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

FPL

May 15, 2002

L-2002-070
10 CFR 50.12
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 for
10 CFR 50 Appendix R K1 Exemption Clarification/Request

The March 5, 1987 NRC safety evaluation report (SER) for the St. Lucie fire protection features states that 25 feet of vertical separation exists between raceways containing redundant divisions of safe shutdown cables in the Unit 1 containment. The statement in the SER does not match the actual plant condition. On October 4, 2000, via FPL letter L-2000-164, Florida Power & Light (FPL) resubmitted exemption K1 to correct the discrepancy identified in the NRC SER for the St. Lucie Unit 1 containment building regarding vertical separation criteria.

Following discussions with the NRC staff, FPL supplemented that submittal with a risk-informed evaluation of exemption K1 via FPL letter L-2001-153, dated June 28, 2001. After additional discussions with the NRC staff, the risk informed approach was terminated and the NRC formally transmitted a request for additional information via NRC letter "Request for Additional Information Regarding the 10 CFR Part 50, Appendix R, Exemption Request K1 for the St. Lucie Plant, Unit 1 (TAC No. MB0300)," dated August 31, 2001. The FPL response to the NRC RAI superceded the information provided by FPL letter L-2001-153 and was submitted by FPL letter L-2001-267, dated November 29, 2001. Subsequently, the NRC staff had additional questions, and formally transmitted a request for additional information via NRC letter "St. Lucie Plant, Unit 1 - Request For Additional Information Regarding The 10 CFR Part 50, Appendix R, K1 Exemption Clarification/Request (TAC NO. MB0300), dated March 5, 2002. This letter provides the FPL response to the latest NRC RAI.

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

Very truly yours,

Donald E. Jernigan
Vice President
St. Lucie Plant

A006

DEJ/KWF

Attachment 1 -FPL Response to NRC RAI Dated March 5, 2002....................................6 Pages
Attachment 2 -Fire Hazard Assessment of Exposure to Safe Shutdown
Raceways at St. Lucie Plant [Hughes & Associates, 2002].......................230 Pages

FPL Response to NRC RAI Dated March 5, 2002

Following NRC review of FPL's November 29, 2001 RAI submittal, "Fire Hazard Assessment of Exposure to Safe Shutdown Raceways, St. Lucie Unit 1" the NRC staff determined that additional information and/or clarifications were needed. In the RAI, the NRC requested responses to the following questions:

NRC QUESTION 1

What is the "Factor of Safety" built into your evaluation conclusions? Provide the critical spacing for the base case.

FPL RESPONSE:

The critical separation distance was calculated and is provided in Table 9 of Section 8.5 of Attachment 2. Section 9 in Attachment 2 has a more complete discussion of safety factors.

NRC QUESTION 2

Figure 3 shows flamemastic coating only on the cable trays. Were the individual cables completely coated also?

FPL RESPONSE:

Section 3.1 of Attachment 2 was revised to be more specific.

NRC QUESTION 3

The IEEE Fire-Induced Vulnerability Evaluation (FIVE) final report, April 1992, utilizes a critical heat flux of 10 kW/m^2 for qualified cable and 5 kW/m^2 for non-qualified cable. Your evaluation utilized 11.7 kW/m^2 for qualified cable and 5.7 kW/m^2 for non-qualified cable from a 1991 IEEE report. Justify using the larger critical heat fluxes.

FPL RESPONSE:

This difference results from "rounding" by the FIVE report. From the April 1992 FIVE Report:

"For qualified cable, a value of 1 $BTU/s/ft^2$ (10 kW/m^2) is suggested for typical screening purposes. For unqualified cable, a value of 0.5 $BTU/s/ft^2$ (5 kW/m^2) is suggested for typical screening purposes."

In the conversion of $BTU/s/ft^2$ to kW/m^2, the values were rounded down. The actual conversion of $BTU/s/ft^2$ to kW/m^2 is as follows:

$$1.0\ BTU/s/ft^2 (1055\ W\text{-}sec/BTU)(10.76\ ft^2/m^2) = 11.4\ kW/m^2$$
$$0.5\ BTU/s/ft^2 (1055\ W\text{-}sec/BTU)(10.76\ ft^2/m^2) = 5.7\ kW/m^2$$

[Note that the evaluation utilized 11.4 kW/m^2, not 11.7 kW/m^2, for qualified cable.] Section 5 of Attachment 2 was revised to show the English and SI units.

FPL Response to NRC RAI Dated March 5, 2002 (Cont.)

NRC QUESTION 4

Worst Case Fire: The modeling used cable loading from Trays M100, C100, and C101 with a total fill of 26%. However, at Plan Point 2307, Trays M120 and C120, has a fill total of 29.3%. Justify why the location chosen is the worst case fire loading?

FPL RESPONSE:

The four-tier array at Plan Point 2305 was selected as the MEFS even though the three tier array has essentially the same target heat flux. For completeness, Plan Point 2305 and Plan Point 2307 have both been modeled and evaluated in detail. Sections 6.1, 6.3, 7.2, 8.1, and 8.2 of Attachment 2 were revised to address Plan Point 2307, Trays M120 and C120.

NRC QUESTION 5

A stacked vertical tray configuration was modeled, but the drawing on page 1 of Appendix A of Attachment 2 shows the cable trays in a side by side configuration. The vertical height is over nine feet and each tray is two feet wide giving the three trays a 54 ft^2 (5 m^2) surface area. The report models a 15-inch wide vertical fire at some undefined height, which doesn't seem to portray the actual configuration. In addition, wouldn't the fire grow horizontally on the lower and upper elevations at the same time? Justify in more depth the vertical cable fire scenario.

FPL RESPONSE:

Section 8.2.1 of Attachment 2 was revised to address the concerns identified above. The NRC question refers to the vertical cable tray run near reference point 2307. The geometry of this horizontal to vertical cable array transition was modeled more accurately and evaluated to determine whether it formed an alternative MEFS. The target cable location was the top tray of the horizontal running cable array, which consists of Trays M100, C100 and C101. This target is exposed simultaneously to nmb a burning length of horizontal and vertical cable tray array. The burning horizontal and vertical array is comprised of trays M120, C120 and L120. Tray L120 in the horizontal array is covered with sheet metal tray covers and does not contribute to the exposure fire in the horizontal position, which is consistent with the MEFS assumptions. All three trays in the vertical configuration are covered with sheet metal tray covers and if involved in a fire would not be expected to substantially contribute to the heat flux to the target. However for purposes of performing a screening calculation the vertical trays are assumed to burn as if they were uncovered and contribute to the flame radiation to the target. The calculated target flux in this arrangement is 3.94 kW/m^2. The calculated target flux for the MEFS for the "horizontal only" case is 3.81 kW/m^2. These are effectively the same results even assuming all three covered vertical trays contribute as if they were open. Clearly these covered trays would not substantially contribute to the heat flux to the target, hence we conclude that the "horizontal only" case is the MEFS.

NRC QUESTION 6

Ventilation within containment can be considerable. Equation (10) assumes no wind effects, but in actual conditions in containment mechanical ventilation produces wind- aided flame spread. Explain why the effect of wind was not considered in this analysis. How would it effect the burning characteristics of the cable trays, the flame propagation speed, the height and location of the fire plume in respect to the target cable tray, smoke detector response time, and the evaluation conclusions?

FPL Response to NRC RAI Dated March 5, 2002 (Cont.)

FPL RESPONSE (question 6):

Air velocity measurements were taken inside containment and Section 8.3 of Attachment 2 was added to address this question, with exception to smoke detector response. Since the measured air flow rates in Containment were relatively low, no significant affect on smoke detector response time is expected.

NRC QUESTION 7

Pages 3-207 to 3-210 in SFPE Handbook of Fire Protection Engineering, 2nd Edition 1995, provide a discussion and correlation to determine the emissive power of large, sooty hydrocarbon fires. For example, Figure 3-11.10, on page 3-208 illustrates that the emissive power for LPG pool fires is a non-linear function of the pool diameter. Based on the experimental data, the following correlation is provided to calculate emissive power of the fire, which is non-linear equation:

$$E_{av} = E_m e^{-SD} + E_s\left(1 - e^{-SD}\right)$$

Where
E_m = maximum emissive power of luminous spots (approximately 140 kW/m^2),
E_s = emissive power of smoke (approximately 20 kW/m^2),
S = a parameter determined using experimental data (0.12 m^{-1}), and
D = diameter of the pool fire (m).

On page 26 of 62 of the St. Lucie Fire Hazard Assessment, Equation (12) is provided to compute the emissive power of the source fire, which is a linear function of cable tray width.

$$E_s = \frac{\dot{Q}_R}{(2.X_s.F_h) + W_t} \qquad (12)$$

Where
E_s = emissive power of the source fire (kW/m^2),
$\dot{Q}_R$ = radiant energy release rate (kW),
X_s = maximum flame spread distance (m),
F_h = flame height from a line fire (m), and
W_t = width of the cable tray (m).

The units of emissive power are kW/m^2, which are not consistent in Equation (12) as:

$$E_s = \frac{kW}{m^2 + m}$$

Since emissive power is an important input to Equation (9) on page 26 of 62 to determine the radiative heat flux to the target (cables), explain why there is a basic difference between these two equations, i.e., linear and non-linear.

FPL Response to NRC RAI Dated March 5, 2002 (Cont.)

FPL RESPONSE (question 7):

The non-linear equation cited in question 7, and similar expressions for large hydrocarbon pool fires are empirical expressions which capture the exponential effect of the pool diameter, D and a parameter to describe the opacity or extinction coefficient of the flame, S, on flame radiation. This form of empirical expression for flame emissive power when used on liquid pool fires is generally linear for flame diameters between 1 m and 100 m in diameter depending on the extinction coefficient and path length correction factor. Similar expressions for flame emissivity are asymptotic at flame diameters greater than one to two meters. This analysis assumes a large diameter fire with a constant radiative fraction. This means that the emissive power is a linear function of energy release rate and that the emissivity is approximately constant. Hence the analysis submitted is consistent with the equations referenced by the NRC in question 7.

The approach taken in the St. Lucie evaluation assumes a large fire of sufficient diameter such that the radiative fraction is a constant fraction of the heat release rate as indicated in Equation 7 of the report. A constant radiative fraction of 0.4 is used in the analysis, which represents a high estimate of thermal radiation yield for large hydrocarbon pool fires, and is representative of the behavior of pool fires in the linear range of the non-linear equation in question 7. The analysis in effect does not credit the reduced path length of the flame geometry in a cable tray fire. The analysis assumes that the fires have a high radiative fraction representative of large turbulent optically thick flames. In addition, the sensitivity analysis given in section 9 is performed for radiative fractions of .3, .4 and .5 to illustrate the impact on the analysis.

Part of NRC question 7 refers to Equation 12 which is a linear expression for the emissive power or radiative heat release of a cable tray fire. A similar response holds for this question as well. The equation assumes a large thermally thick flame, which radiates at a constant fraction of the total energy release rate, representative of a large diameter pool fire. In addition, equation 12 as described in the updated report corrects the total radiative energy release rate by assuming that all of the radiation is emitted from the top and 4 sides of the burning cable tray array. This yields the radiation per unit area of the flame or emissive power, which can then be used in conjunction with the configuration factor to obtain the heat flux to a target.

The remaining part of question 7 concerns the units obtained in Equation 12. There was a typo in equation 12 in the report draft that has been corrected. The equation used in the calculations and editorially corrected in the current draft of the report yields the correct units of kW/m^2.

In summary, the apparent linear nature of the expressions used for radiative fraction are a consequence of the assumption that the flames in the analysis radiate at levels consistent with large diameter flames and where the exponential non-linear expressions are asymptotic or linear above some pool diameter.

Section 6.7 and 6.8 of Attachment 2 was rewritten and Section 8.1 of Attachment 2 was revised to clarify the derivation of these expressions.

FPL Response to NRC RAI Dated March 5, 2002 (Cont.)

NRC QUESTION 8

Table 3 on page 30 of 62 provides the incident heat flux calculation for the maximum expected fire scenario. Provide details for the calculation of $\dot{q}_r''$, including values of all variables, e.g., $F_{s\text{-}t}$, E_s, F_h, etc. Provide the Equation Number used to calculate the values of t_d and $\dot{q}_r''$.

FPL RESPONSE:

As addressed also in response to question 12, $\dot{q}_r''$ is the same as $\dot{q}''_t$. The equation number for $\dot{q}''_t$ is equation 9. Equation number used to calculate t_d is equation 4. The terminology was clarified in Section 6 of Attachment 2. The values requested for $F_{s\text{-}t}$, E_s, and F_h for the MEFS are provided in Section 8.1 and/or Table 4 of Attachment 2.

NRC QUESTION 9

Provide the Equation Number used to calculate Target Heat Flux in the last column of the Table [now Table 12] on page 45 of 62.

FPL RESPONSE:

See Equation 9 in Attachment 2.

NRC QUESTION 10

Provide the values of $W_{p.c}$ in Equation (2).

FPL RESPONSE:

Table 2 was added to Section 6.3 of Attachment 2 and the data is now provided in Appendix A of Attachment 2.

NRC QUESTION 11

Explain the difference between t_b in Equation (4) and t_{dur} in Equation (6).

FPL RESPONSE:

They are the same. Editorial corrections were made to Sections 6.4 and 6.6 of Attachment 2.

FPL Response to NRC RAI Dated March 5, 2002 (Cont.)

NRC QUESTION 12

Equation (9) estimates heat flux at a target, $\dot{q}''_t$, but Tables 5a through 5h provide calculations for $\dot{q}_r$ (kW/m^2). Explain the difference between these two heat fluxes.

FPL RESPONSE:

They are the same. Editorial corrections were made to Sections 6 (Equation (9)) and Tables 10a –10h and 11a-11h of Attachment 2 (formerly Tables 5a through 5h).

NRC QUESTION 13

The values from the SFPE Handbook appear to have been multiplied by 4 in Equation (10). Explain.

FPL RESPONSE:

Section 6.8 of Attachment 2 was revised to provide an explanation for the value used.

HAI Project # 6372

FIRE HAZARD ASSESSMENT OF EXPOSURE TO SAFE SHUTDOWN RACEWAYS, ST. LUCIE UNIT 1

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FIRE HAZARD ASSESSMENT OF EXPOSURE TO SAFE SHUTDOWN RACEWAYS, ST. LUCIE UNIT 1

1. Introduction

Exemption K1 accepted 7 ft horizontal and 25 ft vertical separation without radiant energy shields between redundant safe shutdown trains (cable trays) in containment. In a submittal dated October 4, 2000, Florida Power and Light Company (FPL) requested a revised (clarified) Exemption K1 that requires only 7 ft of horizontal separation (no vertical separation). FPL contended that the 25 ft vertical separation requirement was erroneously stipulated by NRC (an administrative error) due to a misinterpretation of past FPL's submittal(s) related to Exemption K1. On August 31, 2001 (following a phone conference on August 16, 2001), NRC requested additional information that supports a deterministic approach for resolving the issue identified in the October 4, 2000 FPL submittal.

As part of preparing a response to the August 31, 2001 NRC Request for Additional Information, Hughes Associates, Inc. was contracted by FPL to perform a fire hazard assessment/fire model of the area of concern. The fire hazard assessment was performed to demonstrate that 7 ft of horizontal separation without a radiant energy shield is adequate for the redundant cable trays located in the Unit 1 containment above and below the 45 ft elevation and between radial lines 2 and 6. The analysis employs methods and procedures in accordance with Appendix C of NFPA 805 [2001].

2. Scope

The specific scope of this assessment involves the space defined by the containment structure and the interior biological shield between radial lines 2 and 6. The width of this area is approximately 20 ft. The electrical raceways in this area are divided into two separate sections defined by the divisional assignment of circuits: system SA, MA, MC and system SB, MB, MD. The electrical raceways in the containment structure are arranged with 'system' SA raceways installed along the biological shield wall (inner wall of the area). The 'system' SB raceways are installed along the outer wall of the area. Between radial lines 2 and 6, raceways are installed to allow the routing of circuits around the containment structure at both 23 ft-0 in. and 45 ft-0 in. elevations.

3. Problem Geometry and Conditions

The space between the containment structure and the interior biological shield between radial lines 2 and 6 does not contain any significant fire exposure sources. An engineering walkdown conducted during refueling outage SL1-17 to identify potential fire ignition sources found a limited number of motor operated valves (MOVs) and electrical cabinets to be located in the area as defined in Section 3.2.

3.1 Cable Raceway Geometry

The trays are arranged in vertical stacks. The bottom tray in each stack is an instrumentation tray that is provided with a solid bottom and top cover. The circuits in the instrumentation trays are considered to be low energy circuits that are not potential ignition sources. The top tray in each stack also has a solid cover where exposed to overhead traffic (i.e., directly beneath a grating or opening). The top tray in each stack typically carries 480 VAC power circuits. Between the top and bottom tray are either one or two control circuit trays. All trays and exposed cable surfaces are coated with Flamemastic. For trays with one layer of cables, typical in this analysis, effectively all cable surfaces are coated.

In the area of interest, the system SA trays are arranged in two stacks as described above. One stack is located on the 23 ft nominal elevation with another located directly above it at the 45 ft nominal elevation. The highest tray on the 23 ft nominal elevation is at 42 ft-0 in. The lowest tray on the 45 ft nominal elevation is at 54 ft-2 in. A similar configuration exists for the system SB trays. The highest tray on the 23 ft nominal elevation is at 42 ft-0 in. The lowest tray on the 45 ft nominal elevation is at 57 ft-2 in. However, in the area between radial lines 5 and 6, the 'lower' stack of system SB trays transitions to the upper elevation via cable tray risers. The arrangement of these trays is shown in the Figures 1 and 2.

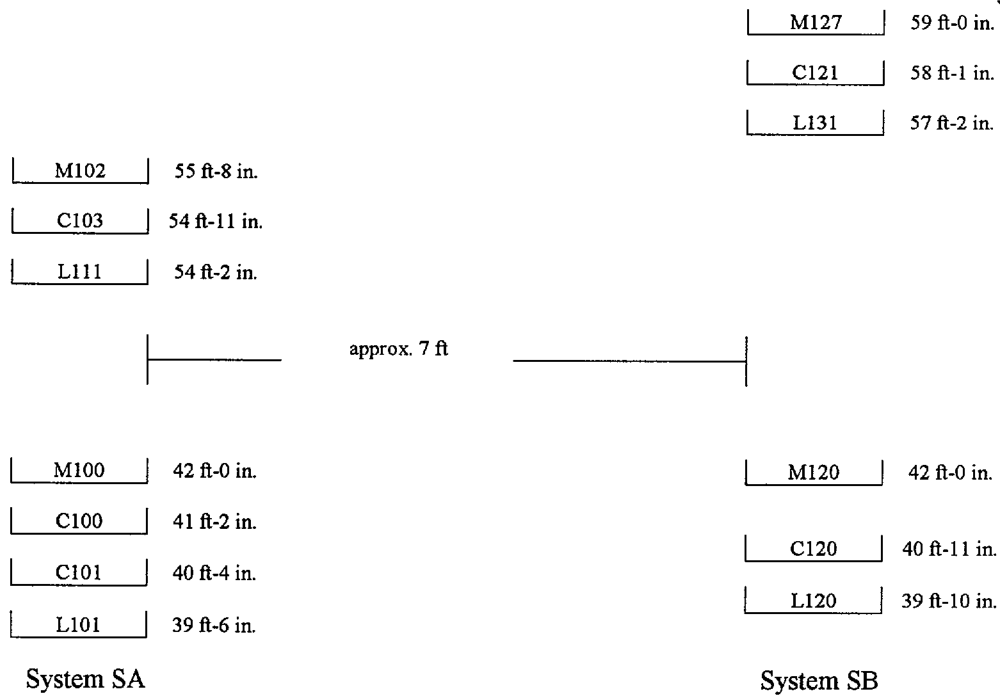

Figure 1 – Arrangement of trays between Radial Lines 2 and 5.5
(Systems SA and SB horizontal separation is 7 ft)
- not to scale -

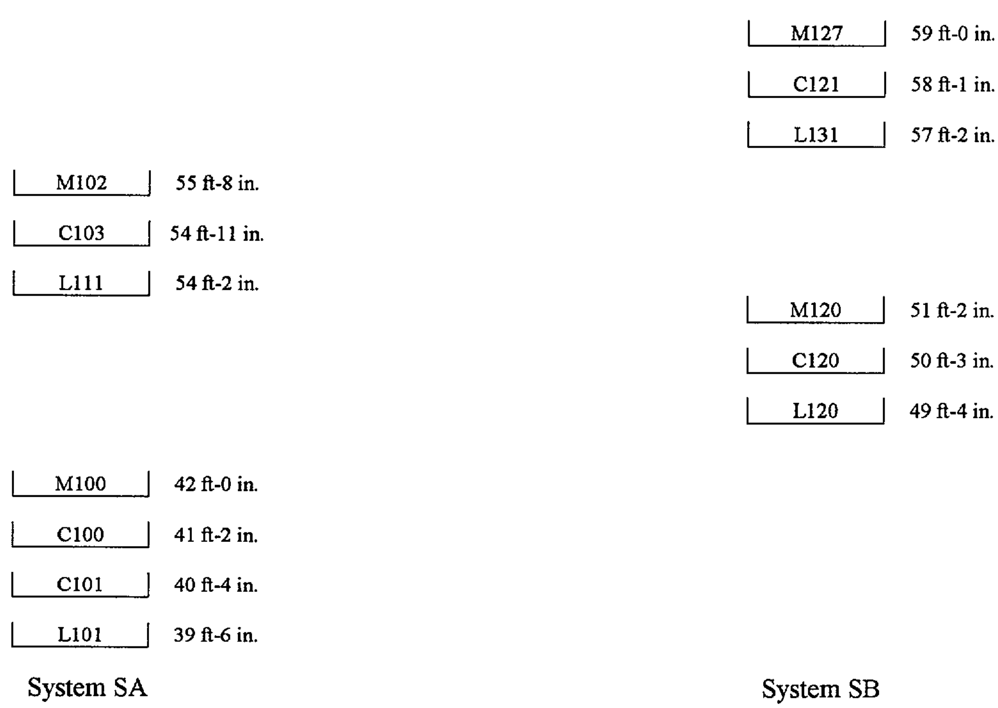

Figure 2 – Arrangement of trays between Radial Lines 5.5 and 6
(Systems SA and SB horizontal separation is 7 ft)
- not to scale -

The system SA and SB tray stacks are separated by a horizontal distance of approximately 7 ft. Based on these elevations, the key interactions distances are 12 ft vertically and 7 ft horizontally.

