Florida Power & Light Company, 6501 South Ocean Drive, Jensen Beach, FL 34957

June 26, 2002

L-2002-130
10 CFR 50.4

U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, DC 20555

Re: St. Lucie Unit 1
Docket No. 50-335
FPL Response to Request for Additional Information
Halon Regulatory Conference Presentation Background

On April 5, 2002, the NRC sent and FPL received Inspection Report 2002-06 that provided notification of a potential white finding and apparent violation of 10 CFR Appendix R requirements for the St. Lucie Unit 1 cable spreading room Halon suppression system (EA-02-033). FPL requested a regulatory conference to discuss the potential white finding and apparent violation, and the meeting was held at NRC Headquarters in Rockville, Maryland on June 20, 2002.

The Staff asked that FPL provide the background information for the material presented during the regulatory conference. This letter submits FPL's CFAST modeling and Significance Determination Process information as requested during the conference.

Please contact us if there are any questions regarding this submittal.

Very truly yours,

Donald E. Jernigan
Vice President
St. Lucie Plant

DEJ/KWF

Attachment 1 –SDP Background Information ....6 Pages
Attachment 2 –CFAST Modeling Background Information........................43 Page

This report presents the results of a re-evaluation of the St. Lucie cable spreading room fire risk scenarios provided in an NRC report dated April 5, 2002 (Reference 1). The NRC report developed six risk scenarios based upon the combustible type which initiates the fire.

Each of the risk scenarios utilized the following six factor formula in the risk quantification:

$$F_{CDF} = F_i * S_f * P1 * P2 * P3$$

where,

F_{CDF} = Fire induced core damage frequency
F_i = Fire initiating event frequency of ignition source
S_f = Severity factor for a challenging fire
P1 = Failure probability of Halon system
P2 = Failure probability of manual suppression by the fire brigade
P3 = Conditional core damage probability, or failure probability of operator to operate remote hot shutdown panel in Electrical Equipment Room 1B

The first scenario considered transformers as the ignition source. The NRC report assumed that the fire started from pressurizer heater transformers and has sufficient time to spread and ignite a cable tray closest to the ignition source. Reference 2 provides a re-evaluation of this fire propagation assumption in the NRC report and concludes that it is highly unlikely that a slow growth fire initiated in a pressurizer heater transformer will ignite or damage the closest cabling given burning of the transformer to completion. However, if arcing in the transformer occurs the fire may be able to quickly propagate to the nearest adjacent cable tray. This arcing potential has been called into question in Reference 3 for dry transformers as are present in the St. Lucie cable spreading room.

The NRC evaluation developed the frequency of transformer fires based on an ABB Power T & D Company study (two dry type transformer fires). This frequency of 2.0E-5/yr was stated to reflect realistic operational experience and will be utilized without modification in this re-valuation.

Neither of these transformer fire data events resulted in arcing. Therefore, to consider the potential for arcing the severity factor must be modified from the NRC evaluation. A zero event approximation will be utilized consistent with approach presented in Reference 4. This yields a severity factor 0f 0.25 based on one assumed arcing event in four fire occurrences.

As in the NRC study, this re-evaluation will conservatively not credit the Halon system with extinguishment of the fire. It will be conservatively assumed that the Halon system will actuate but not suppress a deep seated cable fire. However, the soak time of ten minutes will inhibit fire growth for its duration before the fire is assumed to spread and eventually damage both safety related trains (due to flashover or fire spread without flashover). The NRC evaluation stated that flashover would occur in 23 minutes in the event of an unsuppressed deep seated cable fire. References 2 and 5 concluded that flashover was highly unlikely given cable related fires of any size in the St. Lucie cable spreading room. However, at some point the redundant B safety train may be damaged due to fire spread alone without flashover. This re-evaluation will conservatively assume that both safety trains will be damaged 23 minutes after the Halon soak time is over, the Halon system actuates immediately upon the occurrence of arcing, and arcing immediately results in a deep seated fire in the nearest cable tray. These assumptions result in a minimum of 33 minutes being available for fire brigade response without crediting the Halon system with the potential for extinguishment, and thus represent a conservative upper bound on the overall failure probability to suppress before damage to both safety trains occurs (P1 x P2). Therefore, the value for P1 is conservatively assumed to be 1.0.

The NRC evaluation of P2 was based on the methodology developed in Reference 6. This simplified methodology to credit fire brigade response was not plant specific to either fire brigade practices or plant areas and hence was replaced by a much more plant specific approach in Reference 7. The methodology developed in Reference 7 was employed in all subsequent NRC-sponsored fire risk studies (References 4 and 8) and adopted internationally in Reference 9. Unannounced fire brigade drills times yield a mean estimate of response to the cable spreading room of 10 minutes. Consistent with the methodology presented in References 7, the mean time from smoke detector alarm initiation to manual substantive control of the fire is found to be 15 minutes. Most members of the fire brigade will arrive at the cable spreading room much quicker than the last member who goes to the equipment locker first and then responds (this last fire brigade member's delayed response has been taken as the overall brigade response in the recorded fire drill data). It was found that a best estimate time for smoke detector response was three minutes, for the fire brigade to locate the fire once on the scene was two minutes (this action is assumed to be performed concurrently with the last member arriving at the scene and thus is not added to the time estimate), and three minutes to control further growth of the fire once the fire was located (Reference 7). Thus value for P2 is found to be 1.1E-1. If simplified methodology provided in Reference 10 were employed in the quantification of P2 the value would be 0.1. Since the Reference 7 is much more detailed plant specific approach than Reference 10, the value for P2 is taken to be 1.1E-1.

This reevaluation of the potential for operator recovery from the remote shutdown panel (P3 factor) will utilize the same methodology for evaluation as was employed in the NRC quantification. However, it must be noted that the NRC report misinterpreted the potential for elevated environmental stressors given abandonment of the control room in the event of a cable spreading room fire. In all NRC-sponsored fire risk studies, the potential for elevated stressors was found only in the event of a fire in the control room where the operators may experience elevated temperature or smoke prior to making the abandonment decision. The St. Lucie remote shutdown panel room is not connected either physically or by a credible significant smoke propagation pathway to the cable spreading room. However, its ventilation fan could be failed in the event of a cable spreading room fire (This deficiency has subsequently been corrected therefore a random failure of the fan would have to occur to result in the NRC postulated elevated environmental stressors. It is conservatively assumed in this reevaluation that the fan is always failed upon initiation of the fire). This potential is recognized in the control room abandonment procedure. An analysis of remote shutdown panel heat-up characteristics in the event of loss of ventilation (Reference 11) found that a minimum of three hours without ventilation would be required to result in elevated temperatures sufficient to fail the remote shutdown panel. Most recovery actions taken by operators to place the plant in a stable condition should be completed within 30 minutes after the decision is made to abandon the control room. Therefore, there is an extremely low likelihood of significant elevated temperatures in the remote shutdown panel room prior to performing all recovery actions except for monitoring plant shutdown status even assuming that the ventilation fan is immediately failed and no actions are taken to restore room cooling. To restore room cooling is proceduralized and can be simply accomplished by opening the door and turning on an alternate ventilation fan which is electrically independent of the cable spreading room (there is a high likelihood that the alternate ventilation fan is running and thus the only operator action required to reestablish room cooling is to simply open the door). If it is necessary to start the alternate fan, the switch for the fan is immediately outside the door. This alternate ventilation fan can also be employed to remove any minor amounts of smoke which may enter the remote shutdown panel room. Therefore, it is highly unlikely that the operator will allow failure of the remote shutdown panel due to elevated temperature without first following proceduralized and simple recovery step with at least three hours to simply open a door (during a time well after all significant recovery actions have already been accomplished). The NRC evaluation concluded that the performance shaping factor for reestablishing room cooling was 300. This performance shaping factor is extremely pessimistic and can be contrasted with other typical high stress performance shaping factor evaluations which have concluded that a PSF of at most 10 is appropriate (for example, in the immediate aftermath of a significant earthquake or if errors have previously been made in the performance of a complicated recovery process) (Reference 12). In this reevaluation it is concluded that the performance shaping factor should be 1.0 for opening the door (and possibly starting the alternate ventilation fan) and thus its failure probability is 1.0E-3. The HEP for the operator failing to control the plant from the remote shutdown panel of 0.1 is very conservatively quantified in the original IPEEE study (Reference 13) as compared to NRC-sponsored fire research studies (References 4,7,8,14,15) and other Fire IPEEE evaluations (Reference 12). The typical mean value in other IPEEE studies is 1.0E-2 and in the NRC studies 6.0E-2. The NRC studies assumed a high stress PSF due to environmental stressors present in the control room prior to the abandonment decision and known interactions between the remote shutdown panel and the control room. These factors are not relevant to the St. Lucie cable spreading room fire scenarios. Therefore, it is concluded that the HEP of 0.1 which is adopted for this report from Reference 13 is a very conservative choice for P3. The re-evaluated fire-induced core damage frequency for transformer fires is found to be 5.6E-8/yr.

The second scenario considered 480V MCC 1AB cabinet as the ignition source. The ignition frequency and severity factor from the NRC evaluation are considered to be properly determined and are thus utilized in this re-evaluation.

As was the case for the transformer fire scenario it will be conservatively assumed that all cable fires are deep seated and the Halon system soak time only delays the onset of redundant train damage by 10 minutes. Thus, it is conservatively assumed that P1 is 1.0.

A detailed evaluation of the potential for fire propagation from MCC 1AB to cable run above is documented in Reference 2. It was found that the fire could propagate to cable tray above in 17 minutes (NOTE: it was later determined to take 24.5 minutes to ignite the cable trays. 17 minutes is used although conservative). When the fire brigade arrives in approximately 11 minutes they may decide to manually initiate the Halon system or fight the cabinet fire with portable extinguishers if it is still small enough. It will be conservatively assumed that they are initially unsuccessful in suppressing the fire and they utilize the Halon system after the fire has involved the nearest cable tray above the MCC. From this point in the fire progression, it will be assumed that the fire does not spread further until the Halon system soak time has elapsed. As was the case for the transformer scenario, the time to damage redundant trains from the NRC report of 23 minutes will be utilized. Therefore, the fire brigade has approximately 50 minutes to manually suppress the fire prior to damage being sustained by redundant trains. Thus, P2 is found to be 3.6E-2.

Consistent with the approach taken in the re-evaluation of the transformer fire scenario P3 is taken to be 0.1. The re-evaluated fire-induced core damage frequency for a MCC 1AB fire is found to be 1.7E-8/yr.

The quantification of all terms for the low voltage electrical cabinet fire scenario will be taken as stated in the NRC evaluation with the exception of the failure probability of manual fire suppression. In this evaluation it will be conservatively assumed that the higher voltage MCC 1AB fire analysis results presented in Reference 2 can be extrapolated to lower voltage cabinets. Therefore, P2 is based on 17 minutes time to damage and is found to be 0.32.

No fire data in References 16 and 17 have shown the potential for fire spread from low voltage cabinets. Therefore, assuming the severity factor of 0.12 based high voltage electrical cabinet fires is extremely conservative. The re-evaluated fire-induced core damage frequency for low voltage cabinets is found to be at most 1.1E-8/yr.

The quantification of all terms for the ventilation systems fire analysis will be taken as stated in the NRC report. No specific fire evaluation was performed in Reference 2 or in this report for ventilation systems since the NRC report found the fire-induced core damage frequency to be insignificant. Also, fire protection panels were not re-evaluated here because the NRC report found the fire risk to be insignificant.

The final scenario considered the cable runs as the ignition source. The quantification of all terms will be taken from the NRC report with the exception of P2 and P3. As was the case for the re-evaluation of P3 for transformer and MCC 1AB fire scenarios, the probability of the operator failing to control the plant from the remote shutdown panel is found to be 0.1. The time to damage redundant cable trains of 23 minutes will be taken from the NRC report. Thus P2 is 1.1E-1. The fire-induced core damage frequency for cable runs is found to be 8.4E-8/yr.

