Ignition source peak HRR

Heat release profiles have been developed for a number of transient combustible configurations using the t^2 model including clothing storage racks in change out areas, cardboard box stacks, scaffolding, wood pallet stacks, hydrocarbon pressurized spray, and wood framed offices space, and semi-trucks. As an example, Fig. 4b shows profile for burning of wooden scaffolding.



a. HRR profile for 480 V MCC **b. HRR profile for scaffolding (12 wood planks)**

Figure 4. Fire PRA HRR profiles

2.5 Severity Factor Sample Calculation

Figure 5 presents the CFAST Monte Carlo Results spreadsheet for a fire scenario. This fire scenario models self ignition of an overhead cable tray with the HRR profile presented in Figure 3b. The results spreadsheet provides failure probabilities and MTTFs for all thermal targets. Sprinkler head actuation times and probabilities are also provided if they are included in the CFAST model. Target failure probabilities as a function of Monte Carlo trial number are automatically plotted to verify that convergence has been achieved. Figure 6 presents a sampling of the convergence plots. In this calculation, failure times vary 2003 to 3060 sec and target failure probabilities range from 0.01 to 0.973. The convergence plots show that meaningful results are obtained within 300 trials.

3 FIRE DETECTION AND SUPPRESSION MODELING

Fire detection and suppression are quantified in terms of a non-suppression probability, PNS. NUREG/CR-6850 provides an event tree to quantify PNS (see NUREG.CR-6850, Vol. 2, Fig. P-2) and considers 3 detection categories:

1. Prompt detection by a posted fire watch or by personnel in a continuously occupied area within 5 minutes of fire inception.

2. Automatic detection by smoke or heat detectors,
3. Manual or delayed detection. This occurs if prompt and automatic detection fail.

In the Fire PRA, the NUREG event tree model is replaced with a time dependent model for the fire non-suppression probability. The time-dependent model continues to consider three time phases: prompt, automatic, and delayed, however a simplified event tree is used to quantify the non-suppression probability for the prompt and automatic detection/suppression phases. Quantification of this event tree is performed once and the prompt and automatic failure probabilities are then combined with a time-dependent model for the delayed response phase. The component MTTF from the LHS analysis are input into the time dependent model to calculate the component PNS for a particular fire scenario.

Path	C:\Test	Target Information			
Case root name	Test	Target #			
Plot File Extension	.w.csv	1	2	3	4
Target Failure Analysis	Data Page Col ID with Target Temperatures	K	Q	W	AC
	Failure Threshold, C	205	205	205	205
Analysis Date:	Failure Probability	0.037	0.02667	0.027	0.01
12/20/2010	MTTF, sec	3060	3037.5	3008	3200
3:06:56 PM	Failure Time Std Dev, sec	390.7	343.833	330.9	499.6

FLASHOVER ANALYSIS	
Plot File Extension	.n.csv
Column ID with Gas Temp	B
Flashover Analysis	
Analysis Date:	Results Sumary
12/20/2010 3:07:35 PM	0

TARGET SUMMARY				RESULTS	
CFAST Target #	Target Description	Fail Temp, C	Include ?	Fail Prob	MTTF
1	Standby battery charger	205	x	0.037	3060
2	250 VDC utility bus	205	x	0.027	3038
3	250 VDC control power bus	205	x	0.027	3008
4	Fuse for breaker control spuriously opens	205	x	0.01	3200

Figure 5. Results for the sample fire scenario taken from the CFAST Monte Carlo Results Template

