Evaluation of Selected Control Panel Components Subjected to a Postulated Exposure Fire

Enrico Fermi Atomic Power Plant
Unit 2

Docket No. 50-341

November 1981

The Detroit Edison Co.
2000 Second Avenue
Detroit, Michigan 48226

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1.0 Introduction

The Enrico Fermi Atomic Power Plant Unit 2 (Fermi 2) was designed and built before the promulgation of the fire protection requirements embodied in Title 10 of the Code of Federal Regulations, Part 50, Appendix R (10 CFR 50, Appendix R). In several areas, the requirements of Appendix R are more conservative than the previously accepted design criteria of the Fermi 2 plant. During the U.S. Nuclear Regulatory Commission (NRC) staff's review of the Fermi 2 plant in light of Appendix R, the Detroit Edison Company made a commitment to install additional fire protection features. These commitments are documented in Detroit Edison correspondence with the NRC (Colbert, 1981a–1981g) and in the NRC's Safety Evaluation Report (SER) related to the operation of Fermi 2 (NRC, 1981). For the postulated exposure fire in the control room, Detroit Edison believes that a consideration of the plant-unique features is needed when addressing the requirements of Appendix R.

Because the control room is continuously occupied, an exposure fire in the control room was considered highly improbable and beyond the original design basis. Any exposure fire in the control room would be discovered and extinguished quickly, and damage would be limited to one divisional panel. Therefore, the remote-shutdown features of the Fermi 2 plant were designed to meet the requirements of 10 CFR 50, Appendix A, General Design Criterion 19, which required an evacuation of the control room and the use of the remote-shutdown panel, but did not postulate damage of the circuits in the control panels. Thus, the remote-shutdown features of the Fermi 2 plant were not required to be electrically isolable from the circuits in the control panels.

To help demonstrate that circuits in the control panels at Fermi 2 would remain intact during an exposure fire in the control room and thereby to demonstrate that the remote-shutdown features of the Fermi 2 plant meet the intent of Appendix R, Detroit Edison ran a test in June 1981. The details of the test procedure were discussed and cleared with the NRC staff before the test was run. The test procedure and results are documented in Detroit Edison's report to the NRC (Colbert, 1981g) and the NRC consultant's report (Behn, 1981) and are not repeated here. The test consisted of burning 1 gallon of a flammable liquid (heptane) in front of a simulated control panel and showed that switches and circuits on the control panel remained intact and did not malfunction.

In the Fermi 2 SER, the NRC reported that its consultant had identified the following four deficiencies with the test (Behn, 1981):

1. The mock-up panels did not simulate the plastic components mounted on the control room panels.
2. The fire configuration was altered during the test because of the distortion of the fuel pan.
3. The mock-up panels did not simulate the control room panel ventilation system, which had not yet been designed.
4. The effects of fire suppressants on the components were not demonstrated.

Detroit Edison addressed and responded to these four items in its final report on the control panel fire test (Colbert, 1981g). After reviewing this information, the NRC advised Detroit Edison that three questions remained. One concerned the control panel ventilation and two concerned plastics used in the control panel components.

In response to the NRC staff's concern that flames from an exposure fire in the control room might be drawn into the control panels through the grills on the lowest face, Detroit Edison agreed to install Marinite board on the inside of the grilled face to seal and insulate that surface. However, this modification also required that the control panels be supplied with forced ventilation. In the fire test report, Detroit Edison described the forced ventilation it planned to provide to the control panels. This consisted of vertical feeds to the "hardened" control panels from the overhead duct of the control center ventilation system. After reviewing this description, the NRC was concerned that a fire in one divisional panel might be able to enter the other divisional panel through the common overhead duct supplying the panels. Detroit Edison plans to install fusible-link-operated dampers on each panel's ventilation duct discharge to prevent the spread of a fire from one panel to another.

The first of the NRC's two concerns about plastics in the control panels was that the plastic windows used in the annunciators mounted on the uppermost face of the control panel might distort or melt in the postulated exposure fire. This might result in the plastic falling onto the lower surfaces of the control panel and, perhaps, damaging the switches on those surfaces. Detroit Edison agreed to replace the plastic windows with glass windows on the annunciators to resolve the concern. This was discussed with the NRC in telephone conversations on September 16* and 17†, 1981.

The second of the NRC's two concerns about plastics on the control panels was that the plastic switches mounted on the control panels might distort or melt in the exposure fire. If this occurred, the switches might fall through the panel surface and, perhaps, short or operate spuriously. This did not occur during the panel fire test. However, the NRC felt that further experimental and theoretical verification of the earlier fire test results was needed. In the telephone conversations of September 16 and 17, the NRC and Detroit Edison agreed on the 2-pronged approach to be taken by Detroit Edison to resolve the NRC's remaining concern. Detroit Edison agreed to run an oven test exposing a simulated panel front with the switches mounted on it to an oven temperature conservatively specified by the NRC to be 600°F for a period of 8 minutes, bounding the conditions of the actual panel fire test run by Detroit Edison, to confirm that the switches would remain intact and would not malfunction in the postulated exposure fire. Detroit Edison also agreed to calculate the panel surface temperatures

*Telephone conversation between V. Benaroya, NRC, and W. F. Colbert, Detroit Edison, September 16, 1981.