Postulated Fire Source	Target Distances			
	SA		SB	
	Vertical	Horizontal	Vertical	Horizontal
SA	-	-	15 ft-2 in. [1]	7 ft
SB	12 ft- 2 in. [1]	7 ft	-	-

Note 1: the vertical spacing distances are applicable only between column lines 2 and 5.5. Between column lines 5.5 and 6, the trays have limited vertical spacing, but maintain the 7 ft horizontal spacing.

The minimum 'available' vertical separation of the redundant systems of cable trays is about 12 ft with a horizontal separation of 7 ft. The configuration of this area involves grating that forms the nominal floor elevations at 23 ft-0 in., 45 ft-0 in., and 62 ft-0 in.

3.2 Walkdown Summary

A walkdown of the 23 and 45 ft elevations of containment was conducted on 04/7/2001 during SL1-17 to assess the potential ignition sources and combustibles available in the area from radial line 6 (immediately outside the penetration area) to radial line 2 [FPL, 2002]. Only one SB tray is routed past radial line 3 towards radial line 1.

Below are the detailed walkdown observations:

3.2.1 23 ft Elevation

At the 23 ft elevation, the A and B cable tray stacks are routed approximately 13 ft to 16 ft above the floor and generally follow the bioshield wall (system SA trays) and the outside/annulus wall (system SB trays). Between radial lines 1 and 3, a slab exists at the 45 ft elevation. The system SA trays end near radial line 2, two of three system SB trays end at radial line 3, and the third SB tray ends prior to radial line 1.

The ignition sources present above the 23 ft elevation (below the 45 ft elevation) are relatively small MOVs for the following:

Charging and auxiliary spray valves – I-SE-02-1, 2, 3, & 4;
Supply valves for RCP seal injection – MV-02-1 & 2; and
Safety injection tank 1B1 outlet valve – V3634.

The charging/auxiliary spray valves are located approximately 5 ft to 9 ft-6 in. above floor elevation, between radial lines 1 and 2, and below the slab. The system SB cable tray is located approximately 5 ft above and 3 ft offset from the charging/auxiliary spray valves; all system SA trays ended near radial line 2. The RCP seal injection supply and safety injection tank 1B1 outlet valves are located near the floor elevation. The system SA trays are located directly above these valves by approximately 13 ft. The valves/motors contain an insignificant quantity of grease and do not represent a hazard to either the system SA or SB trays. Electrical cabinets/boxes throughout the area do not contain openings or vents.

No exposed *in situ* combustibles are located between the cable tray stacks. The area between the tray stacks (below the 45 ft elevation grating) contains support steel, piping, conduit, etc. The area below the trays along the bioshield wall contains numerous instruments, tubing, cabinets, and transmitters. None of this equipment is considered a potential ignition source(s) for the cable trays because of the vertical separation. In various locations at the 23 ft elevation, Thermo-Lag 330-1 has been used as a radiant energy shield on conduit. In all cases, the Thermo-lag is encased in stainless steel sheet metal. Therefore, the Thermo-lag material in the radiant energy shields is not considered an intervening combustible.

3.2.2 45 ft Elevation

The A and B cable tray stacks are routed approximately 5 to 15 ft above the floor elevation and generally follow the bioshield wall (system SA trays) and the outside/annulus wall (system SB trays). The system SA trays end near radial line 2; the system SB trays end near radial line 3.

No major ignition sources are present above the 45 ft elevation (below the 62 ft elevation) with exception to four of the eight heater distribution bank panels (PP-124 through PP-131). The heater distribution bank panels are mounted on the bioshield wall and above the 41 ft elevation slab between radial lines 1 and 3. PP-124, PP-126, PP-127, and PP-128 are located approximately 4 feet below and 2 feet offset from the system SA cable trays. These distribution panels contain no openings or vents. The other four panels are located nearer to radial line 1 where no cable trays are present. The system SA trays are located above these panels between radial lines 2 and 3. At this location, the tray loading is significantly diminished since many cables have previously exited the trays.

The motor for the containment fan cooler CFC-1B is located between radial lines 1and 2 where no trays are routed. The system SA trays stop at radial line 2 while the system SB trays stop near radial line 3. The containment fan cooler and motor does not contain significant quantities of combustibles.

Between radial lines 3 and 5, the system SB trays (near the outside/annular wall) are routed directly above and within inches of a heavy gauge metal 3-ft wide HVAC duct. This duct will provide significant protection (heat shield) to the trays should a fire originate below. No exposed *in situ* combustibles are located between the cable tray stacks. The area between the tray stacks (below the 62 ft elevation grating) contains support steel, piping, conduit, etc. In various locations at the 45 ft elevation, Thermo-lag 330-1 has been used as a radiant energy shield on conduit. In all cases, the Thermo-lag material is encased in stainless steel sheet metal. Therefore, the Thermo-lag material in the radiant energy shields is not considered an intervening combustible.

The area below the system SA trays (bioshield wall) contains numerous instruments, tubing, cabinets, and transmitters. None of this equipment is considered a potential ignition source(s) to the cable trays because of the vertical separation. The bottoms of the safety injection tanks are at the 48 ft-4 in. elevation and the tops are well above the 62 ft elevation (~80 ft elevation). These relatively large diameter tanks (~9 ft-2 in. diameter each) are located between the system SA and SB trays and provide a significant amount of shielding above the 45 ft elevation. Considering the HVAC duct, the system SB trays are relatively well shielded from a fire below. The safety injection tanks provide significant shielding from the system SA trays. Where only spatial separation exists between the system SA and SB trays, no combustibles or ignition sources are present. As with the 23 ft elevation, electrical cabinets throughout the area do not contain openings.

3.2.3 Walkdown Conclusions

Potential ignition sources between radial lines 1 and 6 do not contain sufficient quantities of combustibles and are spatially separated such that there is no pathway to propagate a fire to other combustibles. No significant intervening combustibles are present between the system SA and SB trays on either elevation.

On the 45 ft elevation, the system SB trays are shielded for approximately 18 ft from the system SA trays by the safety injection tanks. If a fire occurred below the 45 ft elevation, the system SB trays are shielded from below by an HVAC duct from radial lines 3 to 5. The same HVAC duct is routed between the cable tray stacks from radial line 5 to 6.

The top tray in every stack is covered with a sheet metal top when located under grating or other areas subject to dirt and oil drippings; the cover extends approximately 3 ft beyond the hazard area (Reference drawing 8770-B-328, Sheet 5). All instrument (bottom) trays have solid bottoms. All trays are coated with Flamemastic.

4. Modeling and Calculations

The scenarios evaluated involve the ignition of one of the two raceway systems through some unspecified electrical fault, subsequent growth and spread of the fire along the initially involved set of cable trays, and calculation of the resultant radiant exposure to the uninvolved raceway set. Since the precise ignition, flame spread, and energy release rates of the cables involved are unknown, a range of values is evaluated. The cable tray conditions modeled are described in Section 6 based on the geometries described in Section 3. A typical cross-section of a four-tier cable tray array is shown in Figure 3. Some locations consist of three-tier cable tray arrays. Reference point locations are provided in PSL-FPER-01-052, Rev. 1 [FPL, 2002].

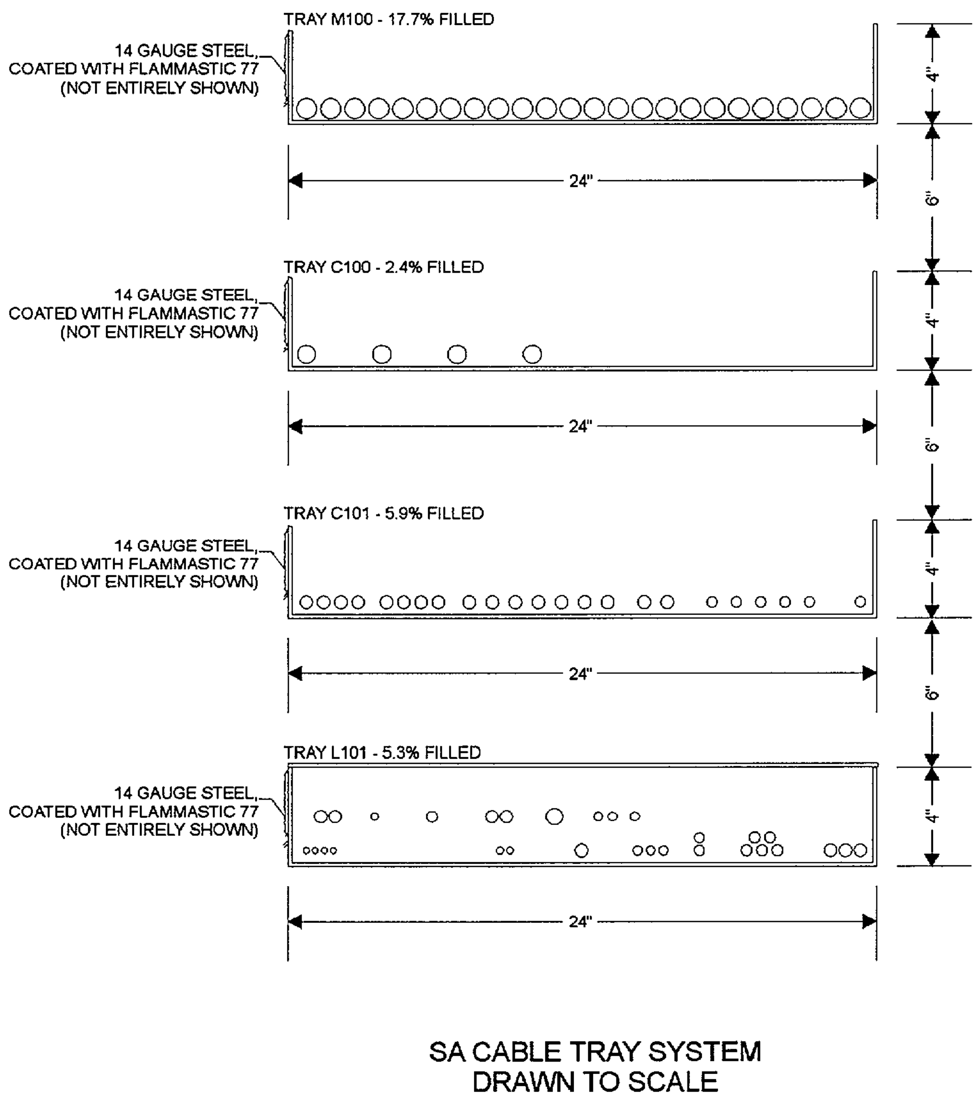

Figure 3 – Schematic diagram of the SA cable tray array at Reference Point 2305

Once ignited, the flame is assumed to travel at a fixed horizontal spread rate in two directions. The number of cable trays involved varies between two and four. The fire spreads from the point of origin to a maximum distance determined by the spread rate and burning duration (see Figures 4a-4d for a depiction of a fire in a four-tier cable tray array). The burning duration is determined by the fuel loading and the energy release rate. The flame geometry is then fixed by the length of trays burning and the flame height. This flame then radiates energy to the target trays located 7 ft away horizontally. The calculations used to estimate the spread and thermal radiation levels are detailed in Section 6.

In addition to the horizontal cable tray array scenario, a combination of a horizontal and-vertical cable array system was considered. The vertical flame spread is assumed to be instantaneous. The analysis that demonstrates that the corresponding horizontal cable tray (only) fire scenario poses a higher exposure threat to the target cable tray as summarized in Section 8.2.1.

The radiant exposure to the horizontally separated safe shutdown system is calculated for the maximum flame spread distance. Beyond the maximum burning duration, the fire at the point of ignition begins to burn out due to fuel consumption.

This calculation is done across a range of horizontal spread rates and heat release rates. The flux calculated is the steady state radiation from a thick line flame of fixed length. The calculated flux and cable surface temperatures are compared to critical flux and temperature levels for both IEEE 383 qualified and unqualified cable as detailed in Section 9.

Section 8 presents results for the Maximum Expected Fire Scenario. The sensitivity analysis of this base case and resulting limiting fire scenarios are given in Section 9.

Section 10 is a calculation of the quantity of additional cable that could be placed in the raceway systems under certain conditions. The results of the analysis conducted are compared with the analogous calculations using the FIVE Methodology.

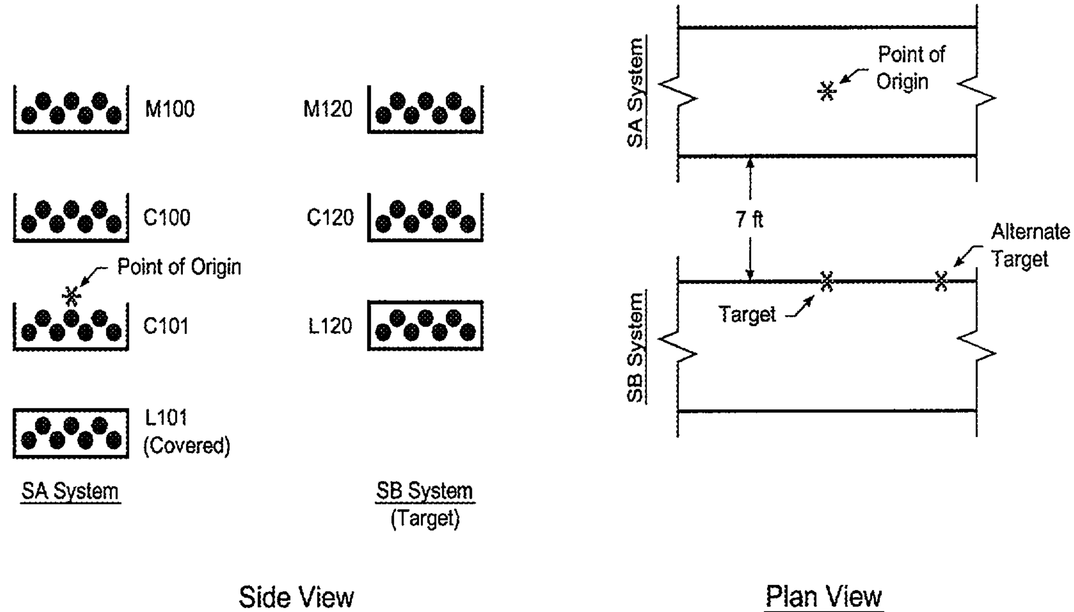

Figure 4a – Ignition of four-tier cable tray array (Reference Point 2305)

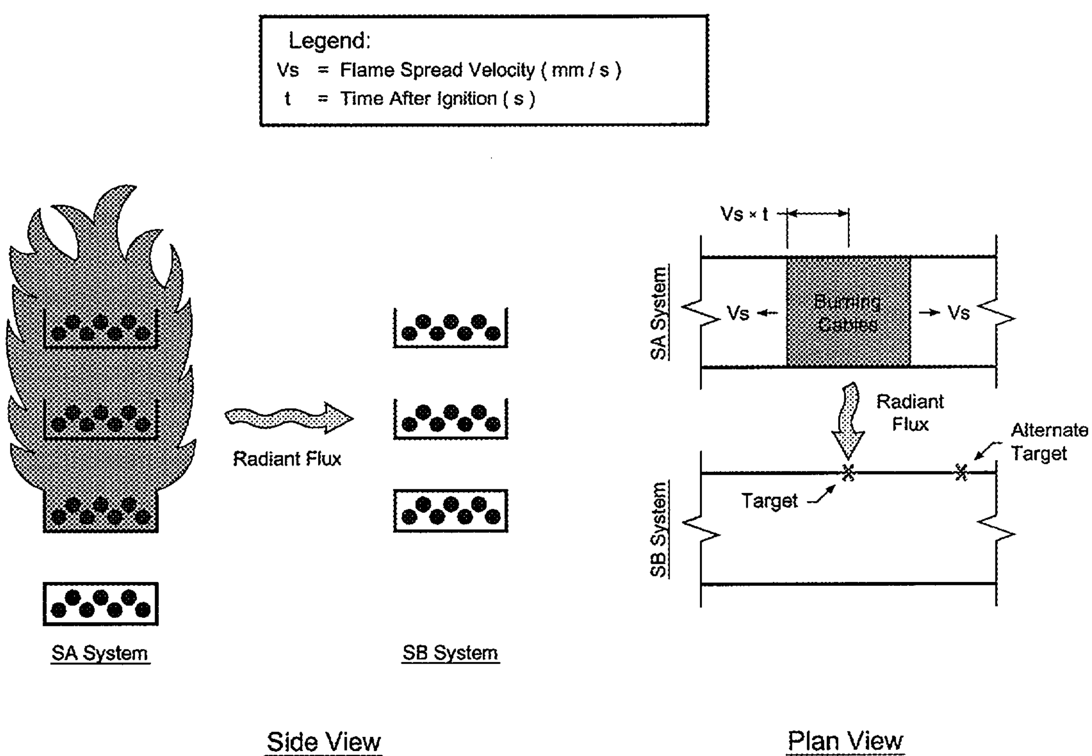

Figure 4b – Initial fire growth in four-tier cable tray array (Reference Point 2305)

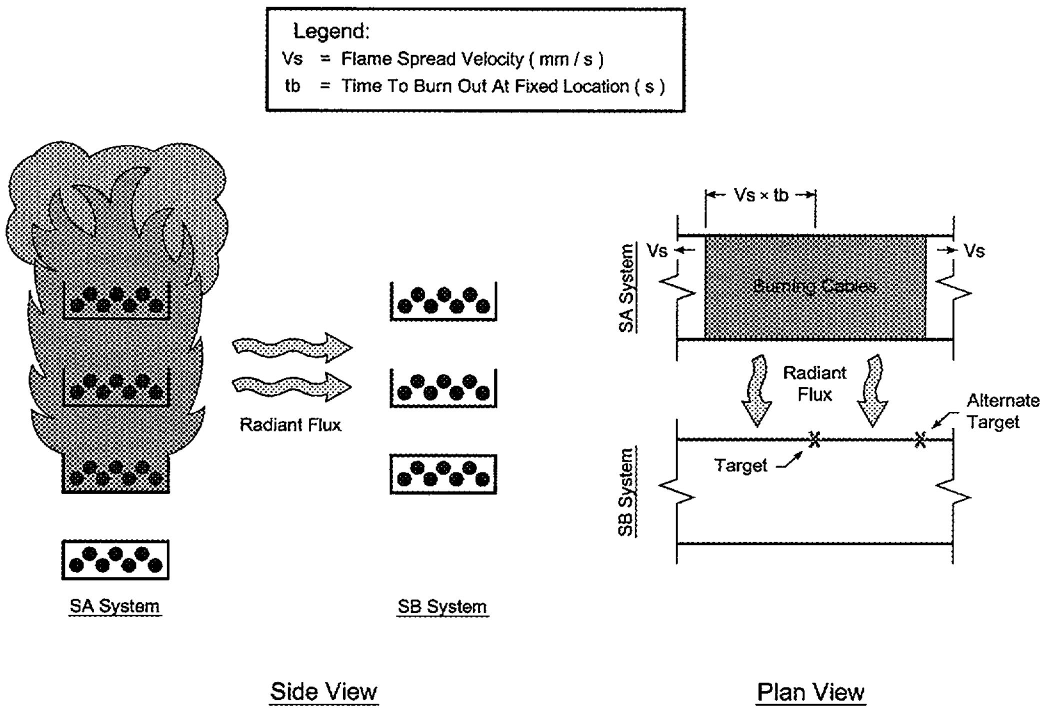

Figure 4c – Four-tier cable tray array fire at a maximum single fire size (Reference Point 2305)

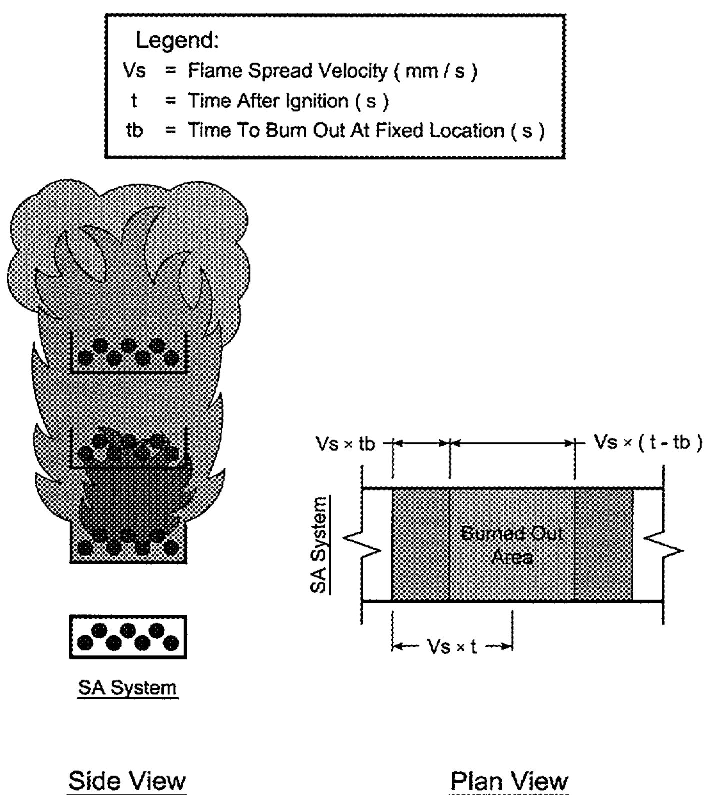

Figure 4d – Four-tier cable tray array fire after burnout occurs (Reference Point 2305)

5. Failure Criteria

Three failure criteria are used in this report, for both IEEE 383 qualified and unqualified cables. Two failure temperatures and critical incident heat fluxes are taken from EPRI references and used in the FIVE Methodology [ERPI, 1991] and are generally accepted as conservative values. The third "critical steady state heat flux" relates these baseline values to the geometry under consideration by accounting for radiative, convective, and conductive losses, for the particular geometry under evaluation. The critical steady state heat flux is calculated in Section 12, and is only used to demonstrate additional conservatism in the analysis when comparing calculated results to the critical temperature and incident heat flux values used.