This report has adopted many of the conservative assumptions from the NRC evaluation and adopted others to insure that the fire induced core damage frequency estimate has been conservatively re-evaluated. In particular, no credit is given for the Halon system suppressing a deep-seated fire, the severity factor for low voltage cabinets is taken from higher voltage cabinet fire data, the potential for arcing in dry transformers is most likely much less than one-quarter, the time for the fire brigade to arrive on the scene is taken from unannounced drills only and is based upon the last member arriving on the scene, no credit is given for flamastic coating on the cables either delaying fire spread or preventing fire damage, a conservative upper bound probability for P3 was assumed as compared with similar fire IPEEE and NRC research quantifications, and no credit was given for cable tray covers delaying fire spread. Thus the total re-evaluated fire induced core damage frequency of 2.0E-7/yr is considered to be a conservative upper bound. Even without crediting the Halon system for other than its soak time, the cable spreading room fire induced core damage frequency is well below the IPEEE reporting criteria (Reference 18).

References

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HAI Project # 6409

Cable Spreading Room Fire Scenario Issues: NRC Analysis Evaluation, Equipment/Cable Tray Fire Scenarios, and Event Timeline

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1.0 Background

The Cable Spreading Room (CSR) at St. Lucie Nuclear Power plant contains several pieces of electrical equipment and cable trays that are needed to safely shutdown the plant. The room contains not only the safe shutdown cable trains, but also the redundant train as well. Therefore, several safety features are located inside of the room to prevent fires from damaging both the safe shutdown cables and the redundant train.

The cable spreading room is 18 ft high, 55 ft wide, and 70 ft – 6 in. deep and is constructed of concrete. The room contains four single doors and one set of double doors that can be used to access outside or other parts of the plant. One of these doors leads to a stairwell that can be used to enter the control room, which is located directly above the cable spreading room. The room has 19,800 cfm of forced fresh supply and exhaust air. In addition, the room contains two re-circulation units, one with a capacity of 9,000 cfm and the other with 6,750 cfm.

The purpose of this report is to respond to FP&L questions related to NRC Hazard and Risk Analyses [NRC, 2002] [Moroney, 2002].

The assumptions and limitations of analysis described in this report are as follows:

- The fire growth rate in cable trays was assumed to be "slow" corresponding to the assumptions made by the NRC [Moroney, 2002]. No analysis was conducted to evaluate the spread of fire along cable trays within a specific area.
- Transient combustible fires were not considered in the analysis.
- In developing the timelines, the environment in the room was modeled as a one-layer system.
- The effects of the Halon 1301 suppression system on suppressing flames and reducing oxygen were not included.
- The heat release rates of the electrical equipment were assumed to be similar to those measured in large-scale fire tests with similar ventilation, fuel loading, fuel types, and fuel distribution.
- Fuel loading inside the electrical equipment was based on cabling and plastic that was visible upon opening the cabinet. Fuel loading was estimated based on data in the literature on similar combustibles. In cases where large portions of the cabinet interior contents were not visible, the fuel loading and distribution were assumed to be similar to the highest fuel loading in fire tests with similar ventilation.
- In electrical equipment fires, all gases from the fires were assumed to be exiting the cabinet from the highest exhaust opening or the top of the door of the cabinet.
- Analysis did not include the possibility of cable ignition due to a high plasma arc from the failure of a piece of high voltage electrical equipment.
- Fire properties such as lower oxygen limit, smoke yields, heat of combustion, radiative fraction, etc. were conservative values from the literature.

- Flamemastic™ coated unqualified cables were assumed to have a damage and ignition temperature the same as IEEE 383 qualified cable.

2.0 Review of NRC CFAST Simulations

Cable tray fire scenarios were previously investigated by the NRC in the Cable Spreading Room (CSR) [Moroney, 2002] using the computer model CFAST [Jones *et al.*, 2000]. The NRC simulated six heat release rate profiles under three different ventilation conditions for a total of eighteen scenarios. The heat release rate profiles corresponded to cable tray fires with a slow growing t^2 fires with a peak heat release rate between 600-kW and 6,000-kW. The three ventilation conditions were: no mechanical ventilation; mechanical supply and exhaust; and mechanical exhaust only. Moroney [2002] concluded that flashover, defined as a smoke temperature greater than 500°C [Walton and Thomas, 1995], could occur within 29-minutes. Moroney [2002] concluded that because flashover is possible, "the CSR area structure could fail and allow fire to spread throughout the plant".

The NRC results were reviewed to ensure that the model results are reasonable for the conditions within the CSR space. In particular, the NRC input files were examined and the input parameters were compared with information obtained during a survey of the CSR space April 29 - 30, 2002 and subsequent review of facility drawings and specifications.

2.1 Unmodified NRC CFAST Runs

The temperature results using the NRC CFAST input files were verified using CFAST Version 3.1.7, the most recent available [Jones *et al.*, 2000]. The results are documented in Table 2-1 below for the eighteen cases that were evaluated by the NRC [Moroney, 2002]. With the exception of one case, the results obtained using the original NRC input files were in agreement with results reported by the NRC. It is suspected that the temperature reported by Moroney [2002] for the 6,000-kW scenario with mechanical supply and exhaust (484 °C peak) actually corresponds to the case where the mechanical ventilation is completely off (also a 484 °C peak).

Table 2-1. Temperature Results in the CSR using the Unmodified NRC Input Data Files

Cable Area (m^2)	HRR (kW)	Peak Upper Gas Layer Temperature (°C)					
		MV Exhaust/ Supply On		MV Exhaust On		MV Off	
		Original[1]	Re-run[2]	Original[1]	Re-run[2]	Original[1]	Re-run[2]
1	600	68	68	68	68	146	146
2	1,200	119	119	119	119	232	232
3	1,800	175	175	175	175	304	304
4	2,400	191	191	233	233	364	364
5	3,000	209	209	292	292	415	415
10	6,000	484	**336**[3]	500 at 29 m	500 at 29 m	484	484

[1]Original value reported by Moroney [2002]
[2]Values obtained when NRC input files ran using CFAST version 3.1.7
[3]Value does not agree with the NRC tabulated value of 484 °C.

Table 2-1 indicates that the CFAST version used in this analysis is the same or produces the same results and that the output is interpreted in the same manner.

2.2 NRC Scenario Discrepancies

Inspection of the input files used by the NRC to predict the conditions in the CSR turned up several discrepancies between what was supposed to be simulated and what actually was simulated. These discrepancies are divided into three categories:

- Significant input file format problems;
- Configuration deviations; and
- Minor input file-format problems/discrepancies.

Appendix A (Sections A.1.1 through A.1.3) contains representative NRC input files with the discrepancies identified in this section explicitly identified.

2.2.1 Significant Input File Format Problems

Significant input file format problems refer to improper input file command syntax. When improper command syntax is encountered by CFAST, the program will do one of two things: it will use default values or it will terminate a simulation and indicate that an error was encountered. The input files used by the NRC for the CSR analysis contained four such command syntax problems:

1) The height of the cable tray fire is 3.0-m above the floor. The command that specifies this condition requires an argument for each time at which a heat release rate is specified, which is three for all eighteen of the NRC scenarios. The input files only contain two arguments: one for time zero and one at a time of 10-sec. CFAST assigns a default value of 0.0-m for all specified times in which an argument has not been specified, which is the last specified time in the NRC input files. This occurs anywhere between 453-sec (time to reach 600-kW peak heat release rate) and 1,431-sec (time to reach 6,000 kW peak heat release rate) for the NRC fire scenarios (see Table 4 in Moroney [2002]). The values are interpolated linearly between the penultimate and last specified times.

   As an example of this, the fire elevation for the case shown in Appendix A (Section A.1.1) is modeled at 3.0-m at 10 sec, decreases linearly with time to an elevation of 0.0-m between 10-sec and 1021-sec (time to reach a peak heat release rate of 3,000 kW), and is modeled at an elevation of 0.0-m from 1021-sec to 3600-sec. Appendix A (Section A.2) contains a portion of the output file for the simulation described in Appendix A (Section A.1.1) that shows the fire location adjusted to the default value of 0.0-m after the last specified time.

The fire in the NRC cases is thus at the correct elevation at 10-sec and is entirely relocated to the floor anywhere between 453 and 1,431-sec, depending on the particular scenario. This has a significant effect on the available supply of oxygen at the fire.

2 - 4) The species yields and fuel composition commands (CO, HCR, and OD) require an argument for each heat release rate specified. When there are an insufficient number of arguments, CFAST reverts to the default values of 0.0 for CO, 0.33 for HCR, and 0.0 for OD at the last specified time. This occurs anywhere between 453-sec (time to reach 600-kW peak heat release rate) and 1,431-sec (time to reach 6,000-kW peak heat release rate) for the NRC fire scenarios. The values are interpolated linearly between the penultimate and last specified times.

The HCR and OD parameter can have a moderate impact on the smoke layer temperature [Jones *et al.*, 2000]; thus the default value of 0.0 versus the intended value of 0.05 is significant for the OD. The default HCR value of 0.33 is not significantly different from the intended value of 0.3. Appendix A (Section A.2) contains a portion of the output file that shows the values for these parameters adjusted to the default values at 10-sec.

2.2.2 Configuration Deviations

Configuration deviations refer to any input parameters that do not represent the physical configuration of the CSR. There are three such deviations identified in the NRC input files:

1) The total natural ventilation opening area in the input files differs from the value cited in the Moroney [2002] report and with visual inspection of the CSR by HAI. Moroney [2002] indicated that the total area of openings in the CSR is about 0.15-m^2, which is consistent with field measurements made by HAI of the cracks around all doors in the CSR. The area of the openings used by the NRC to calculate the conditions in the CSR was 2.25-m^2, which is an order of magnitude greater than the observed value.

2) The NRC assumed a total mechanical ventilation supply of 24,800-cfm and exhaust of 24,800-cfm. The NRC also assumed that the supply flow rate is independent of the exhaust flow rate, *viz.*, the exhaust could function normally without the supply. The actual ventilation conditions in the CSR are somewhat different than assumed by the NRC. Per Drawing 8770-G-870 [1975] and Drawing 8770-G-826 [2001], there are four supply and/or exhaust fans that serve the CSR. These are as follows:

   - HVE-11 exhausts 19,800-cfm directly from the CSR above the east access door;
   - HVS-5A/5B supplies 19,800-cfm fresh air directly to the CSR generally along the west wall of the CSR;

- HVA-4, re-circulation ventilation that supplies and exhausts 9,000-cfm using the same fan.
- HVA-5, re-circulation ventilation that supplies and exhausts 6,750-cfm using the same fan.

The HVA-4 and HVA-5 systems are used for climate control; the air is undiluted and does not pass through HEPA filters (which could remove smoke products). Furthermore, a single fan is used to supply and exhaust air in HVA-4 and HVA-5; there is no credible means for the HVA systems to only supply or only exhaust air. The HVA systems should therefore not be simulated as a fresh air supply or a pure smoke exhaust. The mechanical ventilation conditions in the CSR should thus be modeled using only the HVE-11 exhaust of 19,800-cfm and/or the HVS-5A/5B supply of 19,800-cfm.

3) The elevation of the exhaust fan HVE-11 is about 4-m above the floor as observed during the site survey. The NRC assumed that the exhaust point is 5-m above the floor.

2.2.3 Minor Input File Format Problems/Discrepancies

A minor input file format problem/discrepancy refers to the manner of setting up an input file that may cause deviations in the results. The deviations are generally not overly significant; however they may be eliminated entirely by setting up the input file differently. There are three such problems/discrepancies identified in the NRC input files:

1) The slow 't^2' heat release rate curve was defined by the NRC using three-points: one at time zero, one at ten seconds, and one at the time to reach the peak heat release rate. Because the growth time for the scenarios evaluated is between 453 and 1431 seconds, the heat release rate input essentially grows linearly. The slope of the 't^2' growth rate is positive, which means that a linear approximation *always* overestimates the heat release rate between the endpoints. A common means of reducing this type of deviation is to use more data points (~10) for defining the heat release rate profile.