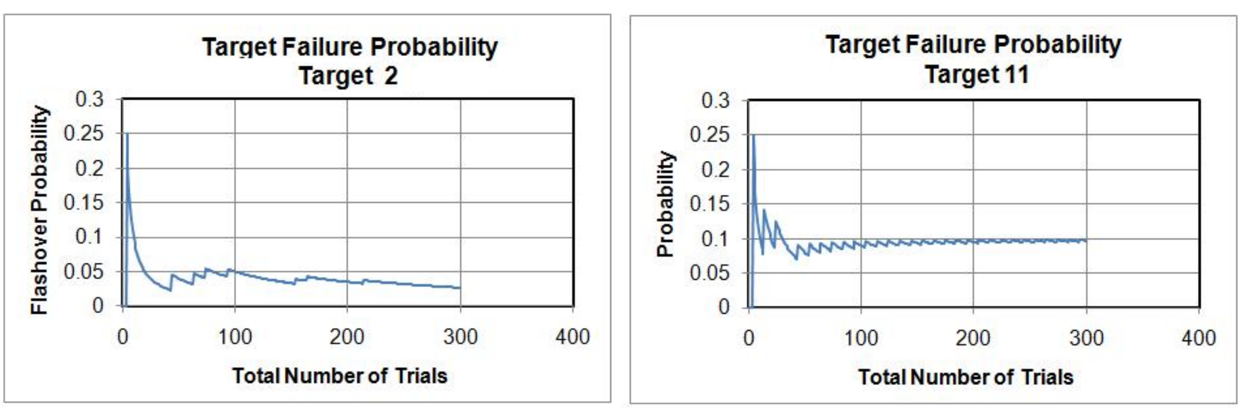


Figure 6. Monte Carlo convergence plots for the sample fire scenario

Figure 7 presents the simplified event tree used to evaluate the prompt and automatic response. Top event split fractions are evaluated for 4 different cases:

- Case 1: Prompt detection/suppression guaranteed to fail for fire areas with low/no occupancy and automatic suppression/detection not available.
- Case 2: Prompt detection/suppression guaranteed to fail for fire areas with low/no occupancy but automatic detection/suppression available. For this case, the event tree quantification is as shown in Fig. 7.
- Case 3: Occupied area, therefore prompt detection/suppression may succeed, but automatic detection/suppression systems are not available.
- Case 4: Occupied area, therefore prompt detection/suppression may succeed and automatic detection/suppression systems are available.

NUREG/CR-6850 states that the failure of automatic detection and suppression systems should be no larger than 0.05. If specific detection/suppression systems are considered, a lower failure probability can be used. For this fire model, a simplified approach is taken in which the failure probability for any automatic detection or suppression system is 0.05.