The failure criteria used in this report are as follows:

1. IEEE 383 qualified cables
   a. Failure temperature of 371°C [EPRI, 1991], and
   b. Critical incident heat flux of 11.4 kW/m^2 which is a direct conversion from 1.0 $Btu/s\text{-}ft^2$ [EPRI, 1991];

2. Non-IEEE 383 qualified cables
   a. Failure temperature of 218°C [EPRI, 1991], and
   b. Critical incident heat flux of 5.7 kW/m^2 which is a direct conversion from 0.5 $Btu/s\text{-}ft^2$ [EPRI, 1991].

The analysis takes credit in some scenarios (exceeding the Maximum Expected Fire Scenario) for the ability of the coating to increase the damage threshold to a level consistent with IEEE 383 qualified cables (11.4 kW/m^2 flux/371 °C temperature for IEEE 383 versus 5.7 kW/m^2 flux/218 °C temperature for non-IEEE 383 cables). This is justified following the data of Klamerus and the conclusion that in all cases coated nonqualified cables yielded improved performance over the IEEE 383 qualified cables [Klamerus, 1978]. In tests involving two 40 percent fill cable trays subject to a gas burner exposure, the time to damage for the coated nonqualified cables (as measured by a short circuit) exceeded by a factor of two (14 minutes v. 7 minutes) those of the IEEE qualified cables. Further, there was no flame propagation from the lower to the upper cable tray for the Flamemastic coated cables while propagation occurred for the qualified cable.

This analysis assumes that the Flamemastic coated cables have damage thresholds equivalent to IEEE 383 qualified cables. While the assumption of a damage threshold equivalent to IEEE 383 qualified cables is justified as described above, in many cases, the damage threshold for unqualified cables is not exceeded, particularly when a transient thermal analysis is performed.

6. Horizontal Cable Fire Spread and Thermal Radiation Tray Model Description

The incident heat flux is calculated using several aspects of the assumed flame spread, the geometry, and test data. Each component of the model is described below. Figures 4a through 4d depict the various stages of the multi-tiered cable tray fire growth.

6.1 Specific Assumptions

The analysis method described in this section is subject to certain cable loading and geometry conditions. The individual trays within the SA and SB systems are vertically separated by 0.3 to 0.6 m (1 to 2 ft). All cable trays are 0.6 m (2-ft) wide [FPL, 2002]. The bottom tray is fully enclosed with galvanized steel; the top tray is enclosed only where there is overhead traffic.

The elevation of the SA and SB systems relative to each other is variable; the minimum horizontal separation is 2.1 m (7 ft).

The four-tier (SA) cable tray system considered in this analysis is shown in Figure 3. The array consists of the following individual cable trays (Reference Point 2305) [FPL, 2002]:

- M100, 17.7 percent filled, 42 ft elevation, partially covered;
- C100, 2.4 percent filled, 41.2 ft elevation;
- C101, 5.9 percent filled, 40.3 ft elevation; and
- L101, 5.3 percent filled, 39.5 ft elevation, fully covered.

The three-tier (SB) cable tray array considered in this analysis consists of the following individual cable trays (Reference Point 2307) [FPL, 2002]:

- M120, 20.4 percent filled, 42.0 ft elevation;
- C120, 8.9 percent filled, 40.9 ft elevation; and
- L120, 8.2 percent filled, 39.8 ft elevation, fully covered.

These sections represent the most heavily loaded portions of the SA and SB tray systems and are thus most conservative for use in this evaluation. The individual cable tray constituents of the SB cable tray system are not material because they are the assumed targets.

All combustible portions of the outer cable jacket are treated as black Polyvinyl Chloride (PVC). The conductor insulation material is either black PVC, cross linked polyethylene (XLPE), or polyethylene (PE). The middle trays are filled 2 and 10 percent respectively; the top tray is filled about 16-21 percent [FPL, 2002]. The bottom tray is not considered because there is no credible heating mechanism.

The material properties for the PVC, XLPE, and the PE insulation and jacket materials that are of importance to this analysis are the density and the heat of combustion. Table 1 summarizes these parameters [Babrauskas, 1997; Babrauskas and Grayson, 1992; Johnson, 1994].

Table 1. Material Properties of Cable Jacket and Insulation Materials

Material	Density (kg/m^3)	Heat of Combustion (kJ/kg)
PVC	1,441	17,950
XLPE	924	23,800
PE	924	46,500

The combustible energy load within the cable trays was determined using the material properties and the cable loading Tables and cable dimensions that were provided by the facility. Refer to Appendix A for a summary of the cable energy load calculations. PSL-FPER-01-052, Rev. 1 contains the detailed calls loading information [FPL, 2002]. The energy load for each of the cable trays in the four-tier SA system is as follows:

- M100 - 73,390 kJ/m;
- C100 - 16,140 kJ/m;
- C101 - 38,200 kJ/m; and
- L101 - 42,680 kJ/m.

The energy load for each of the cable trays in the three-tier SB system is as follows:

- M120 - 89,180 kJ/m;
- C120 - 36,770 kJ/m; and
- L120 - 55,180 kJ/m.

The peak steady state incident heat flux is estimated under the assumption that the fire originates at a single point and spreads away from the ignition location in two directions. The peak incident heat flux occurs when the fire has spread farthest from the point of origin, but before any portion of the tray has become depleted of combustible fuel.

The source fire is treated as a line fire with a base positioned at the lowest burning cable tray. This assumption results in the most conservative (greatest) radiant heat flux exposure to a target cable tray when compared to a pool fire type fire exposure.

6.2 Flame Height

The flame height from a line fire is given by the following equation [Tu and Quintiere, 1991]:

$$F_h = 0.042\,\dot{q}'^{\,2/3}_{tot} \qquad (1)$$

where $\dot{q}'_{tot}$ is the heat release rate per unit length of the entire cable tray system (kW/m).

6.3 Heat Release Rate

The heat release rate per unit length of the cable tray system is a function of the plan area of the cables as follows:

$$\dot{q}'_{tot} = \dot{q}''_{fs} \cdot W_{p,c} \qquad (2)$$

where $\dot{q}''_{fs}$ is the full-scale single cable tray heat release rate (kW/m^2) and $W_{p,c}$ is the maximum plan width of the cables (m). The plan width is equal to the sum of all individual cable outer diameters or 0.61 (the actual cable tray width), which ever is smaller. Appendix A summarizes the calculations for the cable tray arrays, including the plan width of the individual cables. Table 2 summarizes the total plan width of the cables for the reference points under consideration.

Table 2. Plan Width of Cables in Three- and Four-Tier Cable Tray Arrays Considered

Tray System	Reference Point	Number of Trays	Tray ID	Width, $W_{p,c}$ (m)
SA	2305	4	M100	0.502
			C100	0.075
			C101	0.283
			L101	0.367
SB	2307	3	M120	0.61
			C120	0.294
			L120	0.388

The full-scale heat release rate per unit area is determined using the equation [Lee, 1985]:

$$\dot{q}''_{fs} = 0.45 \cdot \dot{q}''_{bs} \qquad (3)$$

where $\dot{q}''_{bs}$ is the heat release rate per unit area measured at an incident heat flux of 60 kW/m^2 in a bench-scale (Cone Calorimeter) apparatus.

6.4 Burning Duration

The burning duration at a single point is in direct proportion to the quantity of combustible material available and the burning rate. The following equation is used to determine the burning duration:

$$t_d = \frac{Q'}{\dot{q}'_{tot}} \qquad (4)$$

where t_d is the fire duration at a specific location (s), and Q' is the energy load of the cable tray system (kJ/m).

6.5 Spread Rate

Evidence suggests the spread rate in cable tray fires is a function of the bench-scale heat release rate [Lee, 1985]. Lee [1985] correlated bench-scale data to moderate-scale tests in terms of an *area* spread rate for a single cable tray *array*. The cable tray array contained six tiers or two cable trays. Each individual tray within the array was 0.46 m wide [Sumitra, 1982].

As noted by Lee [1985], the correlated area spread rate is valid "...only to [for] cable tray arrangements, cable packing densities, and exposure fires similar to those tested by Sumitra."

The arrangement of the SA cable tray system is considerably smaller than those that were tested. Consequently, some modification to the Lee [1985] methods is required before the test results can be applied to the configuration at hand.

There are two key assumptions, both of which would tend to produce an overestimate of the flame-spread rate in the SA system. The first addresses the significance of the cable packing density. The packing density of the Sumitra tests was on the order of 40 percent [Sumitra, 1982; Lee, 1985]. The maximum packing in any of the cable tray arrays is about 20 percent, with many trays having a packing density as low as 2-5 percent. In fact, only one cable tray (M120) has a sufficient number of cables to uniformly cover the entire width of a single cable tray. The assumption made in this analysis is that the flame-spread rate in a sparsely packed cable tray would not significantly change from that of a moderately packed cable tray. It is expected that a sparse cable layout would tend to slow or limit flame spread because of gaps between the combustible material and other localized effects. The assumption is thus conservative.

The second assumption is that the flame spread rate calculated using the Sumitra data would over predict the flame spread rate because there is no pool fire ignition source assumed in the SA cable tray system. Sumitra [1982] used a 0.45 m (1.5-ft) by 0.91 m (3-ft) wide heptane pool fire below the cable tray array as an ignition source. Such a source undoubtedly has a major impact on the maximum flame spread as well as the flame-spread velocity. Ignoring the impact of the ignition source clearly imparts conservatism to the analysis.

Given the above assumptions, the correlation derived by Lee was modified using the actual test observations by Sumitra [1982]. Sumitra noted the number of trays involved before the onset of suppression for each test. This information, along with the burn area at the time suppression as determined by Lee [1985] was used to calculate the actual flame spread rate. Figure 5 shows the flame-spread rate versus bench-scale heat release rate along with a linear curve fit. The following correlation was obtained from the linear curve fit:

$$v_s = (7.55E-3)\cdot \dot{q}''_{bs} - 1.25 \qquad (5)$$

where v_s is the area spread rate (mm/s).

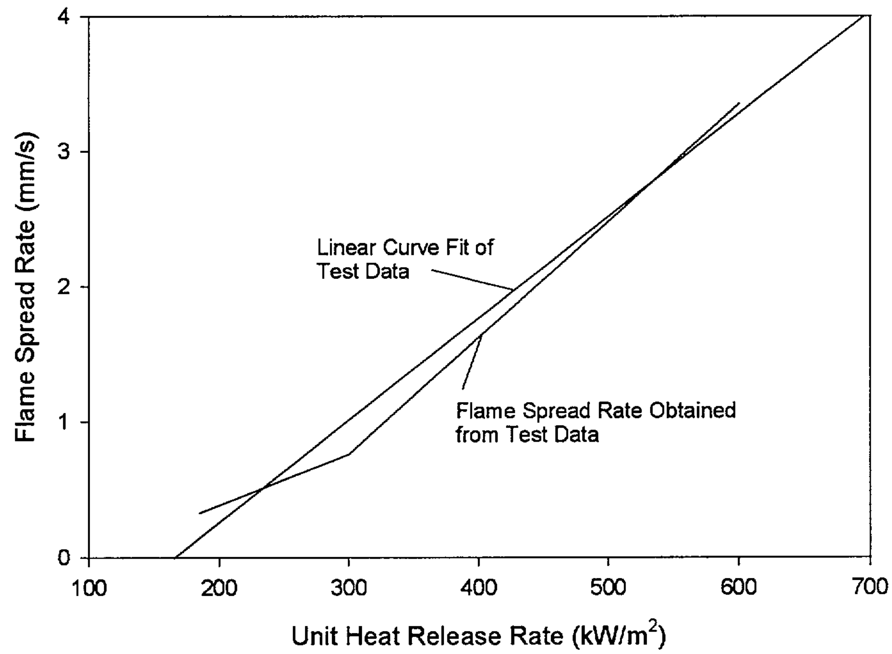

Figure 5 – Flame spread rate as a function of unit heat release rate

The flame spread velocity as calculated using Equation 5 was compared to other test data on cable trays and cable fires for validity. Factory Mutual researcher's observations indicate that the horizontal spread velocity in a communications cables is about 0.63 mm/s for a three-tiered cable tray arrangement [Tewarson *et al.*, 1993]. Investigations of a power cable fault fire [FTIC, 1989] concluded that the spread velocity in these cables was about 2 mm/s. Vertical cable trays with various types of cables have been shown to have a flame spread rate between 2 mm/s and 7 mm/s [Tewarson and Kahn, 1988]. Thus, the flame-spread rate is expected to lie between 0.63 mm/s and 7-mm/s, which is nearly the case for Equation 5.

Test data on vertical cable tray tests indicates that the flame-spread rate in cables is sensitive to the packing density [Hasegawa *et al.*, 1983]. Hasegawa *et al.* [1983] found that cable trays with a packing density of 25 percent had a 50 percent or greater reduction in the flame spread rate. The cable trays that are under consideration have a maximum packing density of about 20 percent and may be as low as 2 to 6 percent filled. Figure 3 shows a scaled drawing of the three open cable trays in the four-tier arrangement (M100, C100, and C101), indicating how sparse the packing actually is. While this effect is not explicitly accounted for in this analysis, it is worthwhile to note because it introduces an element of conservatism.

6.6 Spread Distance

The maximum flame spread distance from the point of origin in one direction is

$$X_s = t_d v_s \qquad (6)$$

where X_s is the distance the flame spreads from the origin before the onset of burnout (m). Note that the total spread distance is *twice* this value because it is assumed that flame spread occurs in two directions.

6.7 Radiant Heat Release Rate

The fraction of total energy released in a fire that is released as radiation is Π_r, the radiative fraction, and depends on the fuel and the size of the fire. Most materials have a radiant fraction between 0.2 and 0.4 [Tewarson, 1995]. This analysis assumes a value of 0.4; a conservative upper bound of 0.5 is also used for comparison.

The radiant heat release rate is thus

$$\dot{Q}_r = \chi_r \dot{Q} \qquad (7)$$

where $\dot{Q}_r$ is the radiant heat released (kW) and $\dot{Q}$ is the total heat released (kW). The total heat release rate is easily determined from the width of the cable tray and the maximum flame spread length as follows:

$$\dot{Q} = \dot{q}''_{fs} \cdot W_{p,c} \cdot (2 \cdot X_s) \qquad (8)$$

where terms defined as before are:

$\dot{q}''_{fs}$ = full-scale heat release rate (kW/m^2) (Equation 3)

$W_{p,c}$ = maximum plan width of the cables (m) (Equation 2)

X_s = maximum flame spread distance (Equation 6)

6.8 Incident Heat Flux to Target

The peak heat flux exposure from one burning tray to the exposed side of another tray is calculated from the estimated emissive power of the burning cable tray. The heat flux at a point target is given by the following equation:

$$\dot{q}_t'' = F_{s-t} E_s \tag{9}$$

where $\dot{q}_t''$ is the incident heat flux at the target (kW/m^2) (SB cable tray system), $F_{s\text{-}t}$ is the radiation shape factor between the source fire and the target, and E_s is the effective average emissive power of the source fire (kW/m^2).

Because the relative elevation of the trays varies, the worst-case incident flux location occurs when there is some part of the SB system directly across from the horizontal and vertical centerline of the rectangular SA system flame. The configuration factor for this case is as follows:

$$F_{s-t} = \left(\frac{2}{\pi}\right)\left\{\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right\} \tag{10}$$

with

$$X = \frac{0.5 \cdot F_h}{S} \qquad Y = \frac{X_s}{S} \tag{11}$$

where F_h is the flame height (m), S is the cable tray separation (2.1 m), and X_s is the maximum flame spread length from the point of origin in either direction (m). Equation 10 was derived from the shape factor equation for a point target located directly across from the corner of a rectangular emitter [Tien *et al.*, 1995]. When the half-flame height and half-flame length are used as input parameters, the total shape factor is four times the result obtained using the Tien *et al.* [1995] equation, and the result is Equation 10.

The effective average emissive power of the source fire is then calculated assuming that the radiant energy is emitted from the flame sides and from the top of the cable tray. The following equation is used:

$$E_s = \frac{\dot{Q}_R}{2 \cdot \left(2 \cdot X_s \cdot F_h + X_s W_t\right)} \tag{12}$$

where W_t is the width of the top cable tray (m).

The effective average emissive power is the heat flux per unit area that the source fire emits as radiation over the entire surface of the flame. It takes the total energy released as radiation $\dot{Q}_r$, and emits it from all sides and the top of the flame. The effective average emissive power is less than the peak emissive power. The effective average emissive power is used instead of the peak emissive power to prevent the model from violating the conservation of energy constraint, i.e., the total available energy radiated, $\dot{Q}_r$, is not exceeded. The effective emissive power may be estimated from the fraction of energy released as radiation and the assumed shape of the flame.

7. Parameters

There are four parameters that have a significant impact on the results of the incident heat flux calculation, described in Section 6:

- The bench-scale heat release rate per unit area, $\dot{q}''_{bs}$;
- The number of cable trays involved in the fire;
- The linear flame spread velocity; and
- The radiant heat release rate fraction.

7.1 Bench-scale Heat Release Rate

The bench-scale heat release rate is a measured value that is generally between 88 and 963 kW/m^2 for cable jacket and insulation materials [Lee, 1985; EPRI, 1991]. The bench-scale heat release rate for most cable materials is between 184 and 530 kW/m^2. The average bench scale heat release rate for non-IEEE cables per the FIVE methodology is 423 kW/m^2 [EPRI, 1991]. Values between 200 and 1,000 are assumed in this analysis. Fire propagation in materials with a lower unit heat release rate is questionable, as evidenced by the correlation developed by Lee [1985] using data obtained by Sumitra [1982].

Document PSL-FPER-01-052, Rev. 1 [FPL, 2002] contains a listing of the type and location of the cables in the general area. The dominant types of cables in the SA tray array considered in this analysis are the following:

- PVC/XLPP: Polyvinyl chloride and cross-linked polyethylene;
- PVC/XLPPP: Polyvinyl chloride and thermosetting polyethylene; and
- PVC/XLPN: Polyvinyl chloride and flame resistant thermosetting polyethylene.