2) Simulations in which fans are connected directly to a compartment node or the exterior of a compartment with no intervening ductwork may incorrectly calculate the contribution of the supply or exhaust to the species concentration in the space (*i.e.*, the oxygen). The NRC input files include fans that are connected directly to the interior of a compartment and to the exterior. A nominal duct segment should be included on each side of a fan to prevent possible calculation problems in CFAST.

3) The first non-zero heat release rate used in the NRC input files corresponds to a 'Medium' fire, not a 'Slow' fire. This is a minor

discrepancy because the time associated with this heat release rate is 10-sec.

2.2.4 *NRC Scenario Results with Discrepancies Corrected*

All discrepancies identified above were corrected and the CFAST was used to re-calculate the peak compartment temperature. The results are shown in Table 2-2. The modified NRC input files result in a maximum compartment temperature of 370 °C at 60 minutes in the case where there is mechanical exhaust but no supply. The mechanical ventilation scenarios are generally predicted to be more severe than originally reported by Moroney [2002] at lower heat release rates and less severe at higher heat release rates. The scenarios in which there is no mechanical ventilation are predicted to be less severe than originally reported in Moroney [2002]. It is significant to note that flashover is no longer predicted for the scenarios evaluated.

Table 2-2. Temperature Results in the CSR using the NRC Input Data Files with Discrepancies Corrected

Cable Area (m^2)	HRR (kW)	Peak Upper Gas Layer Temperature (°C)					
		MV Exhaust/ Supply On		MV Exhaust On		MV Off	
		Original[1]	Updated[2]	Original[1]	Updated[2]	Original[1]	Updated[2]
1	600	68	134	68	135	146	129[3]
2	1,200	119	187	119	188	232	176[3]
3	1,800	175	224	175	226	304	202[3]
4	2,400	191	254	233	255	364	222[3]
5	3,000	209	278	292	280	415	240[3]
10	6,000	484	**366**	500 at 29 m	370	484	262[3]

[1]Original temperatures reported by Moroney [2002]
[2]Temperatures obtained when the discrepancies noted above were corrected
[3]Temperature prior to fire becoming oxygen starved

2.3 NRC Scenario Parameter Adjustments

In several cases, the parameters and/or the simulation used in the NRC analysis summarized by Moroney [2002] are not the optimum values for a cable tray fire in the Cable Spreading Room. These parameters include:

- Oxygen concentration below which combustion is not supported (limiting oxygen concentration);
- Impact of the re-circulation HVA-4 and HVA-5 exhaust/supply fans on the two-layer assumption;
- Smoke yield;
- Radiant heat fraction; and
- The hydrogen to carbon ratio.

The selection of the above parameters was re-evaluated and different values were found to be more appropriate. The impact of each individual parameter on the maximum temperature result was examined using the 3,000-kW peak heat release rate scenario.

The collective impact of all parameters was evaluated for all heat release rate scenarios. Note that all discrepancies identified in Section 2.2 have been corrected for this portion of the analysis.

2.3.1 Limiting Oxygen Concentration

The limiting oxygen concentration or lower oxygen limit (LOL) is set in CFAST as the ratio (percent) of oxygen to other gases below which a flame will not burn [Jones *et al.*, 2000]. The LOL is sensitive to the particular gases present (nitrogen, combustion products, suppression agents, *etc.*) [Beyler, 2002]. Beyler [2002] reports the LOL at flame extinction for air diluted with combustion products as 12.4-percent to 14.3-percent. These values are consistent with other data in which the oxygen concentration at flame extinction was measured in compartment fire tests. Among these are 14-percent measured by Peatross and Beyler [1997] and 13.5 to 14.5-percent measured by Back and Hansen [2000]. A bounding LOL of 12-percent was used in this analysis. The value assumed by the NRC was 2-percent [Moroney, 2002].

Table 2-3 summarizes the impact of the LOL on the 3,000-kW peak heat release rate scenarios. The largest change was in the scenario where there is no forced ventilation. No deviation was noted in the scenarios with forced ventilation because there is adequate oxygen to support the combustion for the size fire.

Table 2-3. Impact of LOL on Peak CSR Temperature for 3,000-kW NRC Scenarios

Model Description	MV On	Exhaust On	MV Off
Original NRC Evaluation (2% LOL)	209 °C	292 °C	415 °C
Discrepancies Fixed (2% LOL)	278 °C	280 °C	240 °C
Discrepancies Fixed (12 % LOL)	278 °C	280 °C	219 °C

2.3.2 Impact of Re-circulation Ventilation System

The re-circulation system exhausts near the floor (HVA-4) and at about 2.8-m (HVA-5). Both systems supply conditioned air at multiple ports located about 2.8-m above the floor [Drawing 8770-G-870, 1975; Drawing 8770-G-826, 2001]. This ventilation system (HVA-4 and HVA-5) would not be a source of fresh air and it would not serve as a designated smoke exhaust system because the same fan supplies and exhausts undiluted CSR air. Because the re-circulation system is not designed to shut off during a fire, it would likely stir a smoke layer and disperse it throughout the room resulting in a one-zone environment.

The NRC evaluation assumed a two-zone environment in all mechanical ventilation scenarios. Another way to model the impact of the re-circulation system on the layer assumption in this space would be to use a one-zone approximation. This condition is applied to the cases where all mechanical ventilation is assumed to function ("MV On"). The results are summarized in Table 2-4 for the 3,000 kW peak heat release rate scenarios. The table shows that treating the compartment as a one-zone environment has a significant impact on the temperature, resulting in a reduction in the peak of over 100°C.

The results from Table 2-2 in Section 2.2 indicate that when there is mechanical ventilation, the exhaust only and the exhaust/supply scenarios result in similar smoke layer temperatures, however the exhaust only scenario is always slightly higher. It can be seen by comparing Tables 2-2 and 2-4 that the one-zone assumption reduces the smoke layer temperature for a given scenario and heat release profile. The re-circulation fans are not designed to shut down on alarm and thus may be functioning during any of the ventilation scenarios postulated. Consequently, by modeling the exhaust/supply scenario as one-zone and the exhaust only as two-zone, the smoke layer temperatures are bracketed in the CSR for a given heat release rate profile.

Table 2-4. Impact of Re-Circulation Ventilation System on Peak CSR Temperature for 3,000-kW NRC Scenarios

Model Description	**MV On**	**Exhaust On**	**MV Off**
Original NRC Evaluation (2-Zone)	209 °C	292 °C	415 °C
Discrepancies Fixed (2-Zone)	278 °C	280 °C	240 °C
Discrepancies Fixed (1-Zone when MV On)	173 °C	280 °C	240 °C

2.3.3 *Smoke Yield*

The smoke yield is the generation rate of solid particulate material per unit mass of fuel consumed. When specified in CFAST, this parameter is normalized via the carbon dioxide (CO_2) generation rate (Soot/CO_2 ratio). This parameter impacts the visibility of the smoke (needed to estimate smoke detection) and the temperature (via thermal radiation properties) [Jones *et al.*, 2000]. The smoke and CO_2 yields are typically measured in a bench scale test apparatus (*i.e.*, the cone calorimeter) and can vary markedly from one material to another [Tewarson, 2002; Babrauskas, 2002].

In general, CFAST predicts a hotter smoke temperature when the normalized smoke yield is reduced. The particulate concentration is also reduced, resulting in a longer smoke detection delay. Typical normalized smoke yields for PE/PVC and XLPE/XLPE electrical cables, common cable materials in the CSR, can range between 0.037 and 0.146 as reported by Tewarson [2002]. The smoke yields for other types of cables that may be present in the space are as high as 0.189 for EPR/Hypalon, 0.234 for PVC/Nylon, and 0.278 for XLPE/Neoprene cables [Tewarson, 2002]. Braun *et al.* [1989] report a narrower range between 0.019 and 0.063, with the lower bound values corresponding to polyolefin-polyethylene cables and the upper bound corresponding to PVC-PVC cables.

Most cables in the CSR are PVC based. As such, a reasonable lower bound estimate for the normalized smoke yield is 0.035, based on the work by Tewarson [2002] and Braun *et al.* [1989]. A lower value is treated as conservative in this analysis because it will result in an increased smoke layer temperature for a given fire scenario (but an increased visibility). The value used by the NRC is 0.05 [Moroney, 2002], which is within the typical range but somewhat less conservative. Table 2-5 summarizes the impact of this parameter on the 3,000-kW peak heat release rate scenarios.

Table 2-5. Impact of Normalized Smoke Yield (OD) on Peak CSR Temperature for 3,000-kW NRC Scenarios

Model Description	MV On	Exhaust On	MV Off
Original NRC Evaluation (OD = 0.05)	209 °C	292 °C	415 °C
Discrepancies Fixed (OD = 0.05)	278 °C	280 °C	240 °C
Discrepancies Fixed (OD = 0.035)	290 °C	293 °C	248 °C

2.3.4 *Radiant Heat Fraction*

The radiant heat fraction is the ratio of radiant heat energy released by the fire to the total heat released by the fire. This parameter is a function of the fuel, the configuration, and the temperature of the compartment. Except for methane and some alcohols, the radiant heat fraction for various types of hydrocarbons and plastics is 0.2 and 0.41 based on test results by Tewarson [1988]. Data available for various types of electrical cables using the chemical heat release rate as the normalizing factor indicate that the radiant heat fraction is between 0.36 and 0.63 [Tewarson, 2002]. A larger radiant fraction will result in a lower gas layer temperature because there is less convective energy in the thermal plume. The radiant energy is dispersed throughout the compartment by CFAST, including some which is intercepted by the smoke layer [Jones *et al.*, 2000]. Most radiant energy is absorbed by the compartment boundaries in a CFAST simulation.

The radiant fraction assumed by the NRC was 0.0 [Moroney, 2002]. A more reasonable lower bound (conservative) estimate would be 0.2 (ethane), which is the minimum value reported by Tewarson [1988].

Table 2-6 summarizes the impact of this parameter on the 3,000-kW peak heat release rate scenarios.

Table 2-6. Impact of Radiant Fraction (Π_r) on Peak CSR Temperature for 3,000-kW NRC Scenarios

Model Description	MV On	Exhaust On	MV Off
Original NRC Evaluation (Π_r = 0.0)	209 °C	292 °C	415 °C
Discrepancies Fixed (Π_r = 0.0)	278 °C	280 °C	240 °C
Discrepancies Fixed (Π_r = 0.2)	257 °C	260 °C	230 °C

2.3.5 *Hydrogen to Carbon Ratio*

The hydrogen to carbon ratio is literally the molecular weight ratio of hydrogen atoms to carbon atoms in the burning fuel. This parameter impacts the smoke species concentration and thus the temperature of the smoke layer (via radiant heating).

The hydrogen to carbon ratio (HCR) for most combustible materials varies between 0.0 (pure carbon, for example) to 0.33 (methane). One notable exception to this is pure hydrogen gas, which is not present in the CSR. For a given fire scenario, CFAST predicts a hotter smoke layer temperature when the HCR is increased. The HCR for electrical cables and electric cable insulation/jacket materials (PVC, PE, Hypalon, PVF, *etc.*) varies between zero for some fluoro-polymers and 0.167 for polyethylene [Tewarson *et al.*, 1993; Tewarson, 2002]. A conservative upper bound would therefore be 0.18. The NRC assumed a value of 0.3 for the HCR [Moroney, 2002].

Table 2-7 summarizes the impact of this parameter on the 3,000-kW peak heat release rate scenarios.