†Telephone conversation between W. Johnston, NRC, and W. F. Colbert, Detroit Edison, September 17, 1981.

theoretically expected in the postulated fire to confirm that they would be less than the test temperature of 600°F and similar to those measured in the fire test.

Part of this report documents the tests and calculations performed by Detroit Edison to resolve the NRC's second concern. Section 2 of this report describes the oven test of the control switches, Section 3 summarizes the calculations done to confirm the panel fire test results, and Section 4 presents Detroit Edison's conclusions from the oven test and the confirmatory calculations. Figures 1-1 and 1-2 are photographs of the control panels and a closeup of panel 601 installed in the Fermi 2 control room. These will aid the reader's understanding of the material presented in Sections 2 and 3 of this report. The photographs also illustrate that the Fermi 2 control room is essentially complete at this time.

Detroit Edison believes that the information presented in this report is sufficient to resolve the NRC's remaining concern. Detroit Edison has concluded that the panel fire test, the oven test, and the calculations confirm its position that the design of the Fermi 2 control room provides adequate protection of the public health and safety and meets the intent of the NRC's requirements for alternate shutdown independent of the control room.

References

Behn, J. D., Gage-Babcock & Associates, Inc. 1981. "Fermi 2 Control Room Fire Test." Letter 7917-4 to V. Benaroya, NRC, June 24.

Colbert, W. F., Detroit Edison. 1981a. "Provision of 1-HR Barriers in Control Room." Letter EF2-53462 to L. L. Kintner, NRC, June 16.

Colbert, W. F., Detroit Edison. 1981b. "Fire Protection Commitments." Letter EF2-53791 to L. L. Kintner, NRC, June 18.

Colbert, W. F., Detroit Edison. 1981c. "Fire Protection Commitments." Letter EF2-53818 to L. L. Kintner, NRC, June 19.

Colbert, W. F., Detroit Edison. 1981d. "Fire Protection Review." Letter EF2-53897 to L. L. Kintner, NRC, June 29.

Colbert, W. F., Detroit Edison. 1981e. "Response to Q 021.32 Fire Protection." Letter EF2-53899 to L. L. Kintner, NRC, June 29.

Colbert, W. F., Detroit Edison. 1981f. "Transmittal of the Updated Fire Hazard Analysis, FSAR Appendix 9B." Letter EF254202 to L. L. Kintner, NRC, July 31.

Colbert, W. F., Detroit Edison. 1981g. "Control Panel Fire Test." Letter EF2-54205 to L. L. Kintner, NRC, July 31.

NRC (U.S. Nuclear Regulatory Commission). 1981. *Safety Evaluation Report Related to the Operation of Enrico Fermi Atomic Power Plant, Unit No. 2.* NUREG-0798.

Figure 1-1. Layout of control panels - Fermi 2 control room.