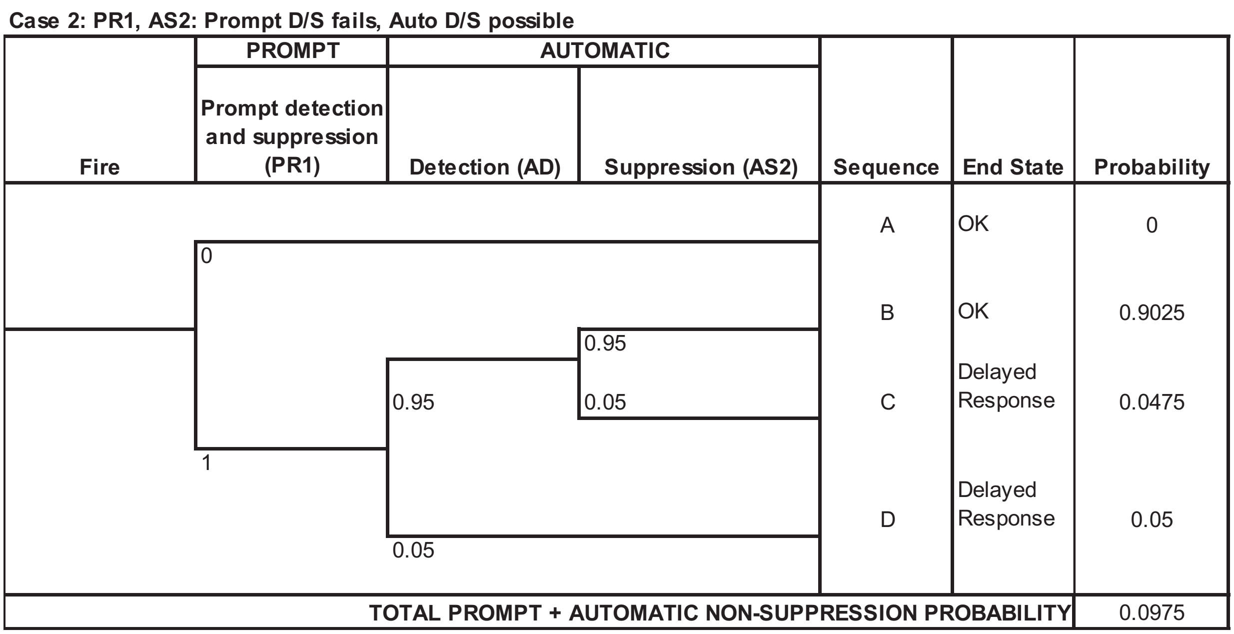


Figure 7. Prompt and automatic detection/suppression event tree quantified for Case 2: An unoccupied area with automatic detection and suppression systems available.

If both the prompt and automatic detection/suppression fail, then delayed fire department suppression is considered. Fire department response follows the model presented in NUREG/CR-6850, Appendix P. Namely, the probability of the fire department failing to suppress the fire is estimated using an exponential distribution of cumulative failure probability for failure within time t:

$$Pr(t) = \exp(-\lambda t) \quad (2)$$

where λ is the fire suppression rate and t is the manual suppression time (t_{ms} in minutes) defined as the component MTTF less the fire detection time (t_{det}) and the fire department response time (16 min based on operator logs). The fire suppression rate is dependent on the fire ignition source and has been evaluated in NUREG/CR-6850 (Vol. 2 Tab P-2) based on a survey of fires in commercial nuclear power plants.

The completed fire detection/suppression model is dependent on the fire area occupancy, the automatic fire detection time, and the fire ignition source, thus several equations are developed. As an example, consider the non-suppression probability model for cable fires in an unoccupied area with automatic detection and suppression available (Case 2). The suppression rate for cable fires taken from NUREG/CR-6850 Vol. 2, Tab P-2, is $\lambda_{cable} = 0.36$, and the probability that a cable fire is not suppressed by the fire department within time t is Pr(t) = exp(-0.36t).

The delayed response curve is combined with the prompt and automatic non-suppression probabilities to yield a complete probability curve. For Case 2 cable fires, this yields,

$$P_{NS} = 0.0975 \qquad t < t_{det} + 16 \text{ min} \tag{3a}$$

$$P_{NS} = 0.0975 * \exp(-0.36 * t_{ms}) \qquad t > t_{det} + 16 \text{ min};\ t_{ms} = MTTF - t_{det} - 16 \text{ min} \tag{3b}$$

For the fire PRA, the complete set of non-suppression probability curves has been included in a spreadsheet to facilitate calculations. As an example, consider results for thr fire scenario provided in Fig. 5 which indicate failure of the standby battery charger at 3060 sec (51 min). Although CFAST indicates a 474 sec detection time, detection is limited to a maximum time of t_{det} = 5 minutes. Since the MTTF is greater than t_{det} + 16 min = 21 min, Eq. 3b is used to evaluate PNS. The available response time is t_{ms} = 51 – 5 – 16 = 30 min, and PNS = 0.0975 * exp(-0.36 * 30) = 1.99E-6. This is the result shown in Fig. 8 for Case 2.

Setup:	
Suppression Curve:	Cable
Suppression Rate:	0.36
Plot Title: ATR Cable Fire Suppression Curves	