Table 2-7. Impact of Hydrogen to Carbon Ration (HCR) on the Peak CSR Temperature for 3,000-kW NRC Scenarios

Model Description	MV On	Exhaust On	MV Off
Original NRC Evaluation (HCR = 0.3)	209 °C	292 °C	415 °C
Discrepancies Fixed (HCR = 0.3)	278 °C	280 °C	240 °C
Discrepancies Fixed (HCR = 0.18)	256 °C	258 °C	235 °C

2.3.6 *Combined Effect of All Parameters*

The impact of all parameters described above on the temperature in the CSR for the NRC fire scenarios was assessed. The results, with all discrepancies identified in Section 2.2 corrected as well, are presented in Table 2-8. This table represents a conservative estimate of the conditions in the CSR using the fire scenarios postulated by the NRC. In all cases, the maximum smoke layer temperature remains well below the flashover temperature of 500°C.

Table 2-8. Temperature Results in the CSR using the NRC Input Data Files with Discrepancies Corrected and Revised Input Parameters

Cable Area (m^2)	HRR (kW)	Peak Upper Gas Layer Temperature (°C)					
		MV Exhaust/ Supply On		MV Exhaust On		MV Off	
		Original[1]	Updated[2]	Original[1]	Updated[2]	Original[1]	Updated[2]
1	600	68	57	68	116	146	109[3]
2	1,200	119	84	119	163	232	151[3]
3	1,800	175	109	175	198	304	179[3]
4	2,400	191	133	233	226	364	198[3]
5	3,000	209	155	292	250	415	198[3]
10	6,000	484	246	500 at 29 m	340	484	198[3]

[1]Original temperatures reported by the NRC [Moroney, 2002]
[2]Temperatures obtained when the discrepancies noted in Section 2.2 were fixed and all parameters modified as described in Section 2.3.
[3]Temperature prior to fire becoming oxygen starved

2.4 Summary

Significant discrepancies were identified in the NRC CFAST files that would change the conclusions reached by Moroney [2002]. Specifically, the maximum temperature in the space was determined to be 370°C, which is considerably lower than the minimum flashover temperature of 500°C. In addition to the noted discrepancies, several of the input parameters used by the NRC were not consistent with cable fire scenarios. When these parameters were modified accordingly, the maximum calculated temperature was further reduced to 340°C. Because flashover is not predicted for the set of heat release rate profiles assumed by the NRC, the conclusion that the CSR structure could fail resulting in fire spread beyond the room of origin should be reconsidered.

3.0 Potential for Cable Tray Ignition by Electrical Equipment Fires

An analysis was conducted to determine whether electrical equipment within the CSR considered to be risk significant by NRR [NRC, 2002] was capable of igniting cable trays located in the upper part of the room. Cables could be ignited by either hot gases spilling out of the cabinet through ventilation openings or through fire plumes extending out of the cabinet. The likelihood that significant flames will extend outside of the equipment is dependent on the combustible fuel load, fuel distribution, cabinet ventilation, and fire heat release rate. This analysis entailed developing heat release rates for fires inside the different electrical equipment in the cable spreading room and determining if these fires could ignite the cable trays above.

3.1 Cabinet Fuel Loading and Ventilation

Onsite surveys were conducted to document the ventilation into the electrical cabinets within the cable spreading room that could potentially be the worst fire sources. During these surveys, nearly all of the electrical cabinets were opened in order to document the fuel distribution and loading. A summary of the electrical cabinets considered in the study and their characteristics is provided in Table 3-1.

Table 3-1. Electrical Equipment Description

Equipment ID		Number of Cabinets	Ventilation Area (m^2)		Fuel Loading per Cabinet (kJ)
No	Name		Lower	Upper	
1	1A3 Transformer and Pressurizer Heater Bus[1]	1	0.31	0.31	743,700
		3	0.016-0.021	0.016-0.021	267,400 - 552,100
2	480 V Reactor Aux. Bldg. MCC 1AB	9	0.013-0.026[2]	0.013-0.026[2]	473,000 – 855,200

1. The 1A3 Transformer and Pressurizer Heater Bus was observed during the survey to be the same as 1B3 Transformer and Pressurizer Heater Bus.
2. Except for one cabinet, all of the ventilation areas are through door leakage.

3.2 Heat Release Rate

The heat release rates of the electrical cabinets inside the cable spreading room were developed using data from large-scale cabinet fire tests with similar ventilation and fuel loading. The heat release rate from electrical cabinets depends on the cabinet ventilation and the fuel loading and fuel distribution inside the cabinet. Fire testing was conducted by Chavez [1987] and Mangs and Keski-Rahkonen [1994, 1996] to evaluate the impact of these variables on the cabinet fire heat release rate. A summary of the test conditions is provided in Table 3-2.

A list of the equipment that heat release rate curves were developed for is provided in Table 3-3. Nearly all of the equipment had more than one electrical cabinet with steel walls from adjacent cabinets in direct contact. Some cabinets had cable feed-through holes, which provide a direct connection to adjacent cabinets. Fires were assumed to originate in one of the electrical cabinets in the equipment and spread to adjacent cabinets in the same piece of equipment after walls had sufficiently heated to ignite combustibles in the adjacent cabinet.

Table 3-2. Electrical Cabinet Fire Test Conditions

Test No.	Ref.	Ventilation Area(m^2)			Fuel Load (kJ)	Peak HRR & Time (kW, min)	Fire Duration (min)
		Type	Lower	Upper			
VTT-I 1	[1]	Vent Grills, Door Ajar	0.050	0.11	924,700	385 @ 40	105
VTT-I 2	[1]	Vent Grills	0.040	0.079	456,200	50 @ 14	45
VTT-I 3-2	[1]	Vent Grills	0.040	0.079	1,358,100	180 @ 15	125
VTT-II 1	[2]	Vent Grills	0.0097	0.054	1,538,700	175 @ 36	105
VTT-II 2	[2]	Vent Grills	0.0097	0.054	1,597,400	110 @ 32	120
VTT-II 3	[2]	Vent Grills	0.0097	0.054	1,509,900	100 @ 13	120
ST #10	[3]	Vent Grills	0.14	0.14	611,530	280 @ 11	50
PCT #1	[3]	Vent Grills	0.14	0.14	784,000	185 @ 12	60
PCT #2	[3]	Open door	1.30	1.30	1,054,000	950 @ 11	40

1. Mangs and Keski-Rahkonen [1994]
2. Mangs and Keski-Rahkonen [1996]
3. Chavez [1987]

Table 3-3. Electrical Cabinet Fire Descriptions

Equipment	No. of Cabinets	Cabinet Width (m)	Cabinet HRR		Exhaust Elevation (m)	Elevation of Lowest Vented Tray (m)
			Peak (kW)	Fig.1 Ref. Curve		
1A3 or 1B3 Transformer	1	1.16	200	#3	2.41	3.15
1A3 or 1B3 Pressurizer Heater Buses	3	0.49	280	#1	2.18	3.15
480 V Reactor Aux. Bldg. MCC 1AB	9	0.60	280	#1	2.26	3.12

The heat release rate in a single electrical cabinet was developed based on a comparison of the experimental data and the actual cabinets in the room. All electrical cabinets had a fuel load and fuel distribution that was similar to those evaluated in the tests, see Tables 3-1 and 3-2. The ventilation into the cabinet was the factor that governed the heat release rate of the cabinet. Each cabinet in the room was assumed to have a heat release rate consistent with one of the four curves shown in Figure 3-1. Each of these curves was developed from testing conducted by Chavez (1987) or Mangs and Keski-Rahkonen [1994, 1996]. The only exception to this was the transformer fire which was assumed to burn at 200-kW [Najafi *et al.*, 1999] until all combustible fuel was expended.

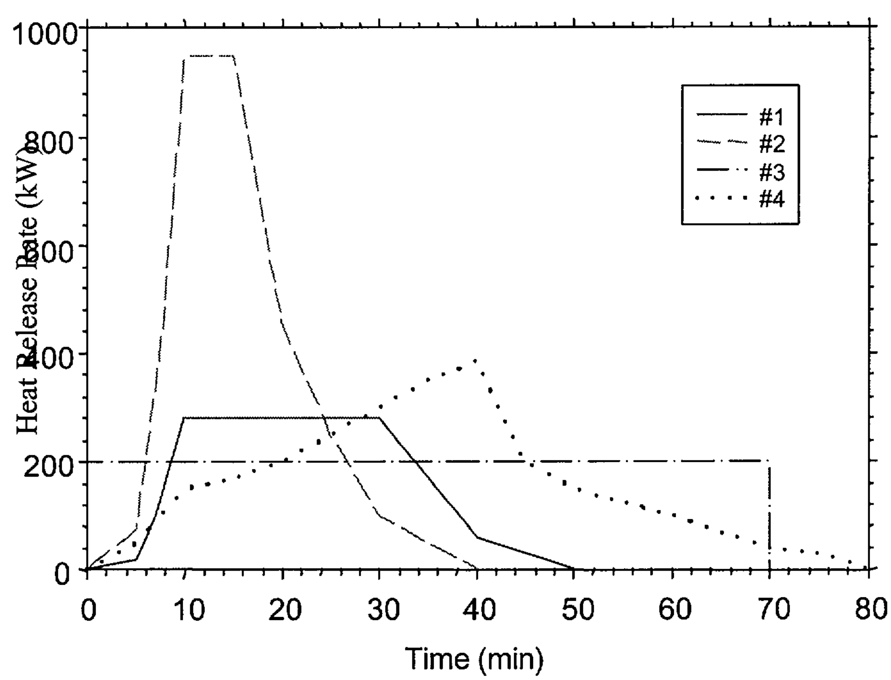
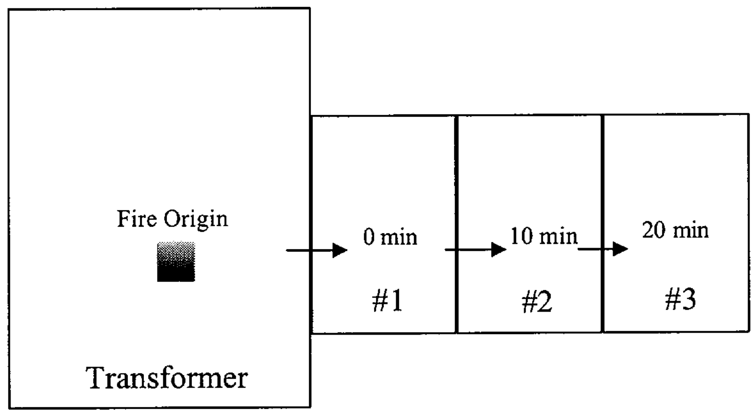


Figure 3-1. Heat release rate of individual electrical cabinets in the cable spreading room. Curve #1 from ST#2 and PCT#1 [Chavez, 1987], Curve #2 from PCT#2 [Chavez, 1987], Curve #3 [Najafi et al.,1999], and Curve #4 from Test 1 [Mangs and Keski-Rahkonen, 1994].

The potential for fire spread to adjacent cabinets was based on experimental data from tests conducted by Chavez [1987] and Mangs and Keski-Rahkonen [1994, 1996]. Chavez [1987] found that electrical cabinets that are not separated by an air gap can transmit sufficient heat to allow autoignition of cables in the adjacent cabinet. Wall temperature data obtained from by Mangs and Keski-Rahkonen [1994, 1996] indicate that fires will spread to adjacent cabinets approximately 10 minutes after ignition of a burning cabinet. Details on the fire development inside the Motor Control Center (MCC) and the transformer with adjacent pressurizer heater buses are provided in Figures 3-2 and 3-3, respectively. A "slow" t^2 fire growth rate bounds the heat release rate profile from all CSR cabinets considered.



Top view showing fire spread to adjacent pressurizer heater buses.