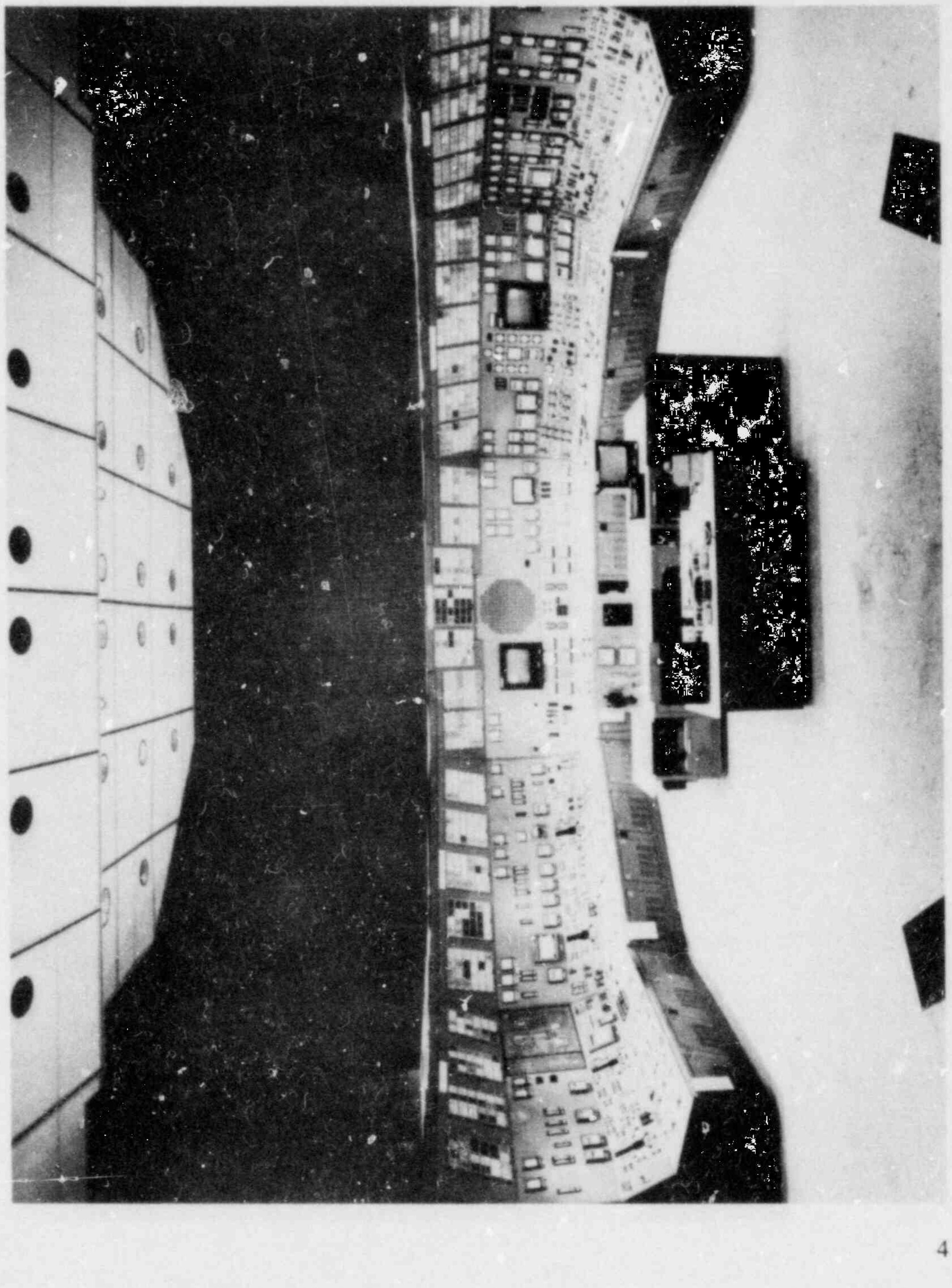
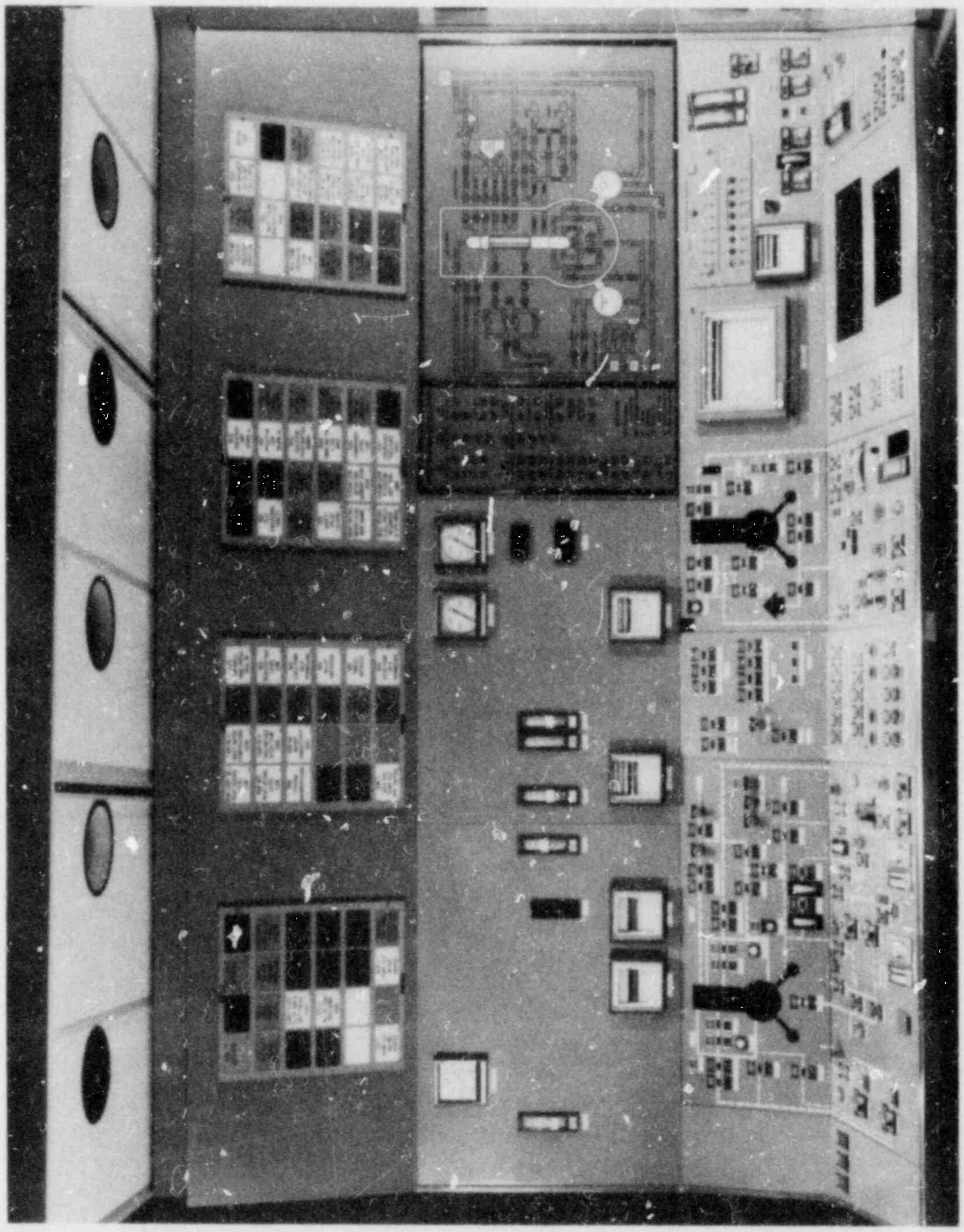