There are lesser quantities of various types of signal cables, coaxial cables, and low power cables.

Most cables considered in this analysis have PVC outer jackets and XLPE insulation. The heat release rate for these types of materials is varied. EPRI [1991] reports values for PE/PVC cable between 312 kW/m^2 and 589 kW/m^2. Cables that contain nylon, PVC and PE are reported to have a unit heat release rate of 212-263 kW/m^2 [EPRI, 1991]. Table 3 summarizes the range of values reported for cables that contain PVC and PE materials. Note that the unit heat release rate is sensitive to the exposure heat flux. The heat flux can vary considerably; however, a typical value is between 50 and 75 kW/m^2. Most of the heat release rate data was obtained using a 60 kW/m^2 or 75 kW/m^2 exposure flux.

Table 3 indicates that most cables with PVC have a unit heat release rate less than 400 kW/m^2. The bulk of the test data suggests that the heat release rate is on the order of 200-300 kW/m^2 even for materials that are not fire retardant. Thus, a maximum expected fire scenario value of 400 kW/m^2 is conservatively assumed in this evaluation.

7.2 Number of Cable Trays Involved

The maximum number of cable trays in close proximity (less than 1.2 m (4 ft) vertical separation) is four in the SA system and three in the SB system. The bottom cable tray is enclosed. However, there is no credible mechanism to heat the bottom tray such that the cables pyrolyze and contribute fuel to the fire. The worst case scenario in a bottom tray would involve an internal cable fire that heats the metal, which then radiates to the surroundings. This scenario would be bounded by an open fire in the trays located above. Hence, the bottom tray is not included in the maximum expected fire scenario. The maximum number of trays for the Maximum Expected Fire Scenario (MEFS) is thus three for the SA system and two for the SB system.

7.3 Flame Spread Velocity

The flame spread velocity calculated using the modified Lee [1985] correlation is expected to yield the most realistic estimate for the St. Lucie cable tray fire scenarios. The flame spread velocity determined using this correlation was doubled in the sensitivity analysis to observe the impact on the results. Also, the measured/estimated horizontal cable tray flame spread rates of 0.63 mm/s and 2 mm/s are used in the sensitivity analysis.

Table 3. Summary of Heat Release Rate Data for Cables that Contain PVC and PE

Cable Type	Exposure Flux (kW/m^2)	Average Unit Heat Release (kW/m^2)	Reference
PE/PVC	60	312	EPRI [1991]
PE/PVC	60	395	EPRI [1991]
PE/PVC	60	589	EPRI [1991]
PE/PVC/Nylon	60	212	EPRI [1991]
PE/PVC/Nylon	60	263	EPRI [1991]
PE/PVC	60	359	Lee [1985]
PE/PVC/Nylon	60	231	Lee [1985]
PVC/PVC	75	210	Braun *et al.* [1989]
PVC/PVC	100	260	Braun *et al.* [1989]
PVC/XLPE	75	1,123[1]	Grayson *et al.* [2000]
PVC/XLPE	75	223[1]	Grayson *et al.* [2000]
RPPVC/XLPE	75	364[1]	Grayson *et al.* [2000]
PVC/XLPE	75	358[1]	Grayson *et al.* [2000]
RPPVC/XLPE	75	211[1]	Grayson *et al.* [2000]
PVC/XLPE	75	176[1]	Grayson *et al.* [2000]
RPPVC/XLPE	75	522[1]	Grayson *et al.* [2000]

Cable Type	Exposure Flux (kW/m^2)	Average Unit Heat Release (kW/m^2)	Reference
PVC/XLPE	75	357[1]	Grayson *et al.* [2000]
RPPVC/XLPE	75	358[1]	Grayson *et al.* [2000]
PVC/PVC	75	394[1]	Grayson *et al.* [2000]
PVC/PVC	75	211[1]	Grayson *et al.* [2000]
RPPVC/PVC	75	254[1]	Grayson *et al.* [2000]
PVC/PVC	75	219[1]	Grayson *et al.* [2000]
PVC/PVC	75	243[1]	Grayson *et al.* [2000]
PVC/PE	75	203[1]	Grayson *et al.* [2000]
PVC/PE	75	516[1]	Grayson *et al.* [2000]
PVC/PVC	75	483[1]	Grayson *et al.* [2000]
PVC/PE	75	272[1]	Grayson *et al.* [2000]
PVC/PE	75	642[1]	Grayson *et al.* [2000]
PVC/PVC	75	435[1]	Grayson *et al.* [2000]
PVC/PE	75	233[1]	Grayson *et al.* [2000]
PVC/PE	75	409[1]	Grayson *et al.* [2000]
PVC/PE	75	396[1]	Grayson *et al.* [2000]

[1]Peak heat release rate
XLPE - Cross Linked Polyethylene
PE – Polyethylene
RPPVC - Reduced Propagation PVC
PVC – Polyvinyl chloride

7.4 Radiant Heat Release Rate Fraction

The radiant heat release rate for cable tray fires is expected to lie between 0.2 and 0.4. A fraction of 0.4 is conservatively used; values of 0.3 and 0.5 are used to quantify the impact of this parameter on the calculation results.

8. Maximum Expected Fire Scenario

8.1 Maximum Expected Scenario Results

A Maximum Expected Fire Scenario (MEFS) may be constructed from the parameters described in Section 7.0 for the three-tier and four tier cable tray arrays. The MEFS is defined as the worst case credible fire scenario. This would consist of three cable trays in the SA system or two cable trays in the SB system containing IEEE 383 cables or equivalent, a bench-scale unit heat release rate of 400 kW/m^2, a horizontal flame spread rate of 1.77 mm/s, and a radiant fraction of 0.4. The target is assumed to be the side of the cable tray located directly across from the burning tray array. As will be shown, this target orientation bounds the one in which the cable is assumed to be heated directly through the gap between cable trays. The results for this

MEFS are given in Table 4 for the SA and SB cable tray systems. The peak fire length is the greatest distance the flames can spread before the onset of burnout. The spread distance (in one direction), which is the velocity multiplied by the total burn time, constantly increases until the fire is extinguished. The target heat flux, $\dot{q}_t''$ (kW), was calculated using Equation 9. The effective average emissive power, E_s (kW/m^2), for the three- and four-tier cable tray configurations was calculated using Equation 12. The burning duration, t_d (s), was calculated using Equation 4 and the spread distance, X_s (m), was calculated using Equation 6. The flame height, calculated using Equation 1, for the three-tray configuration was 1.25 m; the flame height for the four tray configuration was 1.21 m. The radiation configuration factor for the three-tray configuration calculated using Equations 10 and 11 was 0.182; the radiation configuration factor for the four-tray configuration was 0.184.

Table 4. Incident Heat Flux at Target for MEFSs

Number of Trays	Number of Burning Trays	Reference Point	E_s (kW/m^2)	t_d (s)	Maximum Fire Length ($2 \cdot X_s$) (m)	$\dot{q}_t''$ (kW/m^2)
3	2 of 3	2307	20.9	734	2.74	3.81
4	3 of 4	2305	20.4	832	2.94	3.77

The heat flux from the burning maximum expected fire scenario array to the target array was calculated using the methods described in Section 6. The target heat flux is predicted to be 3.81 kW/m^2 for the three-tier cable tray array and 3.77 kW/m^2 for the four-tier cable tray array. It is interesting to note that the target heat flux rate ($\dot{q}_t''$) is slightly larger for the three-tray array despite the fact that the loading percentage of the burning cable trays is nearly the same (26 percent versus 28.2 percent) and there is one less cable tray involved. This occurs because the calculated fire characteristics depend on the particular type of cable (size and composition) contained within the cable trays. The configuration with two burning cable trays contains a greater cable plan area; hence a fire at this location is actually more severe than the one where three-trays are burning.

The calculated MEFS scenario target heat fluxes are less than the critical incident heat flux for non-IEEE 383 cable (5.7 kW/m^2). The heat flux is significantly less than the critical incident value of 11.4 kW/m^2 for IEEE 383 cables. The maximum expected fire scenario, or worst case credible scenario, thus would not exceed the critical incident heat flux or heat the cables in the target cable tray array above the critical temperature. This conclusion holds true even if the maximum expected fire scenario cables were assumed non-IEEE 383 compliant.

Note: Reference Points 2221, 2223, and 2225 contain a greater energy loading than Reference Points 2305 and 2307 (see Appendix A). However, the plan area of the cables is less, resulting in a lower heat release rate and flame height. Using the methodology described above and the same input parameters as the two-tray MEFS, the peak target heat flux for a fire originating at Reference Points 2221 or 2225 is 3.50 kW/m^2*. Similarly, the peak target heat flux for a fire that originates at Reference Point 2223 is 3.48* kW/m^2*. In both cases, the values are less than but nearly equal to the calculated MEFS target heat fluxes. The scenarios are essentially equivalent.*

8.2 Alternate Cable Tray Arrangements

In addition to the baseline maximum expected scenario described in Section 8.1, two additional cable tray arrangements were evaluated in order to establish the maximum expected fire scenario:

1. Target located directly across from a horizontal and vertical cable tray arrangement; and

2. Target located across from a seven tray horizontal array with 2.1 m (7-ft) vertical separation.

These are described below.

8.2.1 Horizontal and Vertical Cable Tray Arrangement

A horizontal and vertical cable tray arrangement around Point 2307 was evaluated and compared with the analogous horizontal cable tray arrangement, which happens to be the three-tier cable tray MEFS. Figure 6 shows a side view of the horizontal and vertical cable tray arrangement. The exposure (burning) cable trays are L120, C120, and M120. Cable Tray L120 is not involved in the horizontal portion but is assumed to ignite in the vertical rise. The target cable trays are L101, C101, C100, and M100. Because this is a specific location, the actual separation distances may be used. Accordingly, the average (horizontal) separation between the horizontal cable tray runs is 2.9 m and the average separation between the vertical runs is 4.12 m, as shown in Figure 6.

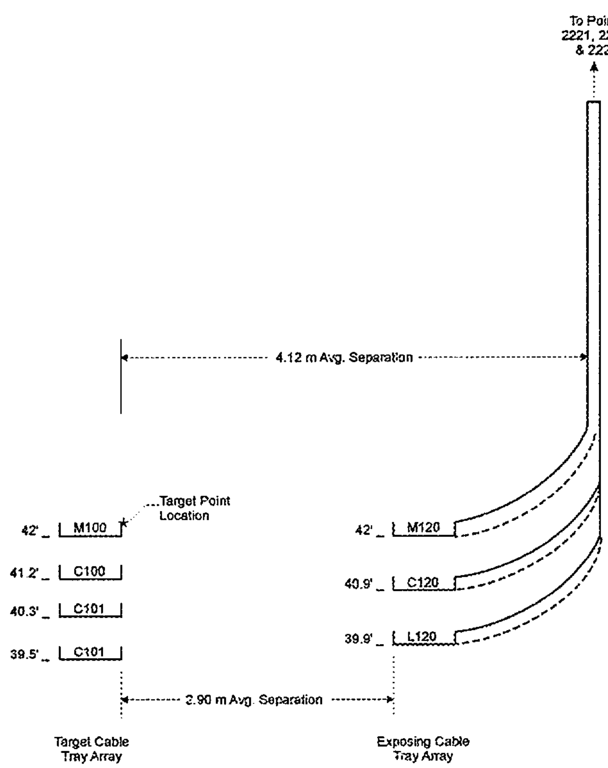

Figure 6. – Side View of Horizontal/Vertical Cable Tray Configuration around Reference Point 2307 (not to scale)

The target heat flux for the corresponding MEFS was shown to be 3.81 kW/m^2, which would be the exposure flux if there were not a vertical rise at the location considered. In this case, the fire is assumed to initiate below the vertical rise and spread horizontally away from the ignition point as previously assumed, however in one direction only. The fire is simultaneously assumed to spread up the vertical cable tray rise instantly. Figure 7 shows the assumed flame geometry for this configuration. The vertical cable trays are modeled as a single radiating panel equal to the plan width of the cable contents, which is less than the total width of the three trays. This is conservative because a larger radiating area would result in a lower emissive power for a given energy release rate.

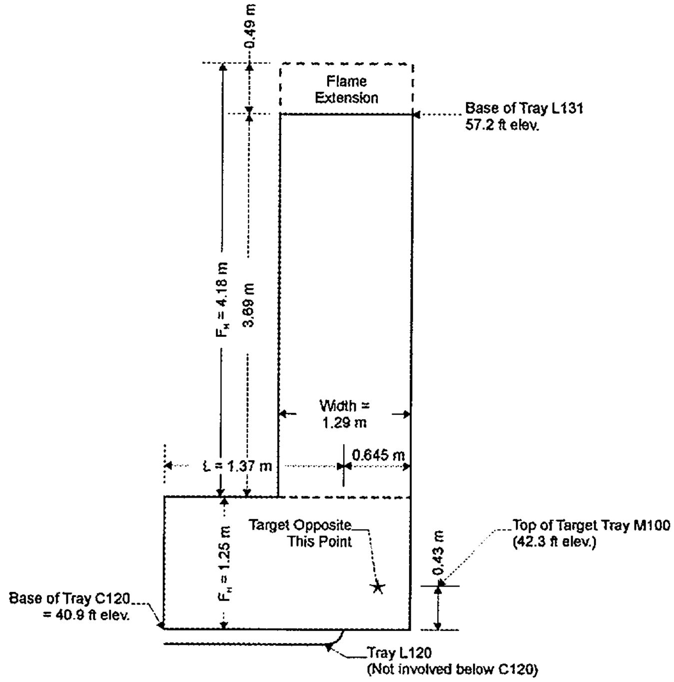

Figure 7. – Flame Dimensions of Horizontal/Vertical Cable Tray around Reference Point 2307 (not to scale)

The target location is not at mid-flame height (0.63 m), as previously assumed for the MEFSs. This is because the target and exposure cable tray arrays elevations are fixed and approximately the same. As such, the most conservative (worst case) target location is at the top of the uppermost target cable tray, which does not correspond to the mid-flame height. This is also shown in Figure 7.

The flame spread distance along the horizontal portion of the cable tray is one-half of the maximum spread distance for the corresponding MEFS, or 1.37 m. The flame height (extension) of the vertical portion of the cable tray was calculated using the following equation [McCaffrey, 1995]:

$$F_{H,V} = 0.055\dot{Q}'^{2/3} \quad (13)$$

where $F_{H,V}$ is the vertical cable tray flame height (m) and $\dot{Q}'$ is the heat release rate per unit width of the vertical cable tray section (kW/m). The heat release rate per unit width may be determined as follows:

$$\dot{Q}' = \dot{q}''_{fs}H_v \quad (14)$$

where H_v is the height of the vertical cable tray rise facing the target (3.69 m). The full scale heat release rate, $\dot{q}''_{fs}$, determined using Equation 3, is 180 kW/m^2, assuming that the MEFS unit heat release rate of 400 kW/m^2 for the cables. The resulting flame height is 4.18 m, and the resulting flame extension above vertical cable tray rise is 0.49 m. This is shown in Figure 7.

The emissive power of the horizontal cable tray section remains unchanged from the MEFS in Table 4, or 20.9 kW/m^2. The emissive power for the vertical portion of the cable tray was calculated using the following assumptions:

- The total flame thickness is equal to the tray depth, or 0.1 m;
- The flame radiates energy parallel to the target in each direction via a region with a width equal to the flame thickness;
- Below the flame extension, the flame radiates all remaining energy toward the target in the region ; and
- In the flame extension region, the flame radiates one-half of all remaining energy toward the target.

where the remaining energy refers to that which is not radiated parallel to the target. These assumptions conservatively ignore all energy conducted through the vertical cable trays and radiated away from the target. In addition, the flame thickness is assumed to be the thickness of the cable tray; thicker flames are not considered. Thus, the energy that is directed toward the target is maximized.

Given the above assumptions, the effective average emissive power is thus calculated as follows:

$$E_{s,v} = \frac{\chi_r \dot{Q}' W_V}{\left[H_V \cdot \left(W_V + 2 \cdot d\right) + 2 \cdot \left(W_V + d\right) \cdot \left(F_{H,V} - H_V\right)\right]} \qquad (15)$$

where $E_{s,v}$ is the effective average emissive power of the vertical cable tray rise (kW/m^2), W_V is the plan width of the cables in the vertical cable tray rise (m), and d is the depth of the cable trays (0.1 m). The plan width of the cable trays is 1.29 m as summarized in Appendix A. Note that vertical cable tray L120 *is included* in this calculation. The resulting emissive power is 49.9 kW/m^2.

The calculation of the heat flux is simply a summation of the energy from the horizontal and vertical sections of the exposure fire. Figure 8 shows the flame regions divided into six regions, labeled A through F. The configuration factor for each region may be determined using $F_{s\text{-}t}$ from Equation 10 as follows:

$$F_{s-t,r} = \frac{F_{s-t}}{4} \qquad (16)$$

where $F_{s\text{-}t,r}$ is the configuration shape factor for any of the sub-regions shown in Figure 8.

The results of the calculation are summarized in Table 5. Note that the target heat flux is the product of the configuration factor and the emissive power for the sub-region.

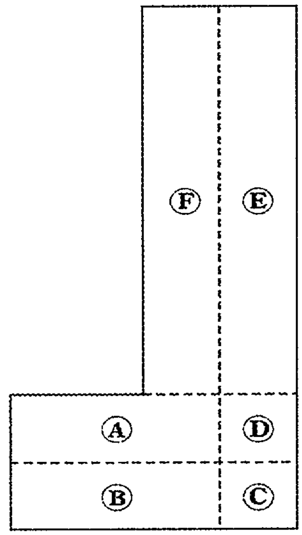

Figure 8. – Sub-division of Horizontal/Vertical Cable Tray Flame Geometry
(not to scale)

Table 5. Summary of Radiant Heat Flux from Horizontal-Vertical Cable Tray Configuration

Sub-Region	Emissive Power, E_s or $E_{s,v}$ (kW/m^2)	Configuration Factor	Target Heat Flux, $\dot{q}_t''$ (kW/m^2)
A	20.9	0.035	0.73
B	20.9	0.019	0.40
C	20.9	0.0099	0.21
D	20.9	0.0189	0.40
E	49.9	0.022	1.10
F	49.9	0.022	1.10
Total	N/A	0.126	3.94
Three-Tier MEFS	20.9	0.182	3.81

Table 5 indicates that the three-tier (two burning tray) MEFS and the vertical/horizontal configuration result in essentially the same target heat flux. This is a direct result of the larger configuration factor associated with the geometry when compared to the horizontal-vertical cable geometry. In particular, the MEFS target is always located 2.1 m from the mid-flame height. In contrast, the vertical cable tray distance is significantly further (4.12 m), which more than offsets the increased emissive power and larger surface area.

All three cable trays in the vertical configuration are covered and if involved would not be expected to contribute substantially to the target heat flux. However for purposes of this screening calculation they are assumed to burn and contribute to the flame radiation to the target. Even with this assumption the calculated target flux in this arrangement is 3.94 kW/m^2. The MEFS for the horizontal only case is 3.81 kW/m^2. These are effectively the same results even assuming all three covered vertical trays contribute as if they were open. Clearly these covered trays would not substantially contribute to the heat flux to the target, hence we conclude that the horizontal only case as described in section 8.1 is the MEFS.

8.2.2 Horizontal Array with Vertical Separation

An alternate tray arrangement comprised of seven cable trays as indicated in Figure 2 was evaluated. The analysis consisted of evaluating the possibility of ignition of the three tray array located above the 42 ft-0 in. elevation. If the three trays were ignited, then the total heat flux exposure to the SB cable tray system may exceed the calculated heat flux for the Maximum Expected Fire Scenario. If the three trays do not ignite, then the calculated heat flux for the MEFS would always exceed the heat flux for the cases shown in Figure 2 because the SB system is assumed to be located at mid-flame height. Thus, if it can be shown that cable tray arrays cannot ignite vertically separated cable tray arrays, then the previous assumption of three individual cable trays for the MEFS is conservative.

The potential for multiple cable tray arrays was evaluated by estimating the centerline thermal plume temperature from the lower burning array at the elevation of the upper, target array. If the centerline temperature exceeds the ignition temperature for PVC, then the upper cable tray array could ignite. A specific arrangement is shown in Figure 2. The exposing array consists of cable trays L101, C101, C100, and M100. The target cable tray array consists of trays L111, C103, and M102. If the second cable tray were to ignite, then there is the potential for larger incident heat fluxes to the redundant SB cable tray system.