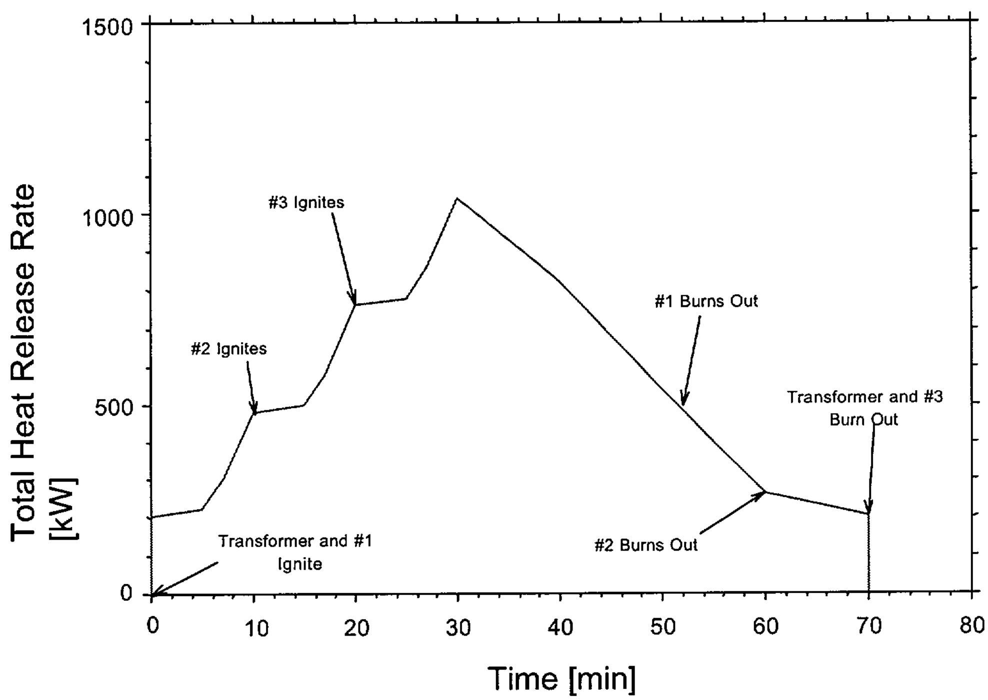
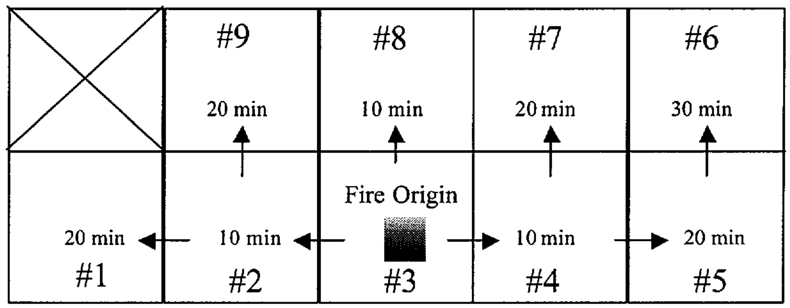


Figure 3-2. Heat Release Rate Profile and Depiction of Fire Spread through the Transformer and Adjacent Pressurizer Heater Buses.



Top View showing fire spread within MCC.

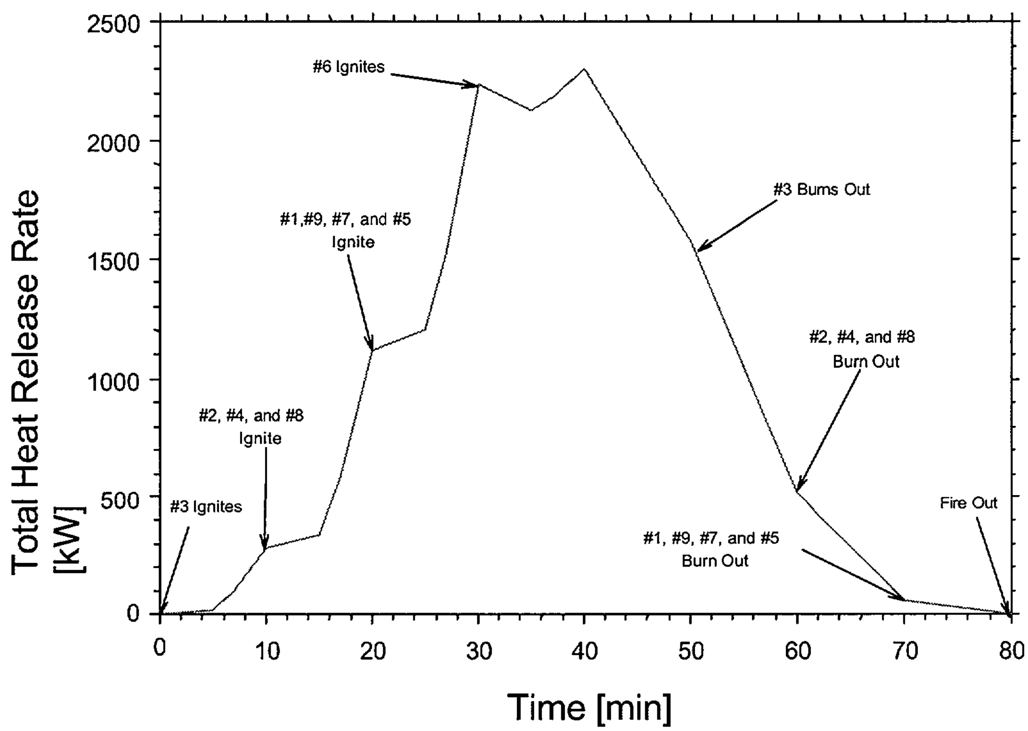


Figure 3-3. Heat Release Rate Profile and Depiction of Fire Spread through the Motor Control Center (MCC) Electrical Equipment.

3.3 Cabinet Fire Exposure versus Fire Exposures in Cable Testing

Cables coated similar to those in the cable spreading room were previously evaluated by Klamerus [1978] in a series tests on two tier, horizontal ladder type cable trays. Two different types of initiating fires were used in the testing:

1. Two 20-kW ribbon burners 4-in. below the lower tray and
2. A 3.0-ft long, 1.5-ft wide, 2-gal Diesel #2 pool fire 4-in. below lower tray.

The heat fluxes from these fires were calculated and compared with the worst case fire exposure expected from the electrical equipment in the cable spreading room, the 1AB Battery Charger. The heat fluxes from these fires to the lower cable tray will be similar to those heat fluxes measured in tests with fires impinging on a flat ceiling [Kokkala, 1989; Hasemi *et al.*, 1995]. As was the case in the fire tests, the highest heat fluxes from the fire to the cable trays are expected to be where the fire impinges on the lower tray. Heat fluxes from the 20-kW fires to the cable trays were estimated using the data from Kokkala [1989], which was developed from tests with similar size fires. Test data from Hasemi *et al.* [1995] were developed with larger diameter (up to 1.0-m) and heat release rate (up to 200-kW) fires and was, therefore, used to estimate the heat fluxes from the cabinet fire and the pool fire. Appendix D provides additional details for calculating the heat fluxes at the impingement point. Table 3-6 contains a summary of the heat fluxes at the impingement point for the fires in the tests and the worst case fire in the CSR. As can be seen from this table, the heat fluxes in the fire tests were 2-4 times higher than those expected from the worst case electrical fire exposure in the CSR. Therefore, the fire exposure used in the test bounds the exposure expected from any electrical cabinet fire inside the cable spreading room. In addition, as long as the gas temperature inside of the cable spreading room remains relatively low, the flame spread measured in the tests with a Flamemastic™ coating would be expected to be bounding.

Table 3-6. Comparison of the Heat Fluxes to Overhead Cable Trays: Fire Test Exposure Data vs. Most Severe Electrical Cabinet Fire

Initiating Fire	HRR (kW)	Flame Height, L_f, (m)	Distance Below Tray, H, (m)	L_f / H	Heat Flux at Impingement Point (kW/m^2)
2 Propane Burners	20 each	0.70	0.11	6.4	65
Diesel #2 Pool	280-650	1.7-2.8	0.11	14-23	90
1AB Battery Charger	950	3.35	3.12	1.07	23

4.0 Timelines for Cabinet Fires

Timelines showing various key events (smoke detector action, heat detector actuation, critical temperature thresholds, cable tray ignition, *etc.*) were developed for fires that originated inside the transformer and the MCC. The transformer was selected to determine whether this fire scenario could result in a complete loss of the space (*i.e.*, flashover) which is equivalent to a severity factor of 1.0 [NRC, 2002]. The MCC fire scenario was considered because the MCC has the highest heat release rate among those considered and is considered to have the second highest core damage frequency [NRC, 2002].

The timeline development included the following:

- Prediction of the transient smoke/gas layer temperature in the CSR;
- Estimation of the time for a single smoke detector to alarm;
- Prediction of the time for two heat detectors to alarm;
- Prediction of the time for overhead cable trays to ignite;
- Estimation of the time at which the mechanical ventilation system would shut down; and
- Calculation of the Halon 1301 suppression system actuation.

The initiating fire had the heat release rate of the electrical equipment. If ignition of the cables was predicted, the heat release rate of the fire was that of the electrical equipment and a growing cable tray fire. Simulations were conducted assuming the cable tray fire growth rate was equivalent to a "slow" growing t^2 fire, which is consistent with the original NRC evaluation [Moroney, 2002]. The modeling took into account the effects of shutting down the ventilation, but the effects of the Halon 1301 activation were not included.

4.1 Smoke Detector Alarm

The CSR room contains 38 Honeywell TC805A ionization smoke detectors that have an approved spacing of 30-ft. The smoke detectors in the CSR are strategically placed on the ceiling with a spacing that does not exceed 14-ft. Based on work by Geiman and Gottuk [2002], the smoke detector alarm can be estimated by the local smoke optical density, *OD*, which is a measure of the light that is obscured due to the presence of the smoke. With a flaming fire, an $OD > 0.072 \pm 0.027\text{-m}^{-1}$ will result in an alarm from 80% of the ionization smoke detectors. Due to obstructions in the upper part of the room and a high forced ventilation rate throughout, an exact alarm time could not be determined. Calculations were performed to estimate the range of times that the smoke detectors could alarm. This time range is a result of various parameters, including the assumed smoke and fuel properties and the alarm threshold. The shortest alarm times were determined in cases where a detector is located directly over a fire (assumed to be on the floor). The *OD* at the detector in this case was determined using plume correlations and a range of smoke properties, as described in Appendix C. Table 4-1 summarizes the results of this calculation. Alarm times were based on the assumption that the fire grows similar to a slow t^2 fire, which bounds the heat release rate for the electrical equipment fires. The longest (bounding) smoke detection times were estimated by using the calculated OD of the smoke layer as determined with CFAST. If the smoke layer OD is calculated to exceed the smoke detector threshold, then actuation is assumed.

Table 4-1. Smoke Detector Alarm Time due to a Local Fire Plume Originating at the Floor of the CSR.

Smoke properties, σ_s (m^2/kg)	Fire Diameter (m)	Smoke Yield (kg/kg)	Heat of Combustion (kJ/kg)	*OD* Threshold (m^{-1})	Alarm Time (min)
7,600	0.9	0.076	25,000	0.1	3.0
10,053	0.9	0.076	25,000	0.1	2.5
12,000	0.9	0.076	25,000	0.1	2.3
10,053	0.0	0.076	25,000	0.1	2.1
10,053	0.9	0.136	25,000	0.1	1.7
10,053	0.9	0.076	15,000	0.1	1.8
10,053	0.9	0.076	35,000	0.1	3.2
10,053	0.9	0.076	25,00	0.045	1.0

Assumptions: slow growing t^2 fire, detector elevation of 5.49-m and surrounding gas temperature of 20°C.

4.2 Heat Detector Alarm

The CSR room also contains 32 Honeywell T4507B, 200°F (93°C) fixed temperature heat detectors with a listed spacing of 25-ft. The manufacturer could not provide an RTI for the detector. In the absence of a specific RTI, the method described in Appendix B of NFPA 72 [1999] was used in this analysis. The NFPA 72 method calculates a detector RTI from the listed spacing and the actuation temperature. For the above rated temperature, the RTI was estimated to range between 21 and 119 $(m\text{-}s)^{1/2}$.