Figure 1-2. Closeup of control panel 601 - Fermi 2 control room.



2.0 Oven Test

On October 15, 1981, the Engineering Research Department of Detroit Edison conducted a test on two types of switches used in the control panels of the Fermi 2 control room. The test was performed to determine whether the coordinated manual control (CMC) switches and the pushbutton switches would remain intact and would continue to function when exposed to a temperature of 600°F for 8 minutes. The temperature and time specified were regarded by Detroit Edison to be extremely conservative and intended by the NRC to bound the conditions to which these switches were exposed during the control panel fire test of June 11, 1981. This section describes the procedure for and the results of the test.

2.1 Procedure

A metal box was built to simulate the angle of the control panel surface in which the pushbutton and CMC switches are installed at Fermi 2. The box formed a complete enclosure for inserting into the oven and completely sealing the oven door opening. The back of the box consisted of a removable plate, and the front was insulated with Marinite board, which Detroit Edison has made a commitment to install on the panels in the Fermi 2 control room. This box is illustrated in Figure 2-1.

One CMC switch and one pushbutton switch were installed on the metal box; the mounting of these switches is shown in Figure 2-1. Four thermocouples were attached to the CMC switch to monitor temperatures of various parts of the switch throughout the test. It was impractical to attach thermocouples to the pushbutton switch because of its relatively small size. Thermocouples were installed between switches to measure the surface temperature of the switch enclosure and the air temperature 2 inches above the switch enclosure. The thermocouple locations are shown in Figure 2-2. The operating electrical contacts of the switches were wired and monitored during the test. The "normally closed" contacts of the CMC switch were wired in series and the "normally open" contacts were wired in parallel. The pushbutton switch was wired in the "normally open" position.

The test was conducted in a 54-kilowatt Lindberg Hevi-Duty electric-circulating oven, type 73-EC-484872-8, S/N 22626. The oven temperature was maintained at 600°F during the entire test. The metal enclosure, with the switches, their instrumentation, and wiring installed, was inserted into the oven door opening, completely sealing the door opening. The temperatures and switch-contact conditions were monitored every 10 seconds during the test with a Fluke Model 2240B data logger. The enclosure was removed after 8 minutes of exposure to the oven temperature of 600°F, and the switches were then inspected for deformation and operation. The results of this inspection are discussed in Section 2.2.

Figure 2-1. Metal enclosure and mounting of CMC switch and pushbutton switch for 600°F oven temperature test.