Equations:	
Case 1: PR1, AS1: Prompt D/S fails, Auto D/S not available	
P_{NS} = 1	$t < t_{det}$ + 5 minutes
P_{NS} = 1.0000	t_{det} + 5 minutes $\le t < t_{det} + t_{fb}$
P_{NS} = 1.0000* exp(-0.36*tms)	$t > t_{det} + t_{fb}$; $t_{ms} = t - t_{det} - t_{fb}$
Case 2: PR1, AS2: Prompt D/S fails, Auto D/S possible	
P_{NS} = 1	$t < t_{det}$ + 5 minutes
P_{NS} = 0.0975	t_{det} + 5 minutes $\le t < t_{det} + t_{fb}$
P_{NS} = 0.0975* exp(-0.36*tms)	$t > t_{det} + t_{fb}$; $t_{ms} = t - t_{det} - t_{fb}$
Case 3: PR2, AS1: Prompt D/S possible, Auto D/S not available	
P_{NS} = 1	$t < t_{det}$ + 5 minutes
P_{NS} = 0.7390	t_{det} + 5 minutes $\le t < t_{det} + t_{fb}$
P_{NS} = 0.7390* exp(-0.36*tms)	$t > t_{det} + t_{fb}$; $t_{ms} = t - t_{det} - t_{fb}$
Case 4: PR2, AS2: Prompt D/S possible, Auto D/S possible	
P_{NS} = 1	$t < t_{det}$ + 5 minutes
P_{NS} = 0.0721	t_{det} + 5 minutes $\le t < t_{det} + t_{fb}$
P_{NS} = 0.0721* exp(-0.36*tms)	$t > t_{det} + t_{fb}$; $t_{ms} = t - t_{det} - t_{fb}$

Non-Suppression Probability Calculator	
User Input:	
Fire detection time from CFAST, sec, t_{det}	474
Component MTTF from CFAST, sec, t_D	3060
1335Intermediate Calculations:	
Component MTTF , min (t)	51.00
Fire detection time + 5 min response time, min (t_{det} + 5 min)	10
Detection time + 16 min Fire dept response time, min ($t_{det} + t_{fb}$)	21
Manual suppression time, min ($t_{ms} = t_D - t_{det} - t_{fb}$)	30

Non-Suppression Probability:				
Case 1	Case 2	Case 3	Case 4	t_D, min
2.04E-05	1.99E-06	1.51E-05	1.47E-06	51

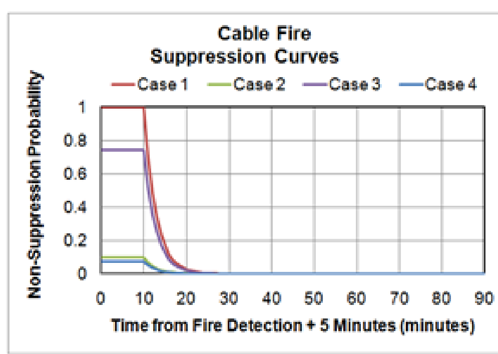


Figure 8. Time-dependent fire suppression model for the sample cable fires (P_{NS} is 1.0 for time less than detection time + 5 minutes)