Calculations were performed to determine when two detection zones would alarm for fires in different locations within the space. When any two thermal detection zones alarm, the Halon 1301 activation sequence is started (see Section 4.3). Due to obstructions in the upper part of the room and a high forced ventilation rate throughout, an exact alarm time could not be determined. The alarm time was estimated by assuming that two heat detection zones were set off by the hot gas layer inside the room. This was estimated using CFAST (see Section 4.5).

4.3 Ventilation Shutdown and Halon 1301 Activation

A fire that causes two thermal detectors to alarm will automatically begin to initiate the Halon 1301 system activation sequence [PSL-FPER-00-007, 2000]. This includes shutting off the exhaust fan, closing the dampers in the supply duct, and releasing the Halon 1301 to suppress the fire after a 30-sec time delay. The effects of shutting down the supply and exhaust ventilation are included in the compartment modeling, but the suppression effects of the Halon 1301 are not.

4.4 Cable Ignition

Cables located above the transformer and the MCC electrical equipment were assumed to ignite only by hot gases issuing from an electrical cabinet fire. Cable ignition via high voltage arcs was not considered. The cables above the transformer and adjacent pressurized heater buses would ignite when the room gas temperature reaches 102°C, while cables above the MCC would ignite when the room gas temperature reaches 86°C. In cases where the cable trays are predicted to ignite, simulations were conducted assuming the cable tray fire grows as a "slow" t^2 fire.

4.5 Fire Timelines

Event timelines using the information obtained in Sections 4-1 through 4-4 were constructed for a transformer fire and a MCC fire. The timelines were created by first calculating the smoke layer temperature versus time using CFAST. Key events (smoke detection, heat detection, critical temperature threshold values, *etc.*) were then added to the temperature plots. Simulations were conducted assuming the room environment was a one-layer system.

4.5.1 Transformer Fire Scenario

The timeline for a transformer fire scenario is shown in Figure 4-1. This scenario assumes that the fire initiates in a transformer (1A3 or 1B3) and spreads to the adjacent pressurizer heater buses (see Figure 3-2). The potential for cable tray ignition via high voltage arcing *was not* considered. The scenario was modeled assuming normal ventilation conditions with all parameters as described in Section 2.3.

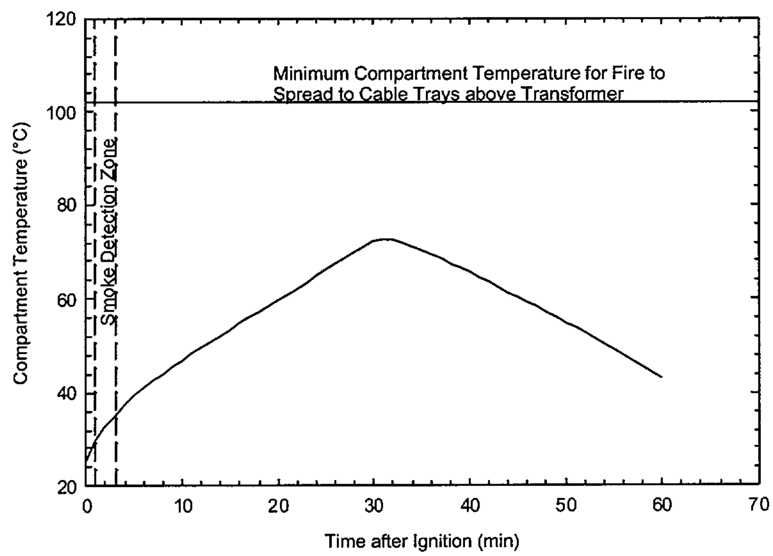


Figure 4-1. Timeline for 1A3 or 1B3 Transformer Fire Scenario

Figure 4-1 indicates that the smoke detectors are expected to actuate between one and three minutes when the smoke layer temperature is less than 40°C. The heat detectors were not predicted to alarm due to hot gas layer heating. Using DETACT (Evans, 1995) and an average gas temperature (50°C), the heat detectors were predicted to alarm at 28 minutes due to a fire plume. As previously mentioned the fire plume will be disturbed by the forced ventilation and overhead obstructions; therefore, modeling the heat detector alarm using a fire plume would result in overly conservative heat detection alarm times. The smoke layer temperature does not exceed the minimum temperature required for the overhead cable trays to ignite *for this scenario* (see Section 4.4). The smoke layer temperature also remains below the threshold for flashover (500°C).

4.5.2 MCC Fire Scenarios

A fire inside the MCC was predicted to ignite cables above the equipment when the gas temperatures reached 86°C, see Figures 4-2 and 4-3. Timelines were developed for two fire scenarios where the MCC was the initiating fire. The first fire scenario shown in Figure 4-2 was where the MCC and cable fire cause the thermal detectors to alarm and the mechanical ventilation shuts down. In the second fire scenario shown in Figure 4-3, the mechanical ventilation remains on. Both simulations were run for 60 minutes. The scenarios were modeled with all parameters as described in Section 2.3.

Figures 4-2 and 4-3 suggest a wider smoke detection range than predicted for the transformer fire scenario: between one and ten minutes. Two heat detectors were predicted to actuate between 28 and 30-minutes. At this time, the mechanical ventilation

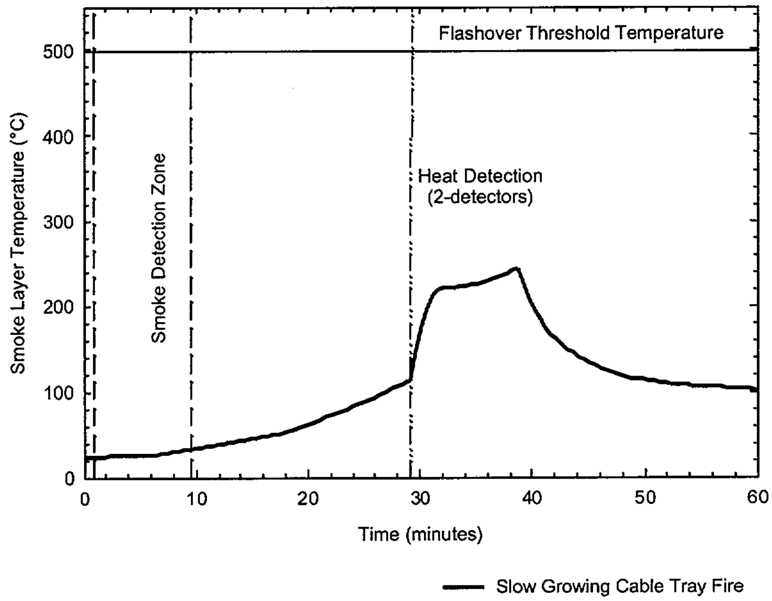


Figure 4-2. Timeline for MCC Fire Scenario
(Mechanical Ventilation Shut Off after Two Heat Detectors Alarm)

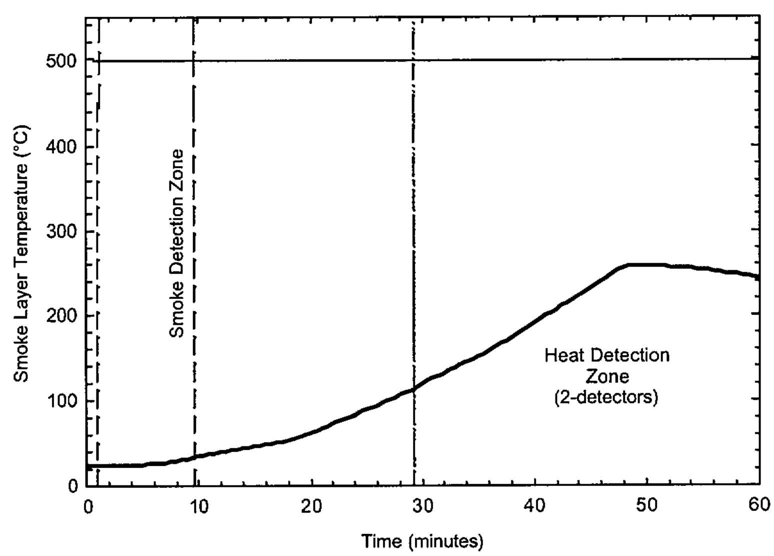


Figure 4-3. Timeline for MCC Fire Scenario
(Mechanical Ventilation Remains On)

is shut off (for the scenario represented in Figure 4-2). In both cases, the smoke layer temperature reaches 86°C (the minimum temperature for overhead cable tray ignition) at about 24.5-minutes. The subsequent cable tray fire is approximated with a "slow" t^2 growth heat release rate. In all cases, the maximum smoke layer temperature does not reach 500°C, the minimum flashover temperature.

5.0 Conclusions

1) Significant discrepancies with actual conditions/configurations were noted in the NRC assessment of cable tray fires in the Cable Spreading Room (CSR). When these discrepancies were corrected, the NRC conclusion regarding flashover could no longer be supported.

2) Several parameters assumed in the NRC evaluation were not consistent with data available for cables. When these parameters are modified in accordance with available data, the maximum compartment temperatures were further reduced.

3) The electrical cabinet fires are similar to cabinets previously tested in terms of size, ventilation, and combustible fuel load. The data suggest that cabinet to cabinet spread is likely if the cabinets are in direct contact. The time delay for such spread is about 10-minutes. The peak heat release rate is expected to fall between 200-kW and 950-kW *per electrical cabinet*. Collectively, the peak heat release rate (including cabinet to cabinet spread) is expected to fall between 1,000-kW and 2,300-kW for the electrical cabinets considered in the CSR.

4) The worst case cabinet fires postulated in the CSR would expose the overhead cable trays to a maximum heat flux of about 23 kW/m^2. This value is 2-3 times less than that estimated for the fire exposure used in the testing of coated cables. As long as the room temperature remains relatively low, the flame spread measured in the tests on Flamemastic™ coated cables is expected to be bounding.

5) Smoke detectors are predicted to actuate between one and ten minutes for typical equipment fire scenarios. The heat detectors are not predicted to actuate for the transformer fire scenarios. For the MCC fire scenario, two heat detectors are predicted to activate between 28 minutes and 30 minutes, depending on the assumed growth rate of the cable fire.

6) The timeline for the transformer fire scenario indicates that smoke detectors actuate but heat detectors do not. The maximum smoke layer temperature is less than 75 °C, which is below flashover, and the minimum temperature for the overhead cable trays to ignite.

7) The timelines for the MCC fire scenarios indicate that the smoke detectors and two heat detectors actuate. The MCC fire is predicted to ignite the overhead cable trays. Flashover was not predicted when the cable fire was assumed to have a slow growth rate. In the scenario with a slow growing cable tray fire, gas temperatures were predicted to be less than both the cable damage temperature and temperature for flashover conditions.