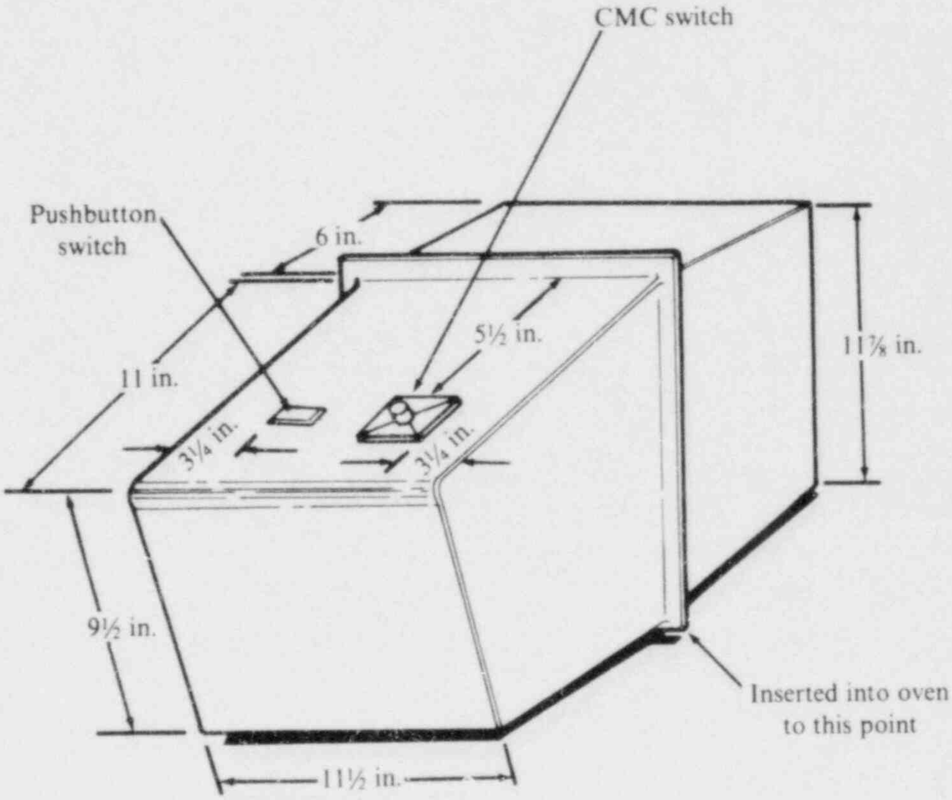
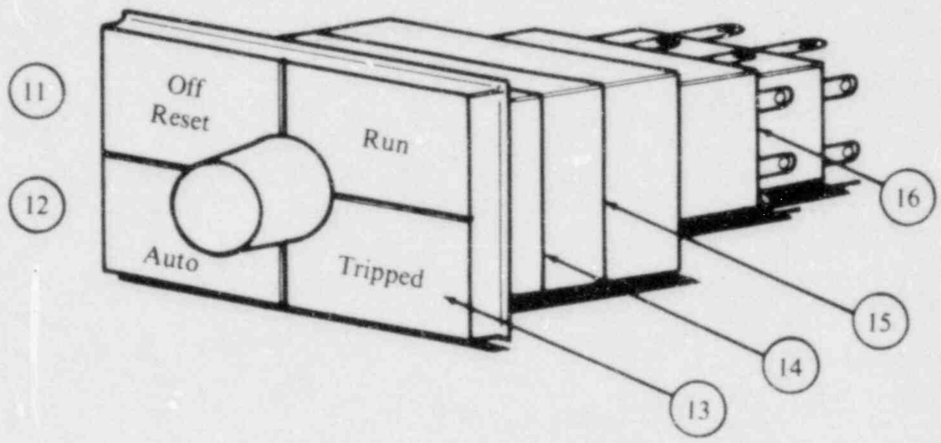


Figure 2-2. Location of thermocouples on CMC switch during elevated temperature test of 600°F.



TC11 – Air temperature 2 inches above switch enclosure and between switches
TC12 – Surface temperature of switch enclosure between switches
TC13 – Inserted in surface of plastic actuator display cover plate
TC14 – ¼ inch inside and between junction of white lamp housing and black cam housing
TC15 – ¼ inch inside and between junction of cam housing and lamp transformer housing
TC16 – ¼ inch inside and between switch contact blocks

Key: TC = thermocouple.

An overall calibration of the data logger, including a sample of the thermocouple wire used and the isothermal connecting block, was made just after the test. The results are shown in the calibration certificates in Appendix A of this report.

2.2 Results

Visual inspection showed that the actuator display cover panel of the CMC switch and the actuator knob, which are above the control panel surface, were deformed, but intact and supporting the switch. The operating sections of the switch located inside the enclosure showed no damage or deformation from the elevated temperature. The indicating lights and switch contacts were unharmed and were operational during and after the test.

No deformation or damage could be found on the pushbutton switch, and it functioned normally during and after the test.

Figure 2-3 shows the temperatures measured as a function of time during the oven test; refer to Figure 2-2 for the location of the thermocouples. The peak temperatures recorded are summarized in Table 2-1.

2.3 Conclusions

Both switches remained intact and functional during this test. They would be expected to remain in place on the control panel surface in the postulated control room exposure fire, and would not be expected to malfunction.

Figure 2-3. Temperature profile of temperature-monitoring positions during 600°F oven test.