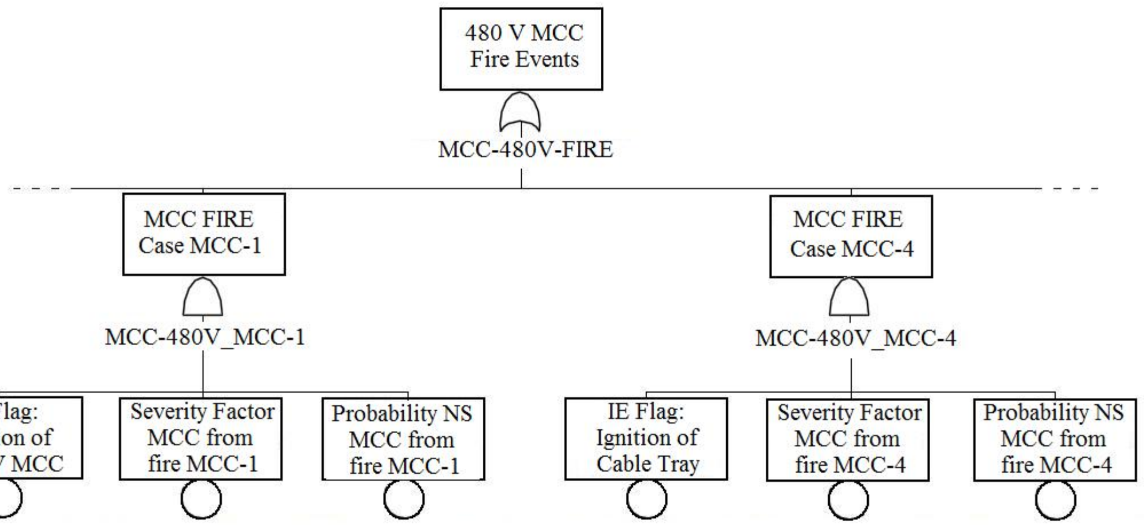


Figure 9. Fault tree for component failure due to all fires

4 COMPONENT FAILURE PROBABILITY DUE TO A FIRE

The probability of component failure due to a fire event is the product of the fire initiating event frequency, the severity factor, and the non-suppression probability. The severity factor and non-suppression probability are a function of the fire scenario and the component, thus separate severity factors and non-suppression probabilities are calculated for each fire affecting a given component. Overall, in the fire PRA, 127 fire scenarios were analyzed in 32 different fire areas to produce 639 severity factor and non-suppression probability basic events. All possible fires leading to component failure are then included in the fault trees for component failure as demonstrated in Figure 9.

5 CONCLUSIONS

The approach outlined above for detailed fire modeling combining the CFAST computer program with a Monte Carlo analysis using Latin Hypercube Sampling was successfully used in the fire PRA to develop fire severity factors. This method is an alternative to using the severity factor determination method relying on predetermined heat release rate bins outlined in Appendix E of NUREG/CR-6850 and can be used to calculate severity factors for ignition sources not addressed in NUREG/CR-6850.

The CFAST Monte Carlo analysis also provides component mean time to failure which can then be input into a time dependent model for fire detection and suppression to calculate component non-suppression probabilities. This was also successfully implemented as part of the fire PRA.

This approach results in development of separate severity factors and non-suppression probabilities for each safe shutdown component for each fire ignition source.

6 REFERENCES

1. NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Methodology." Electric Power Research Institute (EPRI), Palo Alto, CA, and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD: 2005, EPRI TR-1011989 and NUREG/CR-6850 (September, 2005).
2. Jones, W.W., R.D. Peacock, G.P. Forney, and P.A. Reneke, "Consolidated Model of Fire Growth and Smoke Transport (Version 6): Technical Reference Guide," NIST SP 1026, National Institute of Standards and Technology, Gaithersburg, MD (December, 2005).
3. NUREG-1824, "Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 5: Consolidated Fire and Smoke Transport Model (CFAST)," U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD, 2007, and Electric Power Research Institute (EPRI), Palo Alto, CA, NUREG-1824 and EPRI 1011999 (January, 2006).
4. T. Elicson, "Addressing Uncertainty in Detailed Fire Modeling of Nuclear Power Plant Single Compartment Fire Scenarios Using Constrained Monte Carlo Sampling," PSA 2008, Knoxville, TN (September 7-11, 2008.
5. K.A. Notarianni, "The Role of Uncertainty in Improving Fire Protection Regulation," PhD Thesis, Carnegie Mellon University, Pittsburgh, PA (2000).
6. S. Hostikka and Keski-Rahkonen, O., "Probabilistic Simulation of Fire Scenarios," Nucl. Eng. And Design, 224, pp.301-311(2003).
7. SAND98-0210, "A User's Guide to LHS: Sandia's Latin Hypercube Sampling Software," Sandia National Laboratories, Risk Assessment and Modeling Department, Albuquerque, NM (1998).
8. NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plant", National Fire Protection Association, Brainerd, MA, Standard 805, 2001 Edition.
9. DOE-EH-4.2.1.4-Final CFAST Code Guidance, "CFAST Computer Code Application Guidance for Documented Safety Analysis Final Report", Section 5.2.2, U.S. U.S. Department of Energy Office of Environment, Safety and Health (July, 2004).
10. NUREG/CR-6931, "Cable Response to Live Fire (CAROLFIRE)," US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC and Sandia National Laboratories, Albuquerque, NM, NUREG/CR-6931 and NISTIR 7472, Nowlen, S.P. and F. J. Wyant (April, 2008).
11. NUREG-1805, "Fire Dynamics Tools (FDTs): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program," US Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Division of System Safety and Analysis, Washington, DC (December, 2004).