The centerline plume temperature for a line fire is given by the following equation [Quintiere and Grove, 1998]:

$$T_c = T_\infty + \left(0.83 \cdot T_\infty^{1/2} \cdot \dot{q}'_{tot}\right)^{2/3} \cdot Z^{-1} \qquad (17)$$

where T_c is the centerline plume temperature (K), T_4 is the ambient temperature (K), and Z is the height of the base of the target cable tray array above the base of the burning cable tray array (m). The height of the target cable tray array is 4.5-m (14.7-ft) above the base of the exposing cable tray. The resulting centerline plume temperature is 88 °C. This is significantly less than the ignition temperature of PVC, thus ignition of the upper cable tray is not possible given a fire in the lower tray array.

Cable tray system SB was evaluated in the same manner (refer to Figure 2). The vertical separation is less (6-ft), however the number of trays involved is only two (M120 and C120). The calculated plume center line temperature at the base of cable tray L131 is 114 °C, which is also significantly less than the ignition temperature of PVC.

The results of these calculations indicate that the worst case scenario is a three-tier or four-tier horizontal tray array radiating to a target directly across from the centerline of the flame.

8.3 Impact of Mechanical Ventilation

Containment areas generally have large ventilation flow rates associated with maintaining the required air pressures. Large ventilation flow rates may in turn lead to localized air currents in or around the cable trays that could potentially impact a fire.

Air currents that are parallel to the flame axis (vertical) would have no impact on the fire: the flame would not tilt and it would not spread faster along the cable trays. Air currents that are perpendicular (horizontal) may cause the flame to deflect or increase the spread flame spread rate in the cable trays. A threshold horizontal air-speed value is determined in this section for the two- and three-tier cable tray MEFSs. In addition, this section evaluates the potential impact of air currents that exceed the threshold value on the MEFSs in terms of an increased radiant heating, increased convective cooling, and increased flame spread rate.

8.3.1 Threshold Air-Speed

Full scale test data indicates that there is a minimum threshold velocity, below which a flame would not tilt [Mudan and Croce, 1995; Drysdale, 1999]. This threshold velocity is based on the buoyant momentum of the fire and may be calculated using the following equation [Mudan and Croce, 1995]:

$$u_c = \left(\frac{g\dot{m}''D}{\rho_v} \right)^{1/3} \qquad (18)$$

where u_c is the critical air speed (m/s), g is the acceleration of gravity (9.81 m/s), D is the characteristic diameter (m), $\dot{m}''$ is the mass loss rate per unit area of the source fire (kg/m^2-s), and ρ_v is the density of the combustion products (kg/m^3). The mass loss rate may be estimated using the following equation:

$$\dot{m}'' = \frac{N\dot{q}''_{fs}}{\Delta H_c} \qquad (19)$$

where N is the number of cable trays, and ΔH_c is the heat of combustion (kJ/kg).

The characteristic diameter for this case is conservatively assumed to be 0.61 m, or the width of the upper cable tray. A larger characteristic diameter would result in a greater threshold airspeed. The combustion products are assumed to be 1,000 °C, thus the density of the combustion products is 0.28 kg/m^3 [Holman, 1990]. The heat of combustion for the MEFS is the average of PVC and XLPE, or 20,875 kJ/kg (see Table 1). Table 6 summarizes the results of this calculation for the two- and three-cable tray MEFSs.

Table 6. Threshold Airspeed for Deflecting Flames

Number of Trays	Point Location	Mass Loss Rate, $\dot{m}''$ (kg/s)	u_c (m/s)	u_c (ft/min)
2	2307	0.0172	0.71	140
3	2305	0.0259	0.82	161

Measured Airspeeds

Sample airspeeds were obtained in the area under consideration as detailed in PSL-FPER-01-052 Rev. 1 [FPL, 2002]. Attachment 3 of that reference contains the measured data as well as the location of the sample points. The results indicated that the maximum horizontal airspeed is 0.47 m/s (94 fpm) and the average air speed is 0.32 m/s (62 fpm). These values are approximately one-half of the critical air speed for flame deflection. The flow velocity data obtained indicates that local effects of ventilation on the fire will not occur. The following discussion gives additional background on the possible effects of forced ventilation flows. These effects are not expected in this analysis due to the low measured air speeds. This suggests that the ventilation would not impact the MEFS.

8.3.2 Flame Deflection Impact on Target Heat Flux

Air speeds in excess of the threshold airspeed could deflect the flame in the direction of air flow. The most severe deflection scenario would occur in a cross-flow in which the air was moving toward the target. In such case, the flame would deflect toward the target and possibly increase the radiant heat flux. The deflection angle may be calculated using the following equation [Mudan and Croce, 1995]:

$$\alpha = \cos^{-1}\left(\frac{u}{u_c}\right)^{-1/2} \qquad (20)$$

where α is the deflection angle (degrees) and u is the actual local air speed (m/s). Figure 9 shows the deflection angle versus the air speed for the two- and three-cable tray MEFSs. As can be seen from the Figure, the flames deflect approximately 30 ° with a local air speed between 0.9 and 1.1 m/s (177 and 216 fpm), depending on the number of trays involved.

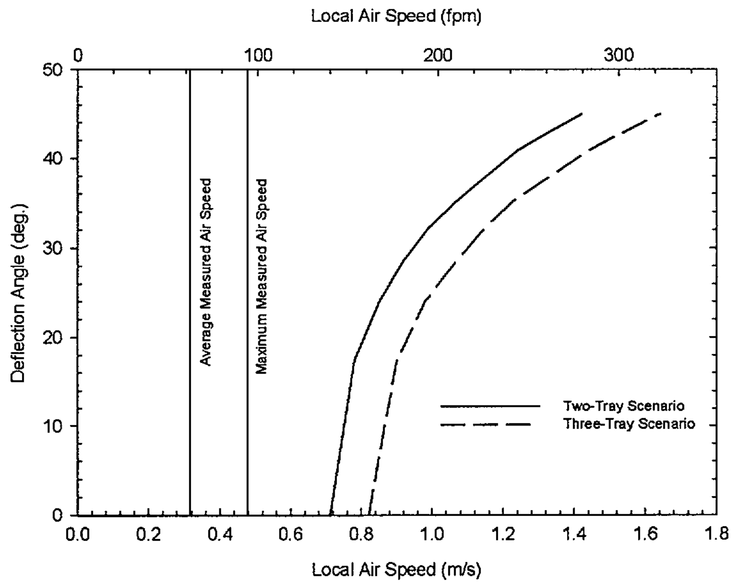

Figure 9. – Flame Deflection versus Local Air Speed

A flame that deflects toward the target could radiate more energy to the target because the flame effectively moves closer to the target. However, the area emitting radiation toward the target decreases, though this effect is most pronounced at large deflection angles. Figure 10 depicts the deflected flame geometry. Note that the flame is conservatively assumed to be located at the edge of the cable tray; the axis of rotation would likely be the *center* of the bottom cable tray.

As seen in Figure 10, the effective radiating area moves closer to the target by a distance equal to:

$$S' = S - F_h \sin\alpha \qquad (21)$$

where S' is the adjusted flame-target separation distance (m). The corresponding reduced effective flame height is given by the following equation:

$$F_h' = F_h \cos\alpha \quad (22)$$

where F'_h is the reduced effective flame height (m).

The configuration factor for the deflected geometry can be calculated using Equations 10 and 11, substituting S' for S and F'_h for F_h. The adjusted target heat flux can then be computed using Equation 9.

Figure 11 summarizes the impact of the flame deflection on the target heat flux for the MEFS flame heights. Note that for the MEFSs, both of which have a flame height of about 1.2 m, the radiant heat flux to the target increases by about 50 percent when the flame is deflected by about 30 degrees. The maximum radiant increase is about 100 percent at a deflection angle of about 45 degrees.

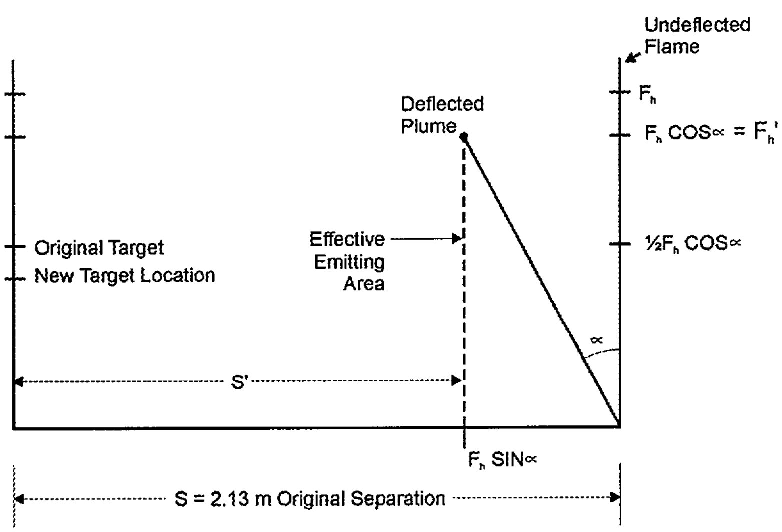

Figure 10. – Deflected Flame Geometry and Dimensions

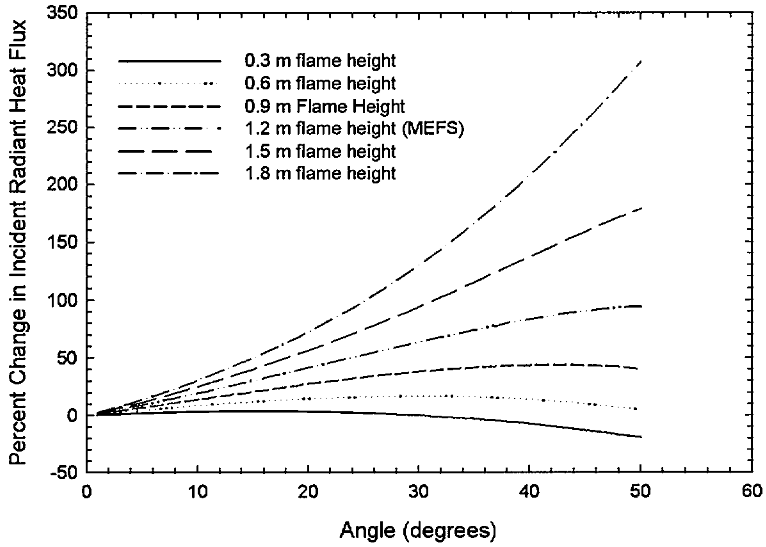

Figure 11. – Impact of Flame Deflection Angle on Target Radiant Heat Flux

8.3.3 Convection Increase due to Localized Air Flow

The local air velocity will increase the convection heat loss (forced convection) at the target cable tray. The increased heat loss capacity due to the increase in convection may be estimated using the difference in forced (ventilation) and natural convection coefficients:

$$\dot{q}''_{c,f} = \frac{(h_f - h_n)\cdot(T_s - T_\infty)}{1000} \qquad (23)$$

where $\dot{q}''_{c,f}$ is the increased convective heat loss due to the local air velocity (kW/m^2), h_f is the forced convection coefficient (W/m^2-K), h_n is the natural convection coefficient (W/m^2-K), T_s is the target surface temperature (°C), and T_∞ is the ambient temperature (20 °C). The factor of 1,000 in Equation 23 is a conversion from W to kW.

Forced Convection

The forced convection coefficient may be estimated for flow across a flat vertical plate using the following equation [Holman, 1990; Atreya, 1995]:

$$h_f = \frac{0.228}{d} \cdot k_f \left(\frac{\rho_f u d}{\mu_f} \right)^{0.731} \mathrm{Pr}_f^{1/3} \tag{24}$$

where k_f is the thermal conductivity of the air evaluated at the film (average) temperature (W/m-K), ρ_f is the density of air evaluated at the film temperature (kg/m^3), d is the characteristic dimension, assumed to be the depth of a single cable tray (0.1 m), μ_f is the dynamic viscosity evaluated at the film temperature (kg/m-s), and Pr_f is the Prandtl Number evaluated at the film temperature. The film temperature is the average temperature of the surface and the free stream air (ambient) [Holman, 1990]:

$$T_f = \frac{T_s + T_\infty}{2} \tag{25}$$

where T_f is the film temperature (°C). The limiting loss will occur when the surface temperature is about equal to the critical failure temperature for the cable contents, or 218 °C for non-IEEE qualified cables. The corresponding film temperature is 119 °C; the thermal conductivity is 0.0337 W/m-°C; the density is 0.898 kg/m^3; the dynamic viscosity is 2.29E-5 kg/m-s; and the Prandtl Number is 0.689.

Assuming a local air speed sufficient to cause a 30 degree deflection in the flame (corresponding to a 50 percent increase in target heat flux), the convection coefficients are as follows:

- Two-burning tray MEFS: 26.5 W/m^2-K (0.9 m/s air speed)
- Three-burning tray MEFS: 30.7 W/m^2-K (1.1 m/s air speed)

Air speeds for the 30 degree deflection were obtained from Figure 9.

Assuming a local air speed sufficient to cause a 45 degree deflection in the flame (corresponding to about a 100 percent increase in target heat flux), the convection coefficients are as follows:

- Two-burning tray MEFS: 36.7 W/m^2-K (1.4 m/s air speed)
- Three-burning tray MEFS: 38.7 W/m^2-K (1.5 m/s air speed)

Air speeds for the 45 degree deflection were obtained from Figure 9. Deflections greater than 45 degrees correspond to a target heat flux increase less than 100 percent, as seen in Figure 11 due to the decreasing emitting area.

Natural Convection

The natural convection coefficient may be estimated using the following equation [Holman, 1990]:

$$h_n = 0.1(Ra)^{1/3} \tag{26}$$

where *Ra* is the Rayleigh Number evaluated at the film temperature. The Rayleigh Number is given by the following [Holman, 1990]:

$$Ra = \frac{g(1/T_f)(T_s - T_\infty)d^3}{\upsilon_f^2} \tag{27}$$

where υ_f is the kinematic viscosity evaluated at the film temperature (m^2/s). The kinematic viscosity at a film temperature of 119 °C is 25.9E-6 m^2/s [Holman, 1990]. The resulting convection coefficient is 5.8 W/m^2-K.

Overall Convection Heat Loss

The overall increase in convection due to localized air flow is summarized in Table 7. The results were calculated using the convection coefficients determined above and Equation 23. The estimated increase in the radiant heat flux is also shown, as obtained from Figure 11. In all cases, the increase in convection is *significantly* greater than the increase in radiant heating. Consequently, it may be concluded that the increased convection heat loss at least compensates for the radiant heat flux gain. As such, cross-flow air velocities that cause flame deflection would not impact the fire scenarios presented in this analysis.

Table 7. Convection Heat Loss due to Local Air Flow near Target Cable Tray (Cable Tray Surface Temperature at 218 °C)

Number of Burning Trays	30 degree Flame Deflection		45 degree Flame Deflection	
	Radiant Heat Flux *Increase* (kW/m^2)	Convective Heat Loss *Increase* (kW/m^2)	Radiant Heat Flux *Increase* (kW/m^2)	Convective Heat Loss *Increase* (kW/m^2)
2	1.7	4.1	3.8	6.1
3	2.3	4.9	4.5	6.5

8.3.4 Flame Spread Increase Due to Localized Air Flow

There is no direct means of quantifying the impact of local air speed on the increase in flame spread should the air velocity and the cable trays be parallel. Tables 10c and 11c show that for the MEFSs, doubling the flame speed from 1.77 mm/s to 3.54 mm/s results in an increase of about 32 percent increase in the target heat flux. Full scale test data on vertical cable trays indicates that the upper limit on flame spread, which would correspond to a 100 percent flame deflection, is on the order of 7 mm/s. It is thus reasonable to conclude that a flame deflection of 45 degrees would at best be on the order of 3.5 mm/s (one-half of 7 mm/s). However, Table 7 indicates that the increase in convective heat loss is about 150 percent greater than the MEFS radiant heat flux. It is concluded that local air currents sufficient to deflect the flame would not impact the fire scenarios presented in this analysis when the air flow is parallel to the cable trays.

8.3.5 Summary (Mechanical Ventilation)

The analysis presented and flow data obtained in the subject plant area indicate that there will be no negative effect of the forced mechanical ventilation on either the heating of targets or the fire spread behavior of the cables.

8.4 Incidental Combustibles

In order to establish that the exposure from one horizontal cable tray array was the worst case, an evaluation of other combustibles located below the two raceway system was evaluated.

The minimum heat release rate/fire size need to expose both SA and SB cable tray systems was calculated using the Heskestad thermal plume and flame height correlations [Beyler, 1986]. Specific fire scenarios are not evaluated; rather, the minimum fire size that could expose two overhead cable trays separated horizontally by 2.1 m (7 ft) to a temperature of 218 °C was determined.

Two types of source fires were considered: a miscellaneous Class A material fire with a unit heat release rate of 400 kW/m^2 [Babrauskas, 1995] and a combustible liquid fire with a unit heat release rate of 2,000 kW/m^2 [Mudan and Croce, 1995]. Cable tray elevations above the floor are between 1.5 m (5 ft) and 6.1 m (20 ft).

The minimum fire size necessary to both trays was first determined using thermal plume equations. The required fire diameter in all cases was found to be greater than 2.1 m (7 ft), typically on the order of 6.1 m (20 ft). The flame height was then calculated using the heat release rate that was calculated. In all cases, the flame height exceeded the height of the cable tray; thus, the flame height correlation is the determining factor. Table 8 summarizes the minimum fire size (heat release rate and diameter) that could cause flame impingement to the cable tray. The minimum diameter is 2.1 m (7 ft), the separation of the two cable trays.

Based on the physical geometry and the combustible survey for the area presented in Sections 3.1 and 3.2 and the small size of any fires involving these fuel packages, there is no thermal exposure risk to the redundant sets of arrays.

Table 8. Minimum Size Fires that could Damage Two Cable Tray Systems Located 2.1 m (7 ft) Apart

Elevation (m [ft])	Class A Material Fire		Combustible Liquid	
	Heat Release (kW)	Diameter (m [ft])	Heat Release (kW)	Diameter (m [ft])
1.5 (5)	1,385	2.1 (7.0)	7,150	2.1 (7.0)
3.0 (10)	3,880	3.5 (11.5)	7,150	2.1 (7.0)
4.6 (15)	11,300	6.0 (20.0)	11,300	2.7 (8.8)
6.1 (20)	22,900	8.5 (28)	22,900	3.8 (12.5)

8.5 Critical Cable Tray Separation Distance

A critical cable tray separation distance may be calculated as a means of presenting one aspect of the safety factor inherent in the calculations. The critical cable tray separation distance determined in this section is defined as the distance at which the maximum target heat flux exactly equals the critical incident heat flux for the cables. Transient effects, which would tend to reduce the critical separation distance further, are not considered.

The equations presented in Section 6 were used to calculate the critical cable tray separation distance. Unlike the previous applications, the distance S is the unknown parameter and the target heat flux, $\dot{q}_t''$ (kW/m^2), is the known parameter. The target heat flux is thus 5.7 kW/m^2 for non-IEEE qualified cable and 11.4 kW/m^2 for IEEE qualified cable [EPRI, 1991]. Table 9 summarizes the calculated critical separation distance for the two and three burning tray MEFSs. The results for non-IEEE qualified and IEEE qualified cable are shown. Note that the percent safety margin is relative the critical separation distance.

Table 9. Critical Cable Tray Separation Distances

Number of Burning Trays	non-IEEE Qualified Cable			IEEE Qualified Cable		
	Critical Separation Distance (m [ft])	*Safety Margin*		*Critical Separation Distance (m [ft])*	Safety Margin	
		m (ft)	%		m (ft)	%
2	1.7 (5.5)	0.45 (1.5)	27	0.82 (2.7)	1.3 (4.3)	159
3	1.7 (5.5)	0.45 (1.5)	27	0.82 (2.7)	1.3 (4.3)	159

The results shown in Table 9 indicate that the actual 2.1 m (7 ft) minimum cable tray separation distance is near, but greater than, the critical separation distance for non-IEEE qualified cable. Likewise, the actual minimum separation is more than two times the critical distance for IEEE qualified cable. Since the coated cables exceed the threshold damage criteria for qualified cables, the minimum separation distance is exceeded by a factor of 1.59 for the worst case. It is important to bear in mind that there is little uncertainty in the separation distance between the trays and the distance will not change unexpectedly. The concept of safety factors and uncertainty analysis is applied to the variable analysis parameters in Section 9 in the discussion of limiting fire scenarios.

9. Sensitivity Analysis and Limiting Fire Scenarios

This section of the report presents results of a systematic variation in the parameters discussed in Section 7. Using the Maximum Expected Fire Scenario (MEFS) as a baseline, this analysis demonstrates the sensitivity of the results of the calculations to variations in the parameters. These results clarify the degree of conservatism and the factors of safety inherent in the calculations. In addition, these calculations are completed over a parameter space that includes conditions that will result in failure. The Limiting Fire Scenario (LFS) calculations are required by Appendix C of NFPA 805 [2001].