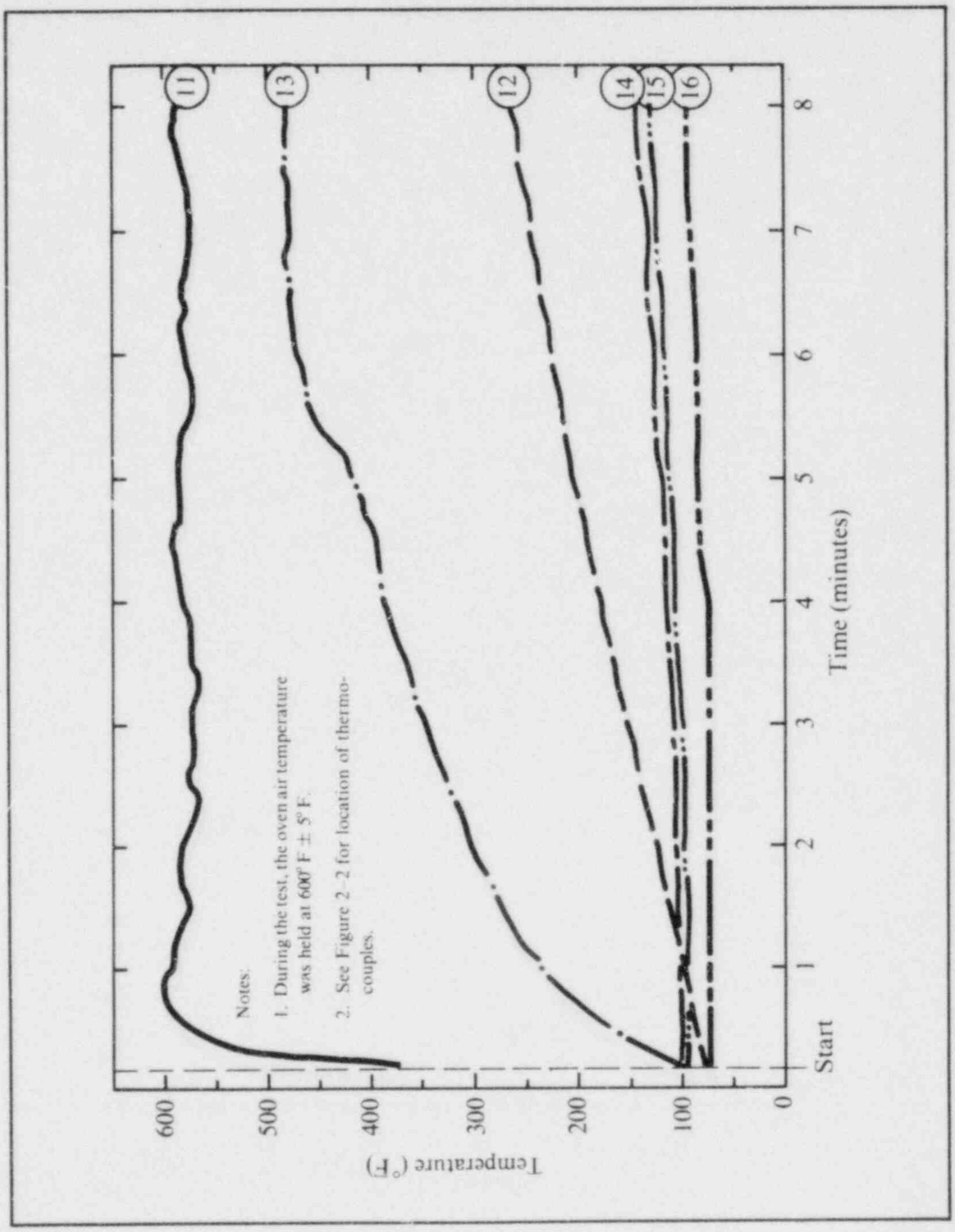


Table 2-1. Summary of Temperatures Measured During Oven Test

Location	Maximum Temperature Measured (°F)	Time (minutes into test)
Oven air	600	Duration of test
Air temperature 2 inches above switches (thermocouple 11)	600.5	0.66
Metal surface temperature between switches (thermocouple 12)	266	8
Surface temperature of plastic cover plate of actuator display of CMC switch (thermocouple 13)	485	8
Body of CMC switch between white plastic lamp housing and black plastic cam housing (thermocouple 14)	146.7	8
Body of CMC switch between plastic cam housing and lamp transformer housing (thermocouple 15)	132.4	8
Body of CMC switch between switch contact blocks (thermocouple 16)	96.4	8

Plume Calculations

3.0 Plume Calculations

This section describes the mathematical analysis of the panel temperature profiles resulting from a 1-gallon heptane fire contained within a 2-foot-square pan located adjacent to the emergency core cooling system (ECCS) operating panels in the Fermi 2 control room. The model, analysis, and results are presented here, and the basis for these calculations was described briefly in Section 1. The analytical results confirm the panel fire test data recorded by Detroit Edison (Colbert, 1981).