6.0 References

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Appendix A. CFAST CSR Evaluation Data

A.1 Analysis of Discrepancies in NRC CFAST Input Files

A.1.1 Scenario with Mechanical Ventilation Off

A representative original NRC input file (HAI Case5-1 [See Section A.3]) without mechanical ventilation is shown below with specific discrepancies as noted.

```
VERSN   3   St Lucie case 5-1  (Original NRC Input File) MV OFF
TIMES 3600  60  60   60   0
TAMB  298. 101300.  0.0
EAMB  298. 101300.  0.0
HI/F   0.0
WIDTH  20.72
DEPTH  14.94
HEIGH  5.48
HVENT  1  2  1  1.5  1.5  0.0
```

HVENT:
The HVENT Command above specifies an opening 1.5 m x 1.5 m located at the floor. Per Table 3, Page 6 of NRC Report, a vent measuring 1 m wide by 0.15 m tall located on the floor is desired. The correct syntax is:

HVENT 1 2 1 1.0 0.15 0.0

```
CEILI  CONCRETE
WALLS  CONCRETE
FLOOR  CONCRETE
CHEMI 16.  10.  2.  24000000.   298.  388.  0.0
LFBO  1
LFBT  2
FPOS  -1.0 -1.0  0.0
FTIME 10.  1012.0
```

FTIME:
There are an insufficient number of time points for defining a quadratic function with positive curvature, viz. a 't2' fire. The linear interpolation always under-estimates the intervening values. Suggest using about 10 points to describe 't^2' part of curve:

FTIME 100. 200. 300. 400. 500. 600. 700. 800. 900. 1012. 3600.

```
FHIGH 3.0 3.0
```

FHIGH:
FHIGH requires an argument (fire height) for each time listed on the FTIME command line PLUS one for time zero. When there are fewer arguments, the default value of zero is used. In the case above, the fire is repositioned to an elevation of 0.0 at 1012-seconds and the elevation is linearly interpolated between 10-seconnds and 1012-seconds because there is one less argument than required.

The command should look as follows for two FTIME arguments:

FHIGH 3.0 3.0 3.0

If the FTIME command with more points (11) is used, the FHIGH corresponding FHIGH command is:

FHIGH 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0

```
FAREA 1.0 1.0
```

Note: the FAREA is formatted in the same manner as FHIGH; however the command is currently not use by CFAST and the arguments are thus immaterial.

FQDOT 0.0 1.172e3 3000e3

FQDOT:

A heat release rate of 1.17 kW at 10 seconds corresponds to a 'Medium' fire, not a 'Slow' fire.

There are an insufficient number of time points for defining a quadratic function with positive curvature, viz. a 't2' fire. The linear interpolation always under-estimates the intervening values. Suggest using about 10 points to describe the 't^2' part of the curve:

FQDOT 0.0 29e3 117e3 264e3 469e3 733e3 1055e3 1435e3 1875e3 2373e3 3000e3 3000e3

```
CJET OFF
CO     0.14  0.14
OD     0.05  0.05
HCR    0.30  0.30
```

CO; OD; HCR
CO, OD, and HCR require an argument (Yield ratio or value) for each time listed on the CO, OD, and HCR command line PLUS one for time zero. When there are fewer arguments, the default value of zero is used for CO and OD and 0.33 for HCR. In the case above, the CO and OD are reset to 0.0 and the HCR to 0.33 at 1012 seconds and varied linearly between 10-seconds and 1012 seconds because there is one less argument than required. The HCR and OD parameters impact the smoke layer temperature when using the constrained feature on CFAST, as is the case here.

The commands should look as follows for two FTIME arguments:

```
CO   0.14 0.14 0.14
OD   0.05 0.05 0.05
HCR  0.30 0.30 0.30
```

If the FTIME command with more points (11) is used, the species commands corresponding to the FHIGH command are:

```
CO   0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14 0.14
OD   0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
HCR  0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30
```

```
STPMAX  1.00
DUMPR   case5-1.hi
```

A.1.2 Scenario with Mechanical Ventilation (Supply and Exhaust) On

A representative original NRC input file (HAI Case5-2 [See Section A.3]) with mechanical ventilation (supply and exhaust) included is shown below with specific discrepancies as noted. The discrepancies identified in Section A.1.1 are present in the file below and are not repeated.

```
VERSN   3     St Lucie case 5-2 (Original NRC Input File) MV ON
TIMES 3600  60  60  60 0
TAMB  298.0 101300.0  0.
EAMB  298.0  101300.0  0.
HI/F   0.0
WIDTH  20.72
DEPTH  14.94
HEIGH  5.48
HVENT  1  2  1   1.5  1.5  0.0
MVOPN  1  3  H  2.8  0.16
MVOPN  2  1  H  2.8  0.16
MVOPN  1  4  H  5.0  0.16
MVOPN  2  6  H  5.0  0.16
MVDCT  1  2  0.5  0.2 0.002 0.0 1.0 0.0 1.0
MVDCT  5  6  0.5  0.2 0.002 0.0 1.0 0.0 1.0
MVFAN  2  3  0.0 500.0  11.70
MVFAN  4  5  0.0 500.0  11.70
INELV  1  2.8  2  2.8  3  2.8
INELV  4  5.0  5  5.0  6  5.0
```

MVOPN, MVDCT, MVFAN, INELV:
1) Fans require a duct segment on both sides for CFAST to calculate the species correctly.
2) Exhaust and supply flow rate should be 19,800-cfm (9.35 m^3/s)
3) Elevation of exhaust should be 4.0-m

The fan system should be as follows:

```
MVOPN 1  4  H  2.8  0.16
MVOPN 2  1  H  2.8  0.16
MVOPN 1  5  H  4.0  0.16
MVOPN 2  8  H  4.0  0.16
MVDCT 1  2  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVDCT 3  4  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVDCT 5  6  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVDCT 7  8  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVFAN 2  3  0.0 500.0 9.35
MVFAN 6  7  0.0 500.0 9.35
INELV 1 2.8  2 2.8  3 2.8  4 2.8
INELV 5 4.0  6 4.0  7 4.0  8 4.0
```

```
CEILI  CONCRETE
WALLS  CONCRETE
FLOOR  CONCRETE
CHEMI 16.0  10.0  2.0  24000000  298.  388.  0.
LFBO  1
LFBT  2
FPOS  -1.0 -1.0  0.0
FTIME 10.0  1012.0
FHIGH 3.0 3.0
FAREA 1.0 1.0
FQDOT 0.0 1.172e3 3000e3
CJET OFF
CO     0.14  0.14
OD     0.05  0.05
```

```
HCR    0.3    0.3
STPMAX  1.00
DUMPR   case5-2.hi
```

A.1.3 Scenario with Mechanical Ventilation (Exhaust Only) On

A representative original NRC input file (HAI Case5-3 [See Section A.3]) with mechanical ventilation (exhaust only) included is shown below with specific discrepancies as noted. The discrepancies identified in Section A.1.1 are present in the file below and are not repeated.

```
VERSN    3     St Lucie case 5-3 (Original NRC Input File) Exh. On
ADUMP case5-3.txt  NWS
DUMPR case5-3.hi
TIMES 3600  60  60  60  0
TAMB  298.0 101300.0  0.
EAMB  298.0  101300.0  0.
HI/F   0.0
WIDTH  20.72
DEPTH  14.94
HEIGH  5.48
HVENT  1  2  1   1.5  1.5  0.0
MVOPN  1  1  H  5.0  0.16
MVOPN  2  3  H  5.0  0.16
MVDCT  2  3  0.5  0.2 0.002 0.0 1.0 0.0 1.0
MVFAN  1  2  0.0 500.0  11.70
INELV  1  5.0  2  5.0  3  5.0
```

MVOPN, MVDCT, MVFAN, INELV:
1) Fans require a duct segment on both sides for CFAST to calculate the species correctly.
2) Exhaust flow rate should be 19,800-cfm (9.35 m^3/s)
3) Elevation of exhaust should be 4.0-m

The fan system should be as follows:

```
MVOPN 1  1  H  4.0  0.16
MVOPN 2  4  H  4.0  0.16
MVDCT 1  2  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVDCT 3  4  0.5 0.2 0.002 0.0 1.0 0.0 1.0
MVFAN 2  3  0.0 500.0 9.35
INELV 1 4.0  2 4.0  3 4.0  4 4.0
```

```
CEILI  CONCRETE
WALLS  CONCRETE
FLOOR  CONCRETE
CHEMI 16.0  10.0  2.0  24000000   298.  388.  0.
LFBO  1
LFBT  2
FPOS  -1.0 -1.0  0.0
FTIME 10.0  1012.0
FHIGH 3.0 3.0
FAREA 1.0 1.0
FQDOT 0.0 1.172e3 3000e3
CJET OFF
CO     0.14  0.14
OD     0.05  0.05
HCR    0.3   0.3
```

STPMAX 1.00

A.2 Partial CFAST Output Showing Impact of Insufficient Arguments on FHIGH, CO, OD, and HCF Commands

A partial output file (HAI Case 5-1 [See Section A.3]) is shown below indicating the effect of an insufficient number of arguments after the FHIGH, CO, OD, and HCN commands. The portion shown in bold-face font is the values used by CFAST for the simulation. Note that at 10-sec, the fire height is 3.0-m but at 453-sec it is relocated to 0.0-m. CFAST performs a linear interpolation between 10-sec and 453-sec. The same holds true for OD [C/CO2] which is 0.05 at 10-sec and 0.0 at 453-sec; HCR [H/C] which is 0.3 at 10-sec and 0.33 at 453-sec; and CO [CO/CO2] which is 0.14 at 10-sec and 0.0 at 453-sec.

```
**      CFAST  Version    3.1.7  Run  5/2/ 2          **
**                                                    **
**              A contribution of the                 **
** National Institute of Standards and Technology    **
**              Gaithersburg, MD  20899               **
**              Not subject to Copyright              **
**                                                    **
**        DOS/4GW Memory Manager Copyright (c)        **
**              Rational System, Inc (1993)           **

CFAST Version    3.1.7      St Lucie case 5-1  (NRCraw)

Data file is case5-1.in     (Checksum 00000000)


OVERVIEW


Compartments    Doors, ...    Ceil. Vents, ...    MV Connects

   1               1             0                    0

Simulation   Print      History    Restart
Time         Interval   Interval   Interval
(s)          (s)        (s)        (s)

  3600        60         60          0

Ceiling jet is off for all surfaces.
History file is case5-1.hi


AMBIENT CONDITIONS

Interior     Interior    Exterior     Exterior    Station    Wind    Wind         Wind
Temperature  Pressure    Temperature  Pressure    Elevation  Speed   Ref. Height  Power
(K)          (Pa)        (K)          (Pa)        (m)        (m/s)   (m)

  298.        101300.      298.        101300.      0.00      0.0     10.0         0.16


COMPARTMENTS

Compartment   Width   Depth   Height   Area     Volume    Ceiling  Floor
                                                          Height   Height
              (m)     (m)     (m)      (m^2)    (m^3)     (m)      (m)
-------------------------------------------------------------------------
    1         20.72   14.94   5.48     309.56   1696.37   5.48     0.00


VENT CONNECTIONS

Horizontal Natural Flow Connections (Doors, Windows, ...)

From         To           Vent    Width   Sill    Soffit  Abs.   Abs.    Area
Compartment  Compartment  Number          Height  Height  Sill   Soffit
                          (m)     (m)     (m)     (m)     (m)    (m)     (m^2)
----------------------------------------------------------------------------------
    1        Outside       1      1.50    0.00    1.50    0.00   1.50    2.25


There are no vertical natural flow connections


There are no mechanical flow connections


THERMAL PROPERTIES
```

```
Compartment    Ceiling      Wall         Floor
------------------------------------------------------------------------
   1            CONCRETE     CONCRETE     CONCRETE


Thermal data base used: THERMAL.DF

Name     Conductivity Specific heat     Density     Thickness  Emissivity              HCL B's (1->5)
CONCRETE      1.75         1.000E+03    2.200E+03    0.150        0.940       0.00E+00  0.00E+00  0.00E+00  0.00E+00
0.00E+00


TARGETS

Target Compartment    Position (x, y, z)          Direction (x, y, z)       Material
-------------------------------------------------------------------------------------

  1      1            7.47    10.36     0.00      0.00      0.00      1.00   CONCRETE  Floor, compartment  1


FIRES

Name: Main Fire

Compartment     Fire Type         Position (x,y,z)         Relative     Lower O2     Pyrolysis
                                                           Humidity     Limit        Temperature
  1             Constrained      7.47  10.36    0.00       10.0          2.00         298.

  Time       Fmass      Hcomb      Fqdot      Fhigh      C/CO2      CO/CO2     H/C        O/C        HCN        HCL
  (s)        (kg/s)     (J/kg)     (W)        (m)        (kg/kg)    (kg/kg)    (kg/kg)    (kg/kg)    (kg/kg)    (kg/kg)
-----------------------------------------------------------------------------------------------------------------------
    0.       0.00E+00   2.40E+07   0.00E+00    3.0       5.00E-02   0.14       0.30       0.00E+00   0.00E+00   0.00E+00
   10.       4.88E-05   2.40E+07   1.17E+03    3.0       5.00E-02   0.14       0.30       0.00E+00   0.00E+00   0.00E+00
 1012.       0.12       2.40E+07   3.00E+06   0.00E+00   0.00E+00   0.00E+00   0.33       0.00E+00   0.00E+00   0.00E+00
```

Time = 0.0 seconds.