The varied parameters include the following:

- Heat release rate of cable,
- Number of cable trays involved,

- Flame spread rate,
- Burning duration (as calculated), and
- Radiative fraction.

Parameters and conditions calculated for the MEFS are given on each Table for comparison. The results of the analysis are shown in Tables 10a-10h for the four-tier cable tray array and Tables 11a-11h for the three-tier cable tray array. The target heat flux, $\dot{q}_t''$ (kW/m^2), was calculated using Equation 9. The effective average emissive power, E_s (kW/m^2), for the three- and four-tier cable tray configurations were calculated using Equation 12. The burning duration, t_d (s), was calculated using Equation 4 and the spread distance, X_s (m), was calculated using Equation 6. Incident heat fluxes that exceed the critical incident heat flux of 11.4 kW/m^2 for IEEE 383 qualified cable are shown in bold.

Table 10a. Cable Tray Incident Heat Flux Results (200 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2\cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
200	2 of 4	0.33	0.3	1,686	36	1.11	6.6	0.21
			0.4				8.8	0.28
			0.5				11.0	0.35
		0.66	0.3		71	2.23	6.6	0.37
			0.4				8.8	0.50
			0.5				11.0	0.62
		0.63	0.3		68	2.12	6.6	0.36
			0.4				8.8	0.48
			0.5				11.0	0.50
		2	0.3		217	6.75	6.6	0.61
			0.4				8.8	0.81
			0.5				11.0	1.02
200	3 of 4	0.33	0.3	1,663	85	1.1	10.9	0.6
			0.4				14.5	0.8
			0.5				18.1	1.0
		0.66	0.3		169	2.19	10.9	1.07
			0.4				14.5	1.43
			0.5				18.1	1.78
		0.63	0.3		162	2.10	10.9	1.03
			0.4				14.5	1.38
			0.5				18.1	1.72
		2	0.3		515	6.67	10.9	1.77
			0.4				14.5	2.36
			0.5				18.1	2.95
200	4 of 4	0.33	0.3	1,552	113	1.02	13.0	0.84
			0.4				17.4	1.12
			0.5				21.7	1.40
		0.66	0.3		226	2.05	13.0	1.52
			0.4				17.4	2.03
			0.5				21.7	2.54
		0.63	0.3		216	1.96	13.0	1.47
			0.4				17.4	1.96
			0.5				21.7	2.45
		2	0.3		685	6.21	13.0	2.62
			0.4				17.4	3.50
			0.5				21.7	4.37
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10b. Cable Tray Incident Heat Flux Results (300 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
300	2 of 4	1.02	0.3	1,124	111	2.29	8.4	0.62
			0.4				11.2	0.84
			0.5				14.0	1.05
		2.04	0.3		222	4.59	8.4	0.91
			0.4				11.2	1.22
			0.5				14.0	1.52
		0.63	0.3		68	1.42	8.4	0.43
			0.4				11.2	0.57
			0.5				14.0	0.71
		2	0.3		217	4.5	8.4	0.91
			0.4				11.2	1.21
			0.5				14.0	1.51
300	3 of 4	1.02	0.3	1,108	263	2.26	13.3	1.74
			0.4				17.8	2.31
			0.5				22.2	2.89
		2.04	0.3		525	4.52	13.3	2.54
			0.4				17.5	3.39
			0.5				22.2	4.23
		0.63	0.3		162	1.40	13.3	1.18
			0.4				17.8	1.57
			0.5				22.2	1.96
		2	0.3		515	4.44	13.3	2.52
			0.4				17.5	3.36
			0.5				22.2	4.20
300	4 of 4	1.02	0.3	1,035	350	2.11	15.8	2.43
			0.4				21.1	3.24
			0.5				26.3	4.05
		2.04	0.3		699	4.22	15.8	3.64
			0.4				21.1	4.86
			0.5				26.3	6.07
		0.63	0.3		216	1.30	15.8	1.63
			0.4				21.1	2.17
			0.5				26.3	2.71
		2	0.3		685	4.14	15.8	3.62
			0.4				21.1	4.82
			0.5				26.3	6.02
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10c. Cable Tray Incident Heat Flux Results (400 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
400	2 of 4	1.77	0.3	843	192	2.99	9.9	1.06
			0.4				13.1	1.41
			0.5				16.4	1.76
		3.54	0.3		334	5.97	9.9	1.39
			0.4				13.1	1.86
			0.5				16.4	2.32
		0.63	0.3		68	1.06	9.9	0.47
			0.4				13.1	0.62
			0.5				16.4	0.78
		2	0.3		217	3.37	9.9	1.13
			0.4				13.1	1.51
			0.5				16.4	1.88
400	3 of 4	1.77	0.3	832	456	2.94	15.3	2.83
			0.4				20.4	3.77
			0.5				25.5	4.71
		3.54	0.3		911	5.89	15.3	3.76
			0.4				20.4	5.02
			0.5				25.5	6.27
		0.63	0.3		162	1.05	15.3	1.24
			0.4				20.4	1.66
			0.5				25.5	2.07
		2	0.3		515	3.33	15.3	3.03
			0.4				20.4	4.04
			0.5				25.5	5.05
400	4 of 4	1.77	0.3	776	606	2.75	18.0	3.93
			0.4				24.0	5.25
			0.5				30.0	6.56
		3.54	0.3		1,213	5.49	18.0	5.38
			0.4				24.0	7.18
			0.5				30.0	8.97
		0.63	0.3		216	0.98	18.0	1.69
			0.4				24.0	2.25
			0.5				30.0	2.81
		2	0.3		686	3.10	18.0	4.24
			0.4				24.0	5.65
			0.5				30.0	7.06
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10d. Cable Tray Incident Heat Flux Results (500 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
500	2 of 4	2.52	0.3	675	274	3.40	11.1	1.48
			0.4				14.8	1.97
			0.5				18.5	2.46
		5.04	0.3		548	6.80	11.1	1.86
			0.4				14.8	2.48
			0.5				18.5	3.10
		0.63	0.3		68	0.85	11.1	0.49
			0.4				14.8	0.66
			0.5				18.5	0.82
		2	0.3		217	2.70	11.1	1.29
			0.4				14.8	1.72
			0.5				18.5	2.15
500	3 of 4	2.52	0.3	665	649	3.35	17.0	3.86
			0.4				22.6	5.14
			0.5				28.3	6.43
		5.04	0.3		1,297	6.71	17.0	4.91
			0.4				22.6	6.54
			0.5				28.3	8.18
		0.63	0.3		162	0.84	17.0	1.27
			0.4				22.6	1.70
			0.5				28.3	2.12
		2	0.3		515	2.66	17.0	3.34
			0.4				22.6	4.48
			0.5				28.3	5.61
500	4 of 4	2.52	0.3	621	864	3.13	19.9	5.32
			0.4				26.5	7.09
			0.5				33.1	8.87
		5.04	0.3		1,724	6.25	19.9	6.96
			0.4				26.5	9.28
			0.5				33.1	**11.60**
		0.63	0.3		216	0.78	19.9	1.70
			0.4				26.5	2.27
			0.5				33.1	2.84
		2	0.3		621	2.48	19.9	4.60
			0.4				26.5	6.13
			0.5				33.1	7.33
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10e. Cable Tray Incident Heat Flux Results (600 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2 \cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}_t''$ (kW/m^2)
600	2 of 4	3.28	0.3	562	356	3.69	12.2	1.89
			0.4				16.2	2.53
			0.5				20.3	3.16
		6.6	0.3		562	7.42	12.2	2.33
			0.4				16.2	3.11
			0.5				20.3	3.88
		0.63	0.3		68	0.71	12.2	0.51
			0.4				16.2	0.68
			0.5				20.3	0.85
		2	0.3		217	2.25	12.2	1.41
			0.4				16.2	1.87
			0.5				20.3	2.34
600	3 of 4	3.28	0.3	554	844	3.64	18.4	4.85
			0.4				24.5	6.46
			0.5				30.7	8.08
		6.6	0.3		1,699	7.32	18.4	6.02
			0.4				24.5	8.02
			0.5				30.7	10.03
		0.63	0.3		162	0.7	18.4	1.29
			0.4				24.5	1.72
			0.5				30.7	2.15
		2	0.3		515	2.22	18.4	3.57
			0.4				24.5	4.76
			0.5				30.7	5.95
600	4 of 4	3.28	0.3	517	1,124	3.39	20.9	6.63
			0.4				27.8	8.85
			0.5				34.8	11.06
		6.6	0.3		2,262	6.83	20.9	8.46
			0.4				27.8	11.28
			0.5				34.8	**14.10**
		0.63	0.3		216	0.65	20.9	1.70
			0.4				27.8	2.26
			0.5				34.8	2.83
		2	0.3		686	2.07	20.9	4.80
			0.4				27.8	6.39
			0.5				34.8	7.99
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10f. Cable Tray Incident Heat Flux Results (700 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2 \cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}_t''$ (kW/m^2)
700	2 of 4	4.04	0.3	482	439	3.83	13.2	2.31
			0.4				17.5	3.08
			0.5				21.9	3.85
		8.08	0.3		878	7.79	13.2	2.79
			0.4				17.5	3.72
			0.5				21.9	4.66
		0.63	0.3		68	0.61	13.2	0.52
			0.4				17.5	0.70
			0.5				21.9	0.87
		2	0.3		217	1.93	13.2	1.49
			0.4				17.5	1.99
			0.5				21.9	2.48
700	3 of 4	4.08	0.3	475	1,048	3.87	19.7	5.82
			0.4				26.3	7.77
			0.5				32.8	9.71
		8.08	0.3		2,080	7.68	19.7	7.08
			0.4				26.3	9.44
			0.5				32.8	**11.80**
		0.63	0.3		162	0.6	19.7	1.29
			0.4				26.3	1.72
			0.5				32.8	2.15
		2	0.3		515	1.90	19.7	3.7
			0.4				26.3	4.93
			0.5				32.8	6.17
700	4 of 4	4.04	0.3	443	1,385	3.58	22.9	7.88
			0.4				30.5	10.50
			0.5				38.1	**13.12**
		8.08	0.3		2,796	7.17	22.9	9.87
			0.4				30.5	**13.16**
			0.5				38.1	**16.44**
		0.63	0.3		216	0.56	22.9	1.65
			0.4				30.5	2.24
			0.5				38.1	2.80
		2	0.3		686	1.77	22.9	4.89
			0.4				30.5	6.52
			0.5				38.1	8.15
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10g. Cable Tray Incident Heat Flux Results (800 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
800	2 of 4	4.79	0.3	422	521	4.0	14.0	2.73
			0.4				18.7	3.63
			0.5				23.4	4.54
		9.58	0.3		1,041	8.08	14.0	3.26
			0.4				18.7	4.34
			0.5				23.4	5.43
		0.63	0.3		68	0.53	14.0	0.53
			0.4				18.7	0.71
			0.5				23.4	0.89
		2	0.3		217	1.69	14.0	1.55
			0.4				18.7	2.07
			0.5				23.4	2.54
800	3 of 4	4.79	0.3	416	1,233	3.98	20.8	6.72
			0.4				27.8	8.96
			0.5				34.7	11.21
		9.58	0.3		2,466	7.97	20.8	8.12
			0.4				27.8	10.82
			0.5				34.7	**13.53**
		0.63	0.3		162	0.53	20.8	1.29
			0.4				27.8	1.72
			0.5				34.7	2.15
		2	0.3		515	1.66	20.8	3.78
			0.4				27.8	5.03
			0.5				34.7	6.29
800	4 of 4	4.79	0.3	388	1,642	3.72	24.2	9.05
			0.4				32.2	**12.06**
			0.5				40.3	**15.07**
		9.58	0.3		3,284	7.43	24.2	11.22
			0.4				32.2	**14.96**
			0.5				40.3	**18.70**
		0.63	0.3		216	0.49	24.2	1.66
			0.4				32.2	2.21
			0.5				40.3	2.77
		2	0.3		686	1.55	24.2	4.92
			0.4				32.2	6.56
			0.5				40.3	8.20
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 10h. Cable Tray Incident Heat Flux Results (1,000 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2305

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2 \cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
1,000	2 of 4	6.3	0.3	337	685	4.24	15.6	3.55
			0.4				20.8	4.73
			0.5				26.0	5.91
		12.6	0.3		1,369	8.50	15.6	4.18
			0.4				20.8	5.57
			0.5				26.0	6.97
		0.63	0.3		68	0.42	15.6	0.54
			0.4				20.8	0.72
			0.5				26.0	0.90
		2	0.3		217	1.35	15.6	1.63
			0.4				20.8	2.17
			0.5				26.0	2.72
1,000	3 of 4	6.3	0.3	333	1,622	4.19	22.9	8.48
			0.4				30.5	11.31
			0.5				38.2	**14.13**
		12.6	0.3		3,244	8.38	22.9	10.11
			0.4				30.5	**13.48**
			0.5				38.2	**16.84**
		0.63	0.3		162	0.42	22.9	1.27
			0.4				30.5	1.69
			0.5				38.2	2.12
		2	0.3		515	1.33	22.9	3.83
			0.4				30.5	5.10
			0.5				38.2	6.38
1,000	4 of 4	6.3	0.3	310	2,160	3.91	26.4	11.23
			0.4				35.3	**14.97**
			0.5				44.1	**18.71**
		12.6	0.3		4,319	7.82	26.4	**13.75**
			0.4				35.3	**18.34**
			0.5				44.1	**22.92**
		0.63	0.3		216	0.39	26.4	1.60
			0.4				35.3	2.14
			0.5				44.1	2.67
		2	0.3		686	1.24	26.4	4.88
			0.4				35.3	6.50
			0.5				44.1	8.13
FOUR-TIER CABLE TRAY ARRAY MEFS				832	456	2.94	20.4	3.77

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11a. Cable Tray Incident Heat Flux Results (200 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}_t''$ (kW/m^2)
200	2 of 3	0.33	0.3	1,548	83	1.02	11.2	0.59
			0.4				14.9	0.79
			0.5				18.6	0.99
		0.66	0.3		166	2.04	11.2	1.07
			0.4				14.9	1.43
			0.5				18.6	1.79
		0.63	0.3		159	1.95	11.2	1.04
			0.4				14.9	1.38
			0.5				18.6	1.73
		2	0.3		504	6.19	11.2	1.85
			0.4				14.9	2.47
			0.5				18.6	3.08
200	3 of 3	0.33	0.3	1,557	120	1.03	13.4	0.89
			0.4				17.8	1.19
			0.5				22.3	1.49
		0.66	0.3		240	2.06	13.4	1.62
			0.4				17.8	2.16
			0.5				22.3	2.70
		0.63	0.3		228	1.96	13.4	1.56
			0.4				17.8	2.08
			0.5				22.3	2.60
		2	0.3		724	6.23	13.4	2.78
			0.4				17.8	3.71
			0.5				22.3	4.64
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11b. Cable Tray Incident Heat Flux Results (300 kW/m² Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m²)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m²)	$\dot{q}_t''$ (kW/m²)
300	2 of 2	1.02	0.3	1,032	257	2.11	13.7	1.74
			0.4				18.2	2.32
			0.5				22.8	2.90
		2.04	0.3		514	4.21	13.7	2.61
			0.4				18.2	3.48
			0.5				22.8	4.35
		0.63	0.3		159	1.30	13.7	1.17
			0.4				18.2	1.56
			0.5				22.8	1.95
		2	0.3		504	4.15	13.7	3.83
			0.4				18.2	5.1
			0.5				22.8	6.38
300	3 of 3	1.02	0.3	1,033	369	2.12	16.2	2.57
			0.4				21.6	3.43
			0.5				27.0	4.28
		2.04	0.3		739	4.24	16.2	3.86
			0.4				21.6	5.14
			0.5				27.0	6.43
		0.63	0.3		228	1.31	16.2	1.73
			0.4				21.6	2.30
			0.5				27.0	2.88
		2	0.3		724	4.15	16.2	3.83
			0.4				21.6	5.10
			0.5				27.0	6.37
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11c. Cable Tray Incident Heat Flux Results (400 kW/m² Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m²)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m²)	$\dot{q}_t''$ (kW/m²)
400	2 of 3	1.77	0.3	774	446	2.74	15.7	2.86
			0.4				20.9	3.81
			0.5				26.1	4.76
		3.54	0.3		891	5.48	15.7	3.90
			0.4				20.9	5.20
			0.5				26.1	6.50
		0.63	0.3		159	0.98	15.7	1.23
			0.4				20.9	1.63
			0.5				26.1	2.04
		2	0.3		504	3.10	15.7	3.07
			0.4				20.9	4.10
			0.5				26.1	5.12
400	3 of 3	1.77	0.3	779	641	2.76	18.4	4.16
			0.4				24.6	5.54
			0.5				30.7	6.93
		3.54	0.3		1,283	5.51	18.4	5.68
			0.4				24.6	7.51
			0.5				30.7	9.47
		0.63	0.3		228	0.98	18.4	1.78
			0.4				24.6	2.38
			0.5				30.7	2.97
		2	0.3		724	3.12	18.4	4.47
			0.4				24.6	5.96
			0.5				30.7	7.46
THREE-TIER CABLE TRAY ARRAY MEFS				714	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11d. Cable Tray Incident Heat Flux Results (500 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2 \cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}_t''$ (kW/m^2)
500	2 of 3	2.52	0.3	619	635	3.12	17.4	3.90
			0.4				23.1	5.21
			0.5				28.9	6.51
		5.04	0.3		1,269	6.24	17.4	5.10
			0.4				23.1	6.80
			0.5				28.9	8.49
		0.63	0.3		159	0.78	17.4	1.25
			0.4				23.1	1.67
			0.5				28.9	2.09
		2	0.3		504	2.48	17.4	3.38
			0.4				23.1	4.50
			0.5				28.9	5.63
500	3 of 3	2.52	0.3	623	913	6.14	20.3	5.61
			0.4				27.1	7.48
			0.5				33.8	9.39
		5.04	0.3		1,826	6.28	20.3	7.33
			0.4				27.1	9.77
			0.5				33.8	**12.21**
		0.63	0.3		228	0.79	20.3	1.80
			0.4				27.1	2.39
			0.5				33.8	2.99
		2	0.3		724	2.49	20.3	4.85
			0.4				27.1	6.46
			0.5				33.8	8.08
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11e. Cable Tray Incident Heat Flux Results (600 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
600	2 of 3	3.28	0.3	516	826	3.38	18.8	4.92
			0.4				25.1	6.56
			0.5				31.4	8.19
		6.6	0.3		1,662	6.81	18.8	6.25
			0.4				25.1	8.34
			0.5				31.4	10.42
		0.63	0.3		159	0.65	18.8	1.26
			0.4				25.1	1.68
			0.5				31.4	2.10
		2	0.3		504	2.06	18.8	3.56
			0.4				25.1	4.75
			0.5				31.4	5.93
600	3 of 3	3.28	0.3	519	1,188	3.41	21.9	6.98
			0.4				29.2	9.30
			0.5				36.5	**11.63**
		6.6	0.3		2,391	6.84	21.9	8.89
			0.4				29.2	**11.86**
			0.5				36.5	**14.82**
		0.63	0.3		228	0.65	21.9	1.79
			0.4				29.2	2.38
			0.5				36.5	2.98
		2	0.3		724	2.08	21.9	5.05
			0.4				29.2	6.73
			0.5				36.5	8.41
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11f. Cable Tray Incident Heat Flux Results (700 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
700	2 of 3	4.04	0.3	442	1,017	3.57	20.1	5.89
			0.4				26.8	7.85
			0.5				33.5	9.82
		8.08	0.3		2,035	7.15	20.1	7.36
			0.4				26.8	9.81
			0.5				33.5	**12.26**
		0.63	0.3		159	0.56	20.1	1.26
			0.4				26.8	1.68
			0.5				33.5	2.10
		2	0.3		504	1.77	20.1	3.67
			0.4				26.8	4.89
			0.5				33.5	6.11
700	3 of 3	4.04	0.3	445	1,463	3.60	23.4	8.27
			0.4				31.2	11.03
			0.5				39.0	**13.78**
		8.08	0.3		2,927	7.19	23.4	10.35
			0.4				31.2	**13.81**
			0.5				39.0	**17.27**
		0.63	0.3		228	0.56	23.4	1.77
			0.4				31.2	2.36
			0.5				39.0	2.95
		2	0.3		724	1.78	23.4	5.14
			0.4				31.2	6.85
			0.5				39.0	8.56
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11g. Cable Tray Incident Heat Flux Results (800 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2 \cdot X_s$ (m)	E_s (kW/m^2)	$\dot{q}_t''$ (kW/m^2)
800	2 of 3	4.79	0.3	387	1,207	3.71	21.3	6.82
			0.4				28.4	9.10
			0.5				35.5	11.37
		9.58	0.3		2,413	7.41	21.3	8.43
			0.4				28.4	11.24
			0.5				35.5	**14.05**
		0.63	0.3		159	0.49	21.3	1.26
			0.4				28.4	1.68
			0.5				35.5	2.10
		2	0.3		504	1.55	21.3	3.72
			0.4				28.4	4.97
			0.5				35.5	6.21
800	3 of 3	4.79	0.3	389	1,735	3.73	24.7	9.48
			0.4				32.9	**12.65**
			0.5				41.1	**15.81**
		9.58	0.3		3,470	7.46	24.7	**11.76**
			0.4				32.9	**15.68**
			0.5				41.1	**19.60**
		0.63	0.3		228	0.49	24.7	1.74
			0.4				32.9	2.32
			0.5				41.1	2.90
		2	0.3		724	1.56	24.7	5.16
			0.4				32.9	6.88
			0.5				41.1	8.60
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}_t''$) exceeds the critical incident heat flux for IEEE 383 cables.