3.1 Analysis

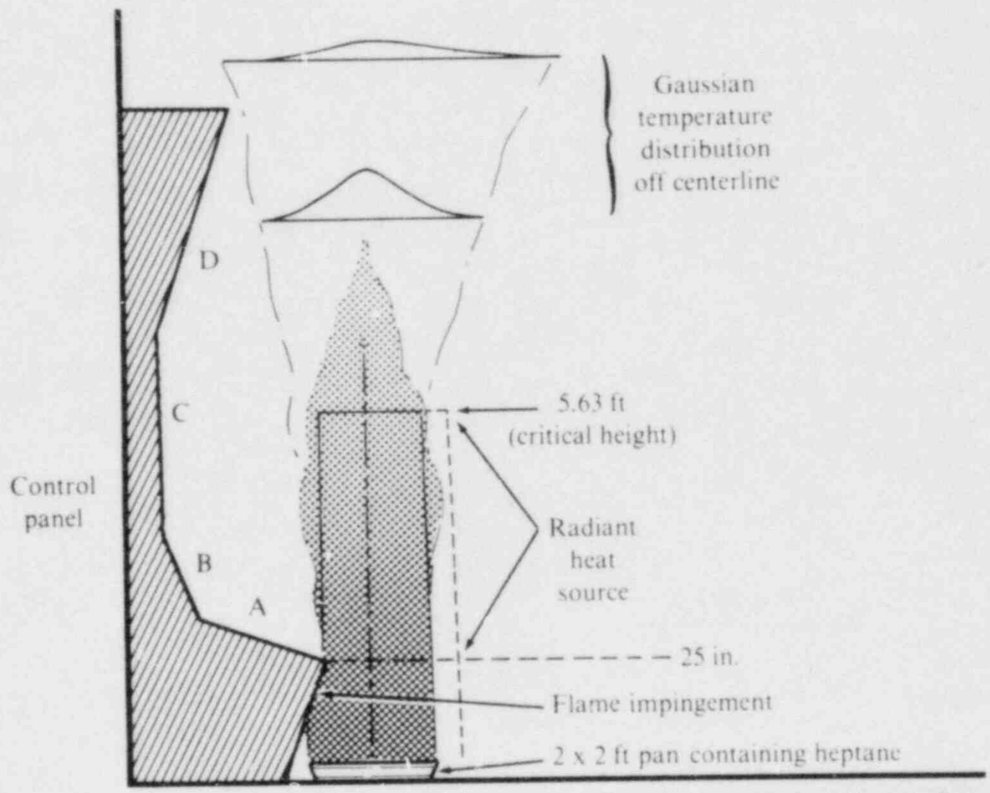
For any calculational procedure, the assumptions and the general approach followed may have significant impact on the final result. This model is no exception. Wherever possible, the model used in these calculations is based on conservative assumptions in order to ensure that the results obtained were bounding.

As stated above, the fire postulated in this model involves 1 gallon of heptane confined within a 2-foot-square pan. It is assumed that there is enough ventilation to fuel the fire with an adequate supply of oxygen without taking credit for the removal of gases and combustion products from the immediate vicinity of the fire. The result of this assumption leads to assurance that the modeled fire bounds the conditions of an actual fire in a typical well ventilated control room.

The location of the postulated fire was taken to be beneath the lower section of a typical control panel in the Fermi 2 control room (Figure 3-1). Tests conducted by Detroit Edison of a similar fire indicated that such a location would tend to deflect the fire plume away from the benchboard (Colbert, 1981). Despite this observed condition, the model fire plume was assumed both to impact the lower panel and to clear the edge of the benchboard and rise vertically (Figure 3-1). This assumption leads to panel heatup attributable to both direct flame impingement and conduction and at the same time results in the worst-case radiation-field incident on the switches located on the benchboard itself.

The target switches are assumed to be the CMC-type switches, which are usually associated with safety-related control functions and were successfully tested in the Detroit Edison control room fire test (Colbert, 1981). Although the switch is normally mounted on the benchboard portion of the control panel at a 20-degree angle (Figure 3-1), the switch face for the fire model was conservatively assumed to be rotated to the upright position to allow for the maximum switch plate surface area to be normal to the fire. This assumption maximizes the radiant heat flux viewed by the switch face. Furthermore, the effects of thermal lag associated with the switch body were ignored and only the mass of the switch plate was considered in the model. Although the switch face is generally light and even reflective, its radiation absorption characteristics were assumed to be equivalent to a gray body with an absorptivity of 95 percent and an emissivity of only 10 percent. Thus, switch heatup was related solely to the conditions on the switch face without any credit for internal-panel cooling effects and minimum reradiation.

Figure 3-1. Vertical cross section of control panel and model exposure fire.



The switch temperature was analyzed at panel locations on the fire centerplane at 1/2-inch intervals from the panel edge (Figure 3-2). This edge was assumed to be within the fire for the entire duration of the fire. The panel itself was assumed to have an absorptivity of 95 percent with no reradiation. Panel thickness was assumed to be 3/16 inch.

Three processes are considered to affect the heating of the control panel: convective heating from the fire plume, radiation from the hot gases and luminous soot of the plume, and conduction up through the benchboard panel. The model treats these processes in one dimension along the fire centerplane, ignoring the heat sinks provided by the floor and in the horizontal direction. Thus, energy deposited anywhere on the panel must move up and away from the fire with minimal credit taken for cooling.