A.3 CFAST Scenarios in this Analysis and Corresponding NRC CFAST Scenarios

The table below provides a cross-reference between the scenarios in this analysis and the specific NRC ventilation and heat release rate scenarios.

Table A-1. NRC-HAI CFAST Scenario Identification

Cable Area (m^2)	HRR (kW)	MV Exhaust/ Supply On	MV Exhaust On	MV Off
1	600	Case1-2	Case1-3	Case1-1
2	1,200	Case2-2	Case2-3	Case2-1
3	1,800	Case3-2	Case3-3	Case3-1
4	2,400	Case4-2	Case4-3	Case4-1
5	3,000	Case5-2	Case5-3	Case5-1
10	6,000	Case6-2	Case6-3	Case6-1

Appendix B. Models for Predicting Hot Gas Temperatures from Cabinet Fires

B.1 Spill Plume

These correlations were used to obtain temperatures within a plume rising out of a burning cabinet. The model input values are heat release rate ($\dot{Q}$ [kW]), plume width (W [m]), and surrounding gas temperature (T_o [°C]). The following equation was taken from NFPA 92B to calculate the height where the temperature reached the damage and ignition temperatures.

$$\dot{m} = 0.36(\dot{Q}W^2)^{1/3}(z_b + 0.25x_H) \text{ solving for } z_b \qquad \text{(B.1)}$$

$$z_b = \frac{\dot{m}}{0.36(\dot{Q}W^2)^{1/3}} - 0.25x_h \qquad \text{(B.2)}$$

where:

z_b = height of ignition or damage temperature in the plume (m)
$\dot{m}$ = mass flow rate of plume at z_b (kg/s)
$\dot{Q}$ = heat release rate of the fire (kW)
W = width of the plume set to the width of the cubicle (m)
x_h = plume depth inside cabinet (m), set to zero

The mass flow is calculated using the following equation:

$$\dot{m} = \frac{(1 - x_{rad})\dot{Q}}{(T_{avg} - T_o)C_p} \qquad \text{(B.3)}$$

where:

x_{rad} = radiative fraction
T_{avg} = average temperature of the plume at height z_b (°C), (ignition and damage)
T_o = surrounding room temperature (°C)
C_p = specific heat capacity of air (kJ/kg K)

The horizontal distance for damage and ignition temperatures in the plume were found using the following equation [Law and O'Brien, 1981]:

$$x_{max} = 0.6\left(\frac{z_b}{H}\right)^{\frac{1}{3}} + \frac{1}{3}H \qquad \text{(B.4)}$$

where:

H = height of the cabinet (m)
x_{max} = horizontal projection of the plume (m)

B.2 Plumes

Hot gases leaving some cabinets were modeled as plumes. The empirical correlations developed by McCaffery [1979] for plume gas temperatures were used to predict the gas temperatures within the plume,

$$\Delta T = \frac{21.6\dot{Q}^{2/3}}{(Z - Z_o)^{5/3}} \qquad \text{(B.5)}$$

where ΔT is the gas temperature difference with the surrounding gas (°C), $\dot{Q}$ is the heat release rate of the fire (kW), Z is the elevation above the base of the fire (m), and Z_o is the virtual source origin (m).

The virtual source origin, Z_o, was determined using the relation from Heskestad (1983),

$$Z_o = -1.02\,D + 0.083\dot{Q}^{2/5} \qquad \text{(B.6)}$$

where D is the diameter of the fire (m).

Appendix C. Optical Density of Smoke in a Fire Plume

The optical density of the smoke above a fire in the plume region was calculated to estimate when smoke detectors would alarm. From Ostman [1992], the smoke yield is:

$$Y = \frac{\sigma_f}{\sigma_s} \tag{C.1}$$

where, σ_f is the specific extinction area of smoke and σ_s is the specific extinction of soot per unit mass of soot. The value of σ_s is assumed to be a constant ranging from 7,600-12,000 while σ_f is determined through:

$$\sigma_f = \frac{2.31\ OD\ \dot{m}_t\ T\,\Delta H_c}{352.8\dot{Q}} \tag{C.2}$$

where, OD is the optical density (m^{-1}), $\dot{m}_t$ is the total mass flow rate of gas at the detector (kg/s), T is the gas temperature determined from Equation B.5, ΔH_c is the heat of combustion of the fuel (kJ/kg), and $\dot{Q}$ is the heat release rate (kW). Inserting (C.1) into (C.2) and solving for OD,

$$OD = 152.7\frac{\dot{Q}\,Y\,\sigma_s}{\dot{m}_t\,T\Delta H_c} \tag{C.3}$$

The total mass flow rate in the plume was calculated from empirical relations developed from McCaffery [1979],

$$\dot{m}_t = 0.124\dot{Q}\left(\frac{(Z - Z_o)}{\dot{Q}^{2/5}}\right)^{1.895} \tag{C.4}$$

where, Z is the elevation above the fire (m) and Z_o is the virtual source origin (m) determined from Equation B.6.

Using Equations C.3, C.4, B.5, and B.6, the heat release rate that will result in an OD exceeding the alarm threshold can be determined for prescribed soot and fire properties. Assuming a slow growing fire, the heat release rate can be used to determine the time at which the fire plume would cause a smoke detector to alarm.

Appendix D. Calculation of Heat Flux at Point of Fire Impingement

D.1 Approach

The heat flux from a fire to a tray located above the fire was calculated using empirical correlations and experimental data. The heat fluxes to the tray from a fire impinging on the tray are similar to those produced by a fire impinging on a flat ceiling. Two separate experimental studies were conducted to measure the total heat flux from small and large fires impinging on a ceiling. Kokkola (1989) conducted a series of experiments with propane gas fires up to 10.5 kW impinging on a ceiling. As shown in Figure D-1, heat fluxes as high as 60-70 kW/m² were measured when the unconfined flame length, H_f, is 1.5 times the distance between the fire and the ceiling, H. Tests with larger propane fires, up to approximately 200 kW, were conducted by Hasemi *et al.* (1995). Total heat fluxes measured at the point of impingement are shown in Figure D-2. The heat fluxes reach a plateau at approximately 90 kW/m² when the unconfined flame length, L_f, is 2-3 times the distance between the fire and the ceiling, H.

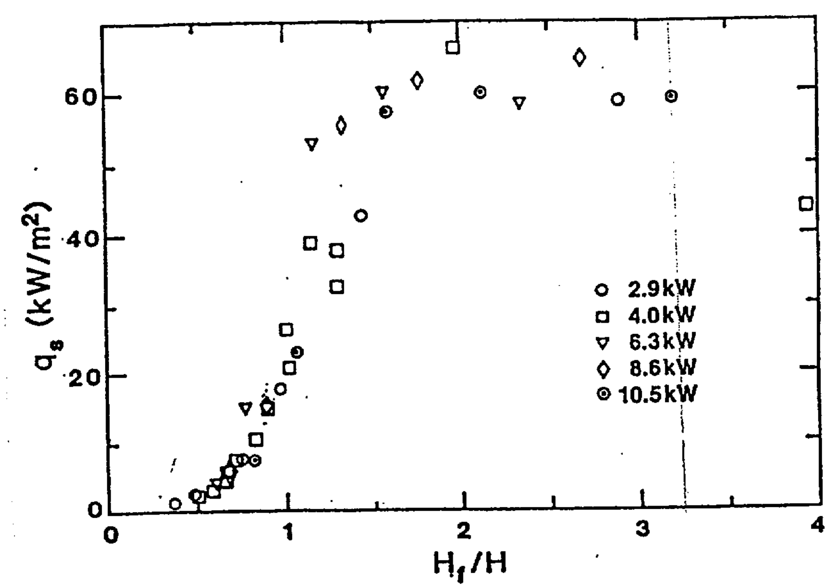

Figure D- 1. The heat flux where the fire impinges on a flat ceiling (Kokkala, 1989). Fire size up to 10.5 kW.

Figures D-1 and D-2 were used along with flame height correlations to estimate the heat flux to a cable tray in the fire tests conducted by Klamerus (1978) and from fires inside the cable spreading room. Both sets of heat flux data are normalized with respect to the unconfined flame height (i.e., flame height of a fire that is not impinging on a ceiling). The unconfined flame height was calculated using the correlation from Hasemi et al. (1995),

$$H_f = L_f = 3.5Q^{*n} D \qquad \text{(D.1)}$$

where,

$$Q^* = \frac{Q}{\rho_\infty T_\infty C_p g^{1/2} D^{5/2}} \qquad (D.2)$$

$n = {}^2/_5$ $\quad Q^* > 1.0$
$n = {}^2/_3$ $\quad Q^* < 1.0$

$\rho_\infty = 1.2\ kg/m^3$ (density of ambient air)
$T_\infty = 300$ K (temperature of ambient air)
$C_p = 1.0$ kJ/kgK (specific heat of air)
D = fire base diameter (m)

By calculating the unconfined flame height using Equations D.1 and D.2 and knowing the distance between the base of the fire and the tray, the total heat flux to the tray where the fire impinges was determined using Figures D-1 or D-2.

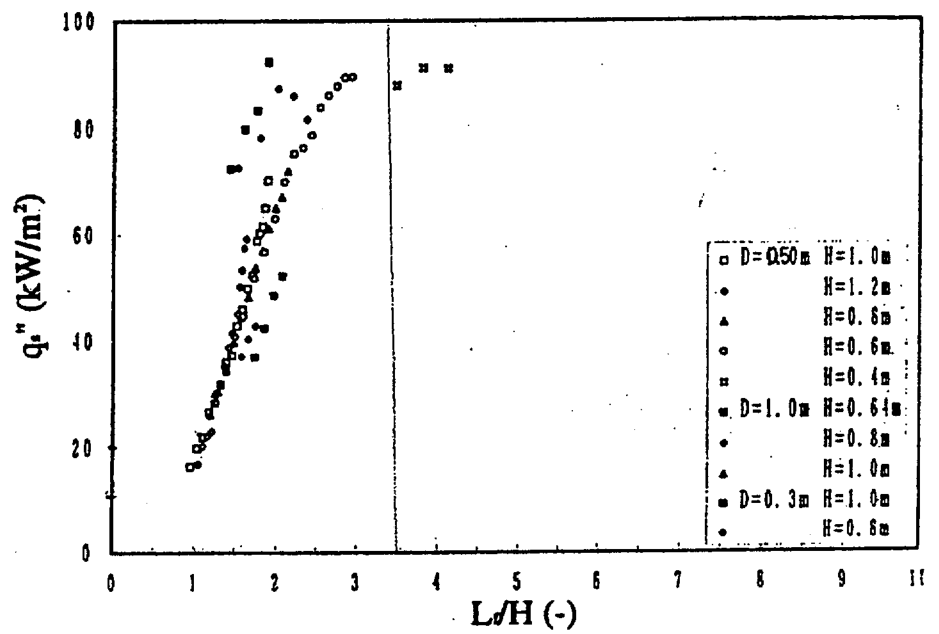

Figure D- 2. The total heat flux where a fire impinges on a flat ceiling (Hasemi, et al., 1995). Fire size up to approximately 200 kW.