Table 11h. Cable Tray Incident Heat Flux Results (1,000 kW/m^2 Unit Heat Release Rate for Cables)

Reference Point 2307

Variable Parameters				Results				
$\dot{q}_{bs}$ (kW/m^2)	No. Burning Trays	v_s (mm/s)	Π_r	t_d (s)	$\dot{Q}_p$ (kW)	$2{\cdot}X_s$ (m)	E_s (kW/m^2)	$\dot{q}''_t$ (kW/m^2)
1,000	2 of 3	6.3	0.3	310	1,587	3.90	23.4	8.60
			0.4				31.2	**11.46**
			0.5				38.9	**14.33**
		12.6	0.3		3,173	7.80	23.4	10.49
			0.4				31.2	**13.98**
			0.5				38.9	**17.48**
		0.63	0.3		159	0.39	23.4	1.24
			0.4				31.2	1.65
			0.5				38.9	2.06
		2	0.3		504	1.24	23.4	3.75
			0.4				31.2	5.00
			0.5				38.9	6.25
1,000	3 of 3	6.3	0.3	312	2,282	3.93	27.0	**11.74**
			0.4				36.0	**15.65**
			0.5				45.0	**19.57**
		12.6	0.3		4,564	7.85	37.0	**14.38**
			0.4				36.0	**19.17**
			0.5				45.0	**23.96**
		0.63	0.3		228	0.39	27.0	1.68
			0.4				36.0	2.24
			0.5				45.0	2.80
		2	0.3		724	1.25	27.0	5.10
			0.4				36.0	6.80
			0.5				45.0	8.50
THREE-TIER CABLE TRAY ARRAY MEFS				774	446	2.74	20.9	3.81

Boldface indicates that the incident heat flux ($\dot{q}''_t$) exceeds the critical incident heat flux for IEEE 383 cables.

The results summarized in these Tables indicate that under worst case credible conditions, the critical incident flux for IEEE 383 qualified cables (11.4 kW/m^2) is not exceeded until the heat release rate per unit area exceeds 500 kW/m^2 for both reference points considered.

The results of these calculations indicate that the failure conditions are not exceeded until the following critical conditions (Limiting Fire Scenarios) are met or exceeded, as summarized in Tables 12 and 13.

Table 12. Summary of Limiting Fire Scenario for Reference Point 2305

Heat Release Rate (kW/m^2)	Number of Burning Trays	v_s (mm/sec)	χ_r	Target Heat Flux (kW/m^2)
400	**3 of 4**	**1.77**	**0.4**	**3.77**
500	4 of 4	5.04	0.5	11.60
600	4 of 4	6.6	0.5	14.40
700	3 of 4	8.08	0.5	11.80
700	4 of 4	4.04	0.5	13.12
700	4 of 4	8.08	0.4	13.16
700	4 of 4	8.08	0.5	16.44
800	3 of 4	9.58	0.5	13.53
800	4 of 4	4.79	0.4	12.06
800	4 of 4	4.79	0.5	15.07
800	4 of 4	9.58	0.4	14.96
800	4 of 4	9.58	0.5	18.70
1000	3 of 4	6.3	0.5	14.13
1000	3 of 4	12.6	0.4	13.48
1000	3 of 4	12.6	0.5	16.85
1000	4 of 4	6.3	0.4	14.97
1000	4 of 4	6.3	0.5	18.71
1000	4 of 4	12.6	0.3	13.75
1000	4 of 4	12.6	0.4	18.34
1000	4 of 4	12.6	0.5	22.92

Boldface indicates the Maximum Expected Fire Scenario for Reference Point 2305

Table 13. Summary of Limiting Fire Scenario for Reference Point 2307

Heat Release Rate (kW/m^2)	Number of Burning Trays	v_s (mm/sec)	χ_r	Target Heat Flux (kW/m^2)
400	**2 of 3**	**1.77**	**0.4**	**3.81**
500	3 of 3	5.04	0.5	12.21
600	3 of 3	3.28	0.5	11.63
600	3 of 3	6.6	0.4	11.86
600	3 of 3	6.6	0.5	14.82
700	2 of 3	8.08	0.5	12.26
700	3 of 3	4.04	0.5	13.78
700	3 of 3	8.08	0.4	13.81
700	3 of 3	8.08	0.5	17.27
800	2 of 3	9.58	0.5	14.05
800	3 of 3	4.79	0.4	12.65
800	3 of 3	4.79	0.5	15.81
800	3 of 3	9.58	0.3	11.76
800	3 of 3	9.58	0.4	15.68
800	3 of 3	9.58	0.5	19.60
1000	2 of 3	6.3	0.4	11.43
1000	2 of 3	6.3	0.5	14.33
1000	2 of 3	12.6	0.4	13.98
1000	2 of 3	12.6	0.5	17.48
1000	3 of 3	6.3	0.3	11.74
1000	3 of 3	6.3	0.4	15.65
1000	3 of 3	6.3	0.5	19.57
1000	3 of 3	12.6	0.3	14.38
1000	3 of 3	12.6	0.4	19.17
1000	3 of 3	12.6	0.5	23.96

Boldface indicates the Maximum Expected Fire Scenario for Reference Point 2307

These results demonstrate a substantial degree of conservatism relative to the MEFS and indicate that extreme variations of the expected parameters are required to exceed the failure criteria.

Additional analysis and calculations presented in Sections 12 and 13 indicate the significant additional conservatism in the analysis.

10. Maximum Allowable Cable Loading

In order to evaluate a limiting condition represented by placing additional cables in the three-tray array evaluated as the maximum expected fire scenario, calculations of the maximum allowable cable loading were conducted. A representative cable with the following characteristics was assumed:

- 0.823-inch (21-mm) outer diameter;
- 45-mil thick PVC jacket;
- 55-mil thick XLPE insulation; and
- 400 kW/m^2 unit heat release rate.

This cable contains the maximum combustible content among the cables in trays C100, C101, and M101. Cables were added until the incident heat flux exceeded the maximum allowable heat flux for IEEE 383 qualified cables, or 11.4 kW/m^2. The results indicated that 199 of the representative cables may be added in any combination in trays M101, C101, and C100 before the incident heat flux exceeds 11.4 kW/m^2.

The number of cables required to exceed the critical heat flux at the location evaluated is sufficient to cover the entire width of the three cable trays. Consequently, the peak heat release rate and the effective emissive power for this location would always exceed that originating from a two tray scenario. Thus, although the actual two-tray fire at Reference Point 2307 (three-tier cable tray array) is nearly the same as the MEFS at Reference Point 2305 (four-tier cable tray array), the number of cables that could be added to Reference Point 2305 is <u>less</u> than at 2307.

While the precise number depends on the cable size and construction, a reasonable limit, with a safety factor of 2, is 99 additional cables meeting the following conditions:

1. IEEE 383 qualified, and
2. Heat release rate less than 400 kW/m^2.

11. FIVE Methodology

The FIVE Methodology for screening potential exposure hazards was used for comparison to the results obtained in Sections 9 and 10. The critical separation distance is based on the classical point source equation [EPRI, 1991; SFPE, 1999], which is given by the following equation:

$$R_{cr} = \sqrt{\frac{\dot{Q}_r}{4\pi \dot{q}''_{cr}}} \quad (14)$$

where R_{cr} is the critical separation distance (m), $\dot{Q}_r$ is the radiant heat release rate (kW), and $\dot{q}''_{cr}$ is the critical heat flux exposure to the target (kW/m^2). The suggested radiant heat release rate per the FIVE methodology is 40 percent of the full heat release rate [EPRI, 1991]. The critical incident heat flux for non-IEEE 383 cables is 5.7 kW/m^2, and the critical steady state heat flux was shown to be between 6 kW/m^2 and 7 kW/m^2.

The total and radiant heat release rate components are a function of the flame spread velocity only, as may be seen by examining Equations 1-11. Table 14 summarizes the results for the five most rapid spread velocities identified in Tables 5a-5h. The maximum heat release rate per flame spread velocity was obtained from Tables 5a-5h.

Table 14. Critical Separation Distances using the FIVE Screening Methodology

Spread Velocity (mm/s)	Radiant Heat Release (kW)	Separation for 11.4 kW/m^2 (m [ft])
12.60	3267	3.02 (9.90)
9.58	2484	2.63 (8.64)
8.08	2095	2.42 (7.93)
6.60	1711	2.18 (7.17)
6.30	1634	2.14 (7.00)
5.04	1307	1.91 (6.30)

The minimum actual cable tray separation is 2.1, (7 ft); thus, scenarios with flame spread rates less than 6.3 mm/s would not exceed the critical heat flux for IEEE 383 qualified or equivalent cables.

12. Steady State Critical Heat Flux

This section of the report describes an additional series of calculations that adjust the EPRI/FIVE Methodology critical incident heat flux to the actual conditions of the problem analyzed in this report. A modified incident heat flux for failure is calculated, called the steady state critical heat flux. The steady state critical heat flux is the minimum heat flux required to heat the surface of the target cable to the critical temperature. The critical flux is a function of the orientation of the cable relative to the exposure fire and the heat losses to ambient. This calculation relates the critical heat flux and failure temperature given in the FIVE Methodology to the cable geometry and exposure problem considered in this report.

The calculated steady state critical heat flux is greater than the failure criteria previously described because it accounts for thermal radiation and convection heat loss, and conduction through the cables is being modeled. It is intended to demonstrate additional conservatism in the analysis.

The steady state critical heat flux was calculated for IEEE 383 rated cable and for non-IEEE 383 rated cable using the finite difference heat transfer model HEATING [Childs, 1998]. HEATING is a finite difference numerical heat transfer program that was developed at Oak Ridge National Laboratories Radiation Safety Information Computation Center to analyze the thermal impact of various high energy research projects. It has one of the longest development histories among computational heat transfer software [Fowler and Volk, 1959; Childs, 1991; Childs, 1998]. Validation studies for this software by Oak Ridge National Laboratories are available in Bryan *et al.* [1986] and Chu [1989]. These validation studies demonstrate that the implementation of the heat transfer equations is correct in HEATING.

The thermal material properties for steel were obtained from Abrams [1978], copper from Holman [1990], and PVC from Marks [1996]. Appendix B summarizes the material properties for each material used in this evaluation. There are two possible exposure scenarios as shown in Figures 12 and 13. The orientation shown in Figure 12, which involves direct exposure to the side of the target cable tray and with heat conduction into cable as shown, was evaluated first.

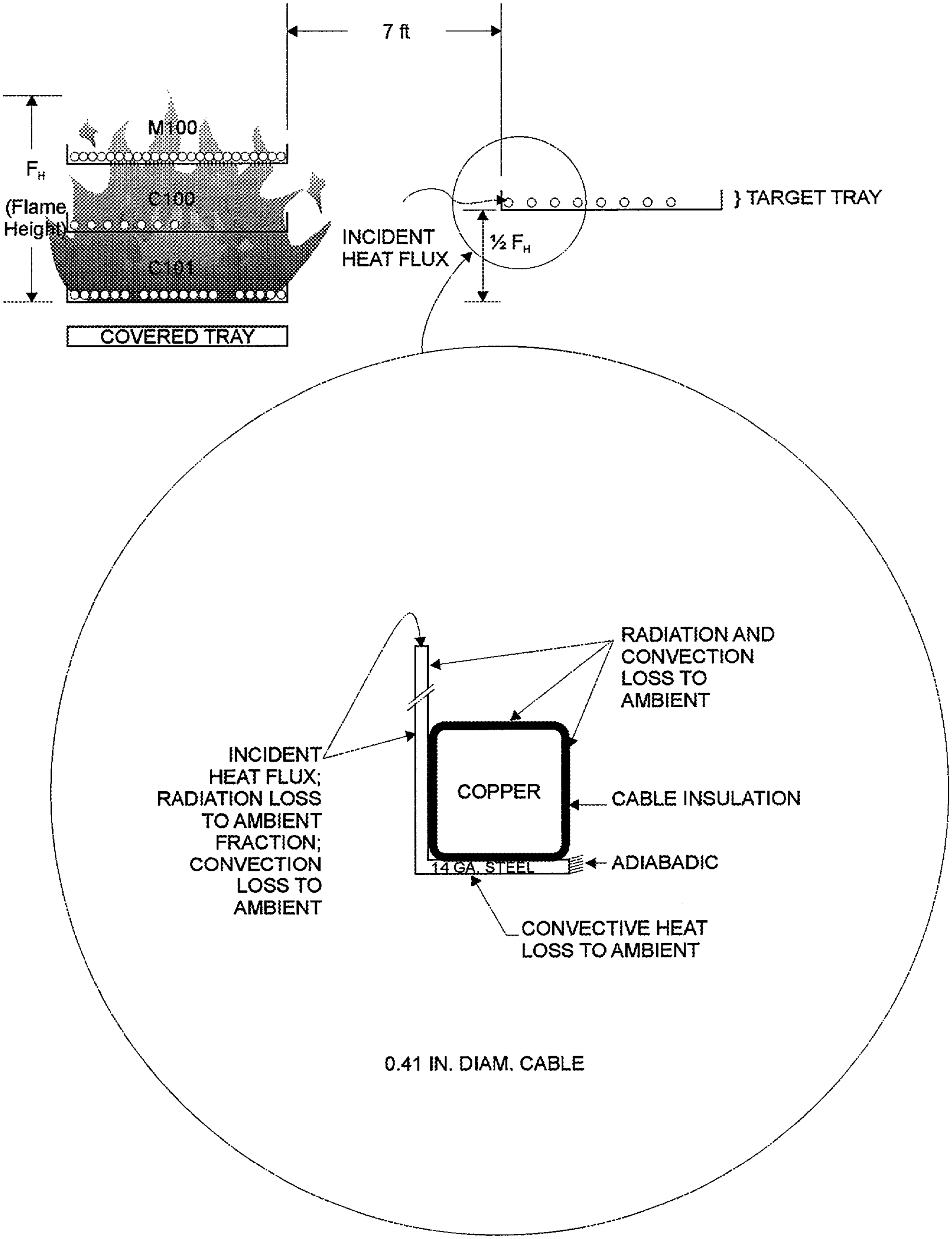

Figure 12 – Target cable tray and cable located directly across burning cable tray

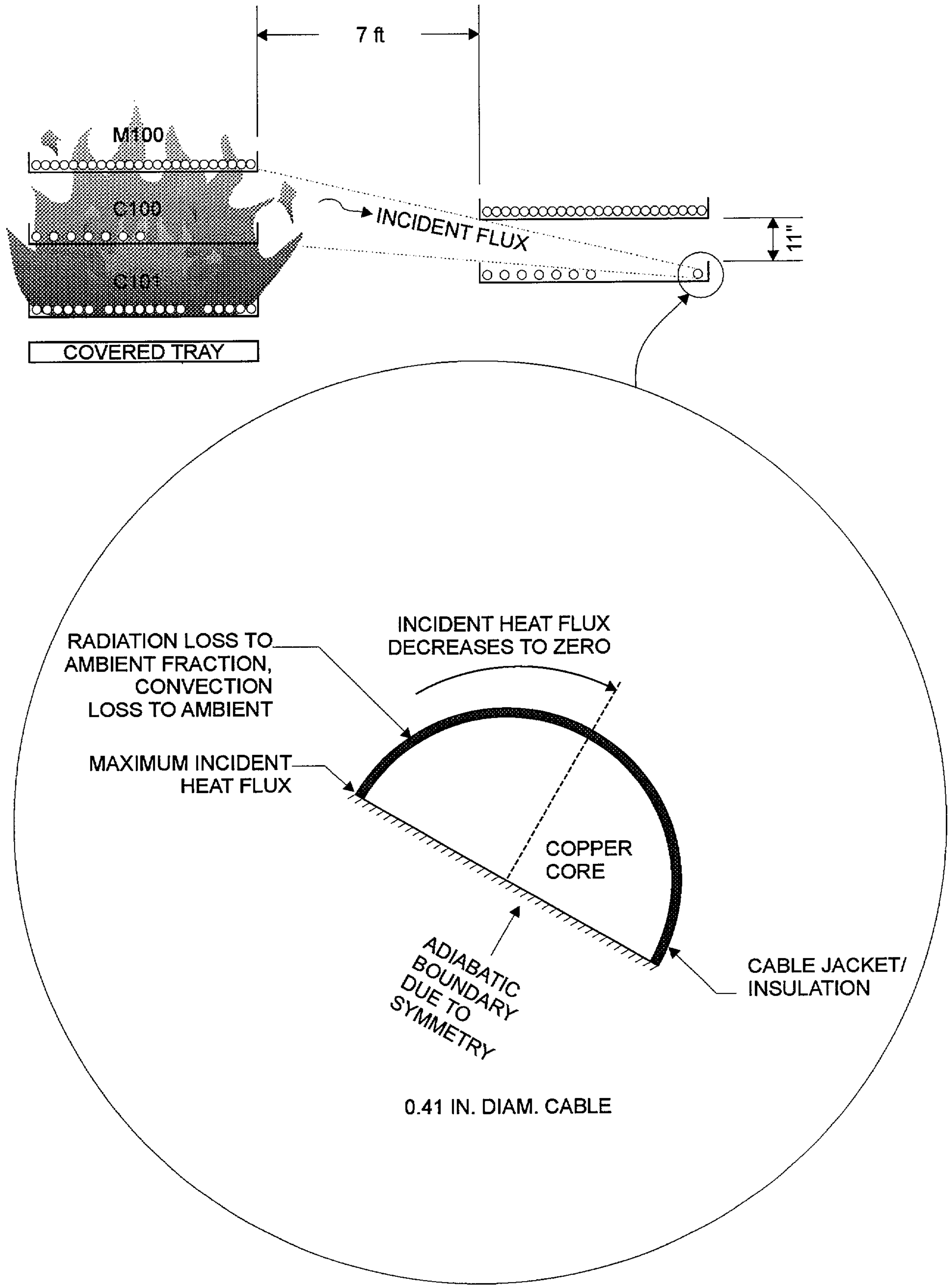

Figure 13 – Direct exposure of cable on far side of target cable tray

The cable was assumed to be square, with each side equal to the smallest size cable diameter [See PSL-FPER-01-052, Rev. 1 (FPL, 2002) for cable loading information]. This approximation was necessary because of the difficulty encountered when mixing rectilinear and cylindrical coordinate systems. The density of the copper was decreased by a factor of 0.78 (area of cylinder cross section divided by area of square cross section) such that the thermal capacity of the core remained constant. The net result is very conservative because the heat flow into the cable is greatly overestimated whereas the thermal capacity remains the same. The energy that is lost to the surroundings is a function of the configuration factor between the fire and the target. The configuration factor will fall between nearly 0 to about 0.4, depending on the size of the fire. Figure 14 summarizes the critical steady state heat flux for non-IEEE 383 qualified cables as a function of the shape factor.

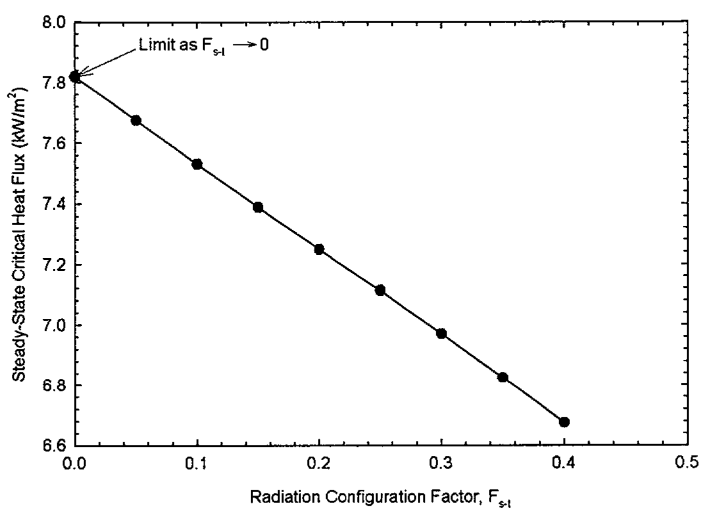

Figure 14 – Critical steady state heat flux as a function of the shape factor for non-IEEE 383 qualified cables

IEEE 383 Qualified Cables

- Failure temperature of 371 °C [EPRI, 1991];
- Critical incident heat flux of 11.4 kW/m^2 [EPRI, 1991]; and
- Critical steady state heat flux between 22.5 kW/m^2 and 24.0 kW/m^2.

non-IEEE 383 Qualified Cables

- Failure temperature of 218 °C [EPRI, 1991];
- Critical incident heat flux of 5.7 kW/m^2; and
- Critical steady state heat flux between 6.4 kW/m^2 and 7.8 kW/m^2 (Figure 14).

The critical steady state heat flux is greater than the critical incident heat flux because the specific geometry is evaluated. The critical incident heat flux is based on small scale test data and generally represents a worst case scenario. Note that one scenario listed in Table 10 and one in Table 11 exceeds the critical steady state heat flux for IEEE 383 qualified cable. Each scenario requires a unit heat release rate of 1,000 kW/m^2, a flame spread velocity of 12.6 mm/s, and a radiant fraction of 0.5. The minimum unit heat release rate that could result in an exposure heat flux that exceeds the non-IEEE 383 qualified cable critical steady state heat flux is 400 kW/m^2.

It is evident that steady state conditions, which account for heat losses and the actual cable orientation, allow for an incident heat flux exposure that is reported by EPRI [1991].

The second configuration shown in Figures 4a-4d was analyzed next. The cable is assumed located in the far corner of the cable tray and intercepts radiation through the aperture formed between the two trays. Because the cable is located further from the flame in this orientation, for a given fire scenario the maximum configuration factor and incident heat flux will <u>always</u> be less than the corresponding exposure to the side tray. A bounding approximation thus assumes that the shape factor is the same for both the side exposure and direct exposure orientations.

Another important consideration for this case is that the radiant heat flux decreases rapidly in either direction when moving away from the maximum, as shown in Figure 13.

The critical steady state heat flux for non-IEEE 383 cables was estimated and calculated using HEATING to be 19.8 kW/m^2 assuming a shape factor of 0.24. The heating calculation includes radiation and convection heat losses, which are particularly important in this case due to the surface dependent incident heat flux. This means that this configuration is bounded by the exposure to the tray that conducts into the cable. This is made obvious by comparing the 6.5 kW/m^2 critical steady state heat flux obtained using a shape factor of 0.24 (see Figure 14) to the 19.8 kW/m^2 critical steady state heat flux. Consequently, the direct cable exposure configuration is not considered further in this evaluation.

12.1 Sensitivity of Steady-State Critical Heat Flux to Boundary Conditions

The sensitivity of the steady state critical heat flux to the assumed target tray boundary conditions was evaluated in accordance with NFPA 805 [2001]. The thermal material properties of the steel, copper, and PVC are well established and do not require parametric study.

There are two key boundary condition assumptions: the radiation emissivity of the cable tray is 0.8 and the convection coefficient is 5.0 W/m^2-°C. The emissivity was selected assuming that there would be a coating of Flamemastic. The emissivity of galvanized steel may be as low as 0.3. The emissivity of the Flamemastic may also be greater than 0.8 but must be less than 1.0. The emissivity is thus assumed to vary between 0.3 and 1.0.

The convection coefficient is based on the local air flow and is difficult to estimate without intensive computation. A value of 5 W/m^2-°C is on the low end of fire exposure conditions. This parameter was varied from 5 W/m^2-°C to 15.0 W/m^2-°C.

The results are summarized in Table 15 for non-IEEE 383 cables. The Table indicates that the steady state critical heat flux is somewhat sensitive to both boundary conditions. The Table suggests that the maximum expected fire scenario critical heat flux is likely under-estimated because the only instances where the value decreased are unrealistic: either zero convection heat loss or complete absorption of all incident thermal radiation.

Table 15. Sensitivity of Steady-State Critical Heat Flux to Boundary Conditions (non-IEEE 383 cables)

Parameter Modification	Steady State Critical Heat Flux (kW/m^2)	Impact
MAXIMUM EXPECTED FIRE SCENARIO	7.1	N/A
Target Emissivity Decreased to 0.3	11.3	+ 4.2 W/m^2
Target Emissivity Decreased to 0.5	8.8	+ 1.7 W/m^2
Target Emissivity Increased to 1.0	6.7	- 0.4 W/m^2
Target Convection Decreased to 0.0 W/m^2-°C	5.6	- 1.5 W/m^2
Target Convection Increased to 10.0 W/m^2-°C	11.3	+ 4.2 W/m^2
Target Convection Increased to 15.0 W/m^2-°C	14.2	+ 7.1 W/m^2

13. Transient Heat Transfer Analysis

An additional analysis was performed that models the transient thermal response of the exposed cables. It focuses on the transient response of non-IEEE qualified cable, and is intended to demonstrate that if the exposed cables were treated as non-qualified cables, the critical failure temperature of these cables would not be exceeded for cases where the critical steady state heat flux for non-qualified cables is exceeded in the calculations presented in Section 10. For IEEE 383 qualified cables or equivalent, this analysis is not important.

A transient heat transfer analysis was performed using basic principles of heat transfer and thermal equilibrium and the finite difference computer model HEATING [Childs, 1998].

The configuration considered is shown in Figure 8. Because of the complexity that arises when mixing cylindrical and rectilinear coordinate systems, the cable cross section was assumed square with a side dimension equal to the diameter of the cable. The density of the copper was reduced in proportion with the increase in volume, namely the thermal capacity of the round and square systems remains constant. The boundary conditions and material properties are as described in Section 6.

The critical temperature is known to be 218°C for non-IEEE 383 compliant cables and 371°C for IEEE 383 cables. Ambient temperature is assumed to be 20°C. A conservative estimate of the convection coefficient is 5 W/m^2-K [Babrauskas, 1979], and the emissivity of the steel is assumed to be 0.8 due to the presence of the Flamemastic fire retardant material. The radiation configuration factor varies from scenario to scenario because of the different fire.

A transient heat transfer analysis of the three-tier and four-tier cable tray scenarios that resulted in a target heat flux greater than the critical steady-state heat flux was performed using HEATING for the side of the cable tray exposure A two-dimensional analysis was performed as shown in Figure 12. In all cases, the smallest cable (0.41 in. diameter) was assumed because there is a smaller heat sink. Figure 12 also depicts the assumed boundary conditions on the cable tray and the cable jacket. The transient analysis calculates the temperature response of the surface of the cable using a transient heat flux from a growing fire as it spreads away from the point of origin. Tables 16 and 17 summarize the peak cable surface temperatures for the three-tier and four-tier cable tray scenarios where the critical steady-state heat flux was exceeded.

Table 16a. Results of Transient Heat Transfer Analysis for Three-Tier Cable Tray Array (Reference Point 2307)

$\dot{q}''_{bs}$ (kW/m^2)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m^2)	Peak Temperature (°C)
400	3 of 3	1.77	0.5	6.93	170
		3.54	0.4	7.51	174
			0.5	9.47	202
		2.0	0.5	7.46	178
500	2 of 3	5.04	0.5	6.80	170
	3 of 3	2.52	0.4	7.48	170
			0.5	9.39	200
		5.04	0.3	7.33	156
			0.4	9.77	190
			0.5	12.21	**222**
		2.0	0.5	8.08	187
600	2 of 3	3.28	0.5	8.19	170
		6.6	0.4	8.34	155
			0.5	10.42	182
	3 of 3	3.28	0.3	6.98	154
			0.4	9.30	188
			0.5	11.63	216
		6.6	0.3	8.89	165
			0.4	11.86	203
			0.5	14.82	**237**
		2.0	0.5	8.41	189
700	2 of 3	4.04	0.4	7.85	153
			0.5	9.82	179
		8.08	0.3	7.36	132
			0.4	9.81	163
			0.5	12.26	191
	3 of 3	4.04	0.3	8.27	163
			0.4	11.03	197
			0.5	13.78	**229**
		8.08	0.3	10.35	172
			0.4	13.81	212
			0.5	17.27	**247**
		2.0	0.4	6.85	163
			0.5	8.56	186

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 16b. Results of Transient Heat Transfer Analysis for Three-Tier Cable Tray Array (Reference Point 2307)

$\dot{q}''_{bs}$ (kW/m^2)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m^2)	Peak Temperature (°C)
800	2 of 3	4.79	0.3	6.82	131
			0.4	9.10	161
			0.5	11.37	189
		9.58	0.3	8.43	136
			0.4	11.24	168
			0.5	14.05	198
	3 of 3	4.79	0.3	9.48	168
			0.4	12.65	207
			0.5	15.81	**240**
		9.58	0.3	11.76	177
			0.4	15.68	218
			0.5	19.60	**255**
		2.0	0.4	6.88	162
			0.5	8.60	184
1,000	2 of 3	6.3	0.3	8.60	139
			0.4	11.46	171
			0.5	14.33	201
		12.6	0.3	10.49	142
			0.4	13.98	176
			0.5	17.48	208
	3 of 3	6.3	0.3	11.74	178
			0.4	15.65	218
			0.5	19.57	**254**
		12.6	0.3	14.38	183
			0.4	19.17	**226**
			0.5	23.96	**254**
		2.0	0.4	6.80	183
			0.5	8.50	**226**

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 17a. Results of Transient Heat Transfer Analysis for Four-Tier Cable Tray Array (Reference Point 2305)

$\dot{q}''_{bs}$ (kW/m²)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m²)	Peak Temperature (°C)
400	4 of 4	3.54	0.4	7.18	167
			0.5	8.97	195
		2.0	0.5	7.06	175
500	3 of 4	5.04	0.5	6.54	169
	4 of 4	2.52	0.4	7.09	166
			0.5	8.87	193
		5.04	0.3	6.96	150
			0.4	9.28	183
			0.5	11.60	215
		2.0	0.5	7.66	178
600	3 of 4	3.28	0.5	8.08	170
		6.6	0.4	8.02	154
			0.5	10.03	181
	4 of 4	3.28	0.3	6.63	148
			0.4	8.85	181
			0.5	11.06	208
		6.6	0.3	8.46	159
			0.4	11.28	195
			0.5	14.10	**228**
		2.0	0.5	7.99	182
700	3 of 4	4.04	0.4	7.77	155
			0.5	9.71	180
		8.08	0.3	7.08	132
			0.4	9.44	163
			0.5	11.80	192
	4 of 4	4.04	0.3	7.88	157
			0.4	10.50	190
			0.5	13.12	**225**
		8.08	0.3	9.87	165
			0.4	13.16	205
			0.5	16.44	**239**
		2.0	0.5	8.15	179

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 17b. Results of Transient Heat Transfer Analysis for Four-Tier Cable Tray Array (Reference Point 2305)

$\dot{q}''_{bs}$ (kW/m^2)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m^2)	Peak Temperature (°C)
800	3 of 4	4.79	0.3	6.72	133
			0.4	8.96	162
			0.5	11.21	191
		9.58	0.3	8.12	169
			0.4	10.82	206
			0.5	13.53	**242**
	4 of 4	4.79	0.3	9.05	162
			0.4	12.06	198
			0.5	15.07	**231**
		9.58	0.3	11.22	170
			0.4	14.96	210
			0.5	18.70	**246**
		2.0	0.4	6.56	156
			0.5	8.20	178
1,000	3 of 4	6.3	0.3	8.48	140
			0.4	11.31	172
			0.5	14.13	203
		12.6	0.3	10.11	143
			0.4	13.48	176
			0.5	16.85	208
	4 of 4	6.3	0.3	11.23	171
			0.4	14.97	210
			0.5	18.71	**246**
		12.6	0.3	13.75	176
			0.4	18.34	218
			0.5	22.92	**257**
		2.0	0.5	8.13	178

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

The tables indicate that none of the scenarios result in a cable surface temperature that exceeds the critical value of 371 °C for IEEE 383 qualified cable. The minimum unit heat release rate that could heat the cables to the critical temperature of 218 °C for non-IEEE qualified cables is 500 kW/m^2.

13.1 Impact of Ambient Temperature on Transient Temperature Calculations

The impact of the ambient temperature on the results was performed in accordance with NFPA 805 [2001]. A bounding estimate of the ambient temperature is 49°C. Tables 18 and 19 summarize the results of this calculation modification.

Table 18a. Results of Transient Heat Transfer Analysis for Three-Tier Cable Tray Array (Reference Point 2307) Ambient Temperature Increased to 49 °C

$\dot{q}''_{bs}$ (kW/m²)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m²)	Peak Temperature (°C)
400	3 of 3	1.77	0.5	6.93	186
		3.54	0.4	7.51	190
			0.5	9.47	215
		2.0	0.5	7.46	193
500	2 of 3	5.04	0.5	6.80	188
	3 of 3	2.52	0.4	7.48	189
			0.5	9.39	214
		5.04	0.3	7.33	174
			0.4	9.77	207
			0.5	12.21	**237**
		2.0	0.5	8.08	202
600	2 of 3	3.28	0.5	8.19	186
		6.6	0.4	8.34	175
			0.5	10.42	200
	3 of 3	3.28	0.3	6.98	172
			0.4	9.30	204
			0.5	11.63	**233**
		6.6	0.3	8.89	184
			0.4	11.86	220
			0.5	14.82	**252**
		2.0	0.5	8.41	202
700	2 of 3	4.04	0.4	7.85	173
			0.5	9.82	198
		8.08	0.3	7.36	153
			0.4	9.81	182
			0.5	12.26	209
	3 of 3	4.04	0.3	8.27	181
			0.4	11.03	215
			0.5	13.78	**246**
		8.08	0.3	10.35	191
			0.4	13.81	**229**
			0.5	17.27	**263**
		2.0	0.4	6.85	177
			0.5	8.56	204

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 18b. Results of Transient Heat Transfer Analysis for Three-Tier Cable Tray Array (Reference Point 2307) Ambient Temperature Increased to 49 °C

$\dot{q}''_{bs}$ (kW/m^2)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m^2)	Peak Temperature (°C)
800	2 of 3	4.79	0.3	6.82	153
			0.4	9.10	181
			0.5	11.37	207
		9.58	0.3	8.43	157
			0.4	11.24	188
			0.5	14.05	217
	3 of 3	4.79	0.3	9.48	188
			0.4	12.65	**223**
			0.5	15.81	**256**
		9.58	0.3	11.76	196
			0.4	15.68	**235**
			0.5	19.60	**271**
		2.0	0.4	6.88	179
			0.5	8.60	203
1,000	2 of 3	6.3	0.3	8.60	160
			0.4	11.46	192
			0.5	14.33	**219**
		12.6	0.3	10.49	163
			0.4	13.98	197
			0.5	17.48	**227**
	3 of 3	6.3	0.3	11.74	193
			0.4	15.65	**236**
			0.5	19.57	**270**
		12.6	0.3	14.38	203
			0.4	19.17	**244**
			0.5	23.96	**270**
		2.0	0.4	6.80	203
			0.5	8.50	**244**

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 19a. Results of Transient Heat Transfer Analysis for Four-Tier Cable Tray Array (Reference Point 2305) Ambient Temperature Increased to 49 °C

$\dot{q}''_{bs}$ (kW/m^2)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m^2)	Peak Temperature (°C)
400	4 of 4	3.54	0.4	7.18	184
			0.5	8.97	210
		2.0	0.5	7.06	189
500	3 of 4	5.04	0.5	6.54	186
	4 of 4	2.52	0.4	7.09	183
			0.5	8.87	208
		5.04	0.3	6.96	169
			0.4	9.28	200
			0.5	11.60	**230**
		2.0	0.5	7.66	196
600	3 of 4	3.28	0.5	8.08	187
		6.6	0.4	8.02	174
			0.5	10.03	199
	4 of 4	3.28	0.3	6.63	167
			0.4	8.85	197
			0.5	11.06	225
		6.6	0.3	8.46	178
			0.4	11.28	212
			0.5	14.10	**244**
		2.0	0.5	7.99	196
700	3 of 4	4.04	0.4	7.77	173
			0.5	9.71	199
		8.08	0.3	7.08	153
			0.4	9.44	182
			0.5	11.80	209
	4 of 4	4.04	0.3	7.88	176
			0.4	10.50	205
			0.5	13.12	**237**
		8.08	0.3	9.87	185
			0.4	13.16	**221**
			0.5	16.44	**254**
		2.0	0.5	8.15	195

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Table 19b. Results of Transient Heat Transfer Analysis for Four-Tier Cable Tray Array (Reference Point 2305) Ambient Temperature Increased to 49 °C

$\dot{q}''_{bs}$ (kW/m²)	Number of Trays	v_s (mm/s)	χ_r	$\dot{q}''_t$ (kW/m²)	Peak Temperature (°C)
800	3 of 4	4.79	0.3	6.72	153
			0.4	8.96	182
			0.5	11.21	208
		9.58	0.3	8.12	188
			0.4	10.82	**224**
			0.5	13.53	**258**
	4 of 4	4.79	0.3	9.05	182
			0.4	12.06	216
			0.5	15.07	**248**
		9.58	0.3	11.22	190
			0.4	14.96	**220**
			0.5	18.70	**263**
		2.0	0.4	6.56	171
			0.5	8.20	197
1,000	3 of 4	6.3	0.3	8.48	162
			0.4	11.31	193
			0.5	14.13	**221**
		12.6	0.3	10.11	163
			0.4	13.48	193
			0.5	16.85	**227**
	4 of 4	6.3	0.3	11.23	191
			0.4	14.97	**228**
			0.5	18.71	**261**
		12.6	0.3	13.75	196
			0.4	18.34	**237**
			0.5	22.92	**238**
		2.0	0.5	8.13	194

Boldface indicates the temperature exceeds the critical temperature of 218 °C for non-IEEE qualified cable

Comparing Tables 16 and 17 to Tables 18 and 19 lead to the conclusion that the increase in ambient to 49°C causes the maximum cable insulation temperature to increase by about 15-20 °C. Even with this increase, there are no scenarios that are predicted to result in cable surface temperature greater than 371 °C, the critical temperature for IEEE 383 qualified cable.

14. Conclusions

14.1 A 7-ft horizontal separation between the SA and SB cable tray systems is adequate to ensure that fire induced failure of both systems will not occur given the fire hazard present.

14.2 The Flamemastic coated cables are equivalent to IEEE qualified cables from the standpoint of damageability performance.

14.3 The critical incident heat flux for IEEE 383 qualified cables is 11.4 kW/m^2. When adjusted for the specific conditions of this installation, the critical steady state heat flux is increased to between 22.5 kW/m^2 and 24.0 kW/m^2. For unqualified cables, the critical incident flux is 5.7 kW/m^2, and the steady state critical flux is between 6.4 kW/m^2 and 7.8 kW/m^2.

14.4 The maximum expected fire scenario (MEFS) as defined in NFPA 805 [2001], Appendix B, consists of a three cable tray array exposing a target cable tray located 7 ft away. A heat release rate of 400 kW/m^2 with a radiative fraction of 0.4 and a flame spread rate of 1.8 mm/s forms the fire source for this maximum expected fire scenario.

14.5 The results of the maximum expected fire scenario indicate that the critical incident flux conditions are not exceeded for either IEEE 383 qualified or unqualified cables.

14.6 An analysis of the effects of forced mechanical ventilation and the collection of air speed measurements in the relevant plant area indicate that there are no negative effects of forced ventilation on the results.

14.7 The limiting fire scenario for the four-tier cable tray array requires a heat release rate of 700 kW/m^2 and a flame spread rate of 8.08 mm/s with three trays involved. If the covered bottom tray is assumed to contribute, then the limiting fire scenario requires a heat release rate of 500 kW/m^2 and greater than expected flame spread rate. Similarly, the limiting fire scenario for the three-tier cable tray array requires a heat release rate of 700 kW/m^2 and a flame spread rate of 8.08 mm/s with two trays involved. If the covered bottom tray is assumed to contribute, then the limiting fire scenario requires a heat release rate of 500 kW/m^2 and a greater than expected flame spread rate. A complete sensitivity analysis and evaluation of limiting fire scenarios is given.

14.8 The use of a steady state critical heat flux that is related to failure temperature results in additional conservatism in the analysis.

14.9 If the Flamemastic coated cables are assumed to have performance equivalent to non-IEEE 383 qualified cables, the limiting fire scenarios can be achieved with a heat release rate of 400 kW/m^2 and an elevated flame spread velocity.

14.10 For cases where an unqualified cable is assumed and heat release rates do not exceed 600 kW/m^2, a transient heat transfer analysis indicates that the failure temperature will not be reached.

14.11 An analysis of limiting conditions of adding additional cables indicates that IEEE 383 qualified cable is used and the heat release rate is limited to 400 kW/m^2, up to 170 cables of a fixed size and construction can be added to a three tray array. If a safety factor of two is assumed, then 85 cables can be added without exceeding the critical heat flux of 11.4 kW/m^2 for IEEE 383 qualified cables.

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