Convective heating that results from a turbulent buoyant diffusion plume is analyzed by using a model by Stavrianidis (1980). This model was developed from data that were obtained from experiments involving three different liquid hydrocarbons in fires up to 2.4 meters in diameter. Stavrianidis' work extends the applicability of earlier work done by Rouse, Yih, and Humphreys (1952) and Zeldovich (1937), providing statistically meaningful correlations of mean plume vertical velocity vector and fire plume temperatures down into the flame front. Conditions off the centerline are predicted in the Stavrianidis model from a Gaussian distribution as a function of distance and elevation based on Batchelor (1954). Values for the mean centerline temperature were calculated for the heptane fire model and compared with a semiempirical relation attributed to Yokoi (1960) and Lie (1972). See also Pinkel (1978) and Campbell (1979). A more complete discussion is provided in Appendix B.

Fire conditions below the Stavrianidis flame height were used in the radiation calculations. The radiation model is taken from Hottel and Sarofim (1967) and was solved by using a Runge-Kutta algorithm for gray-gas radiation accounting for emission by carbon dioxide, water, and soot particles in the flame. Gas temperature within the flame was assumed to be 1763°F (Stavrianidis, 1980; Klamerus, 1978) and was conservatively modeled as a right cylinder defined by the effective radius and the Stavrianidis flame height (Figure 3-1). A more complete development of the switch radiation model is provided in Appendix C.

The thermal conduction in the steel panel was predicted by combining the effects of radiation and conduction in a one-dimensional model that ignores cooling in the second dimension of the panel surface and to the floor. This is accomplished by a modification of the Poisson equation using continuously distributed internal energy sources to account for the radiation effects (El-Wakil, 1971). Numerical solution was achieved through the use of an explicit finite-difference scheme that accounted for the variable boundary conditions (see Appendix D).

The thermophysical characteristics of the postulated heptane fire were derived from Tewarson, Lee, and Piou (1979), Tewarson (1980), and Blinov and Khudiakov (1961). Conservative values were assumed for the heats of combustion as described in the references so as to ensure that no credit was taken for less than efficient combustion.

Figure 3-2. Cross section of the "A" surface of the control panel showing the positions at which the test switch temperatures were calculated.

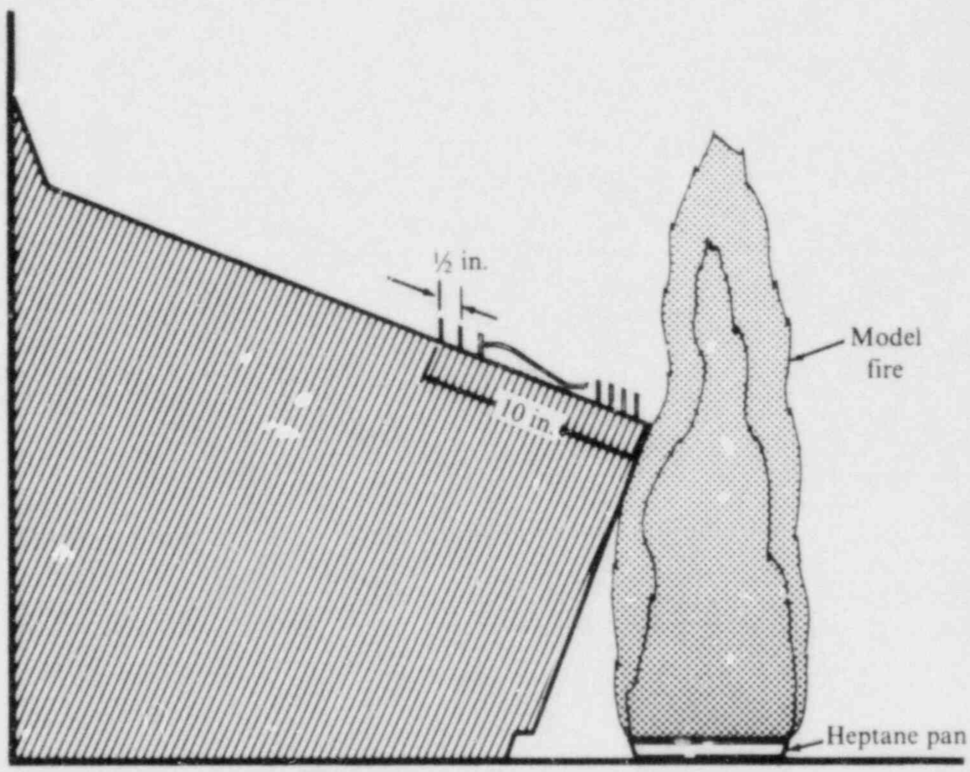


Table 3-1. Fire Characteristics

Parameter	Value
Heat release rate	
Total	2150 kW/m²*
Convective	1150 kW/m²*
Heat of combustion	
Total	43 kJ/g*
Convective	23 kJ/g*
Mass loss rate	50 g/m²-sec*
Flame temperature	1763°F (1235 K)†
Emissivity	
Gas	0.2‡
Soot	0.1‡
Total	0.3‡

*From Tewarson, Lee, and Piou (1979), Tewarson (1980), and Blinov and Khudiakov (1961).

†From Stavrianidis (1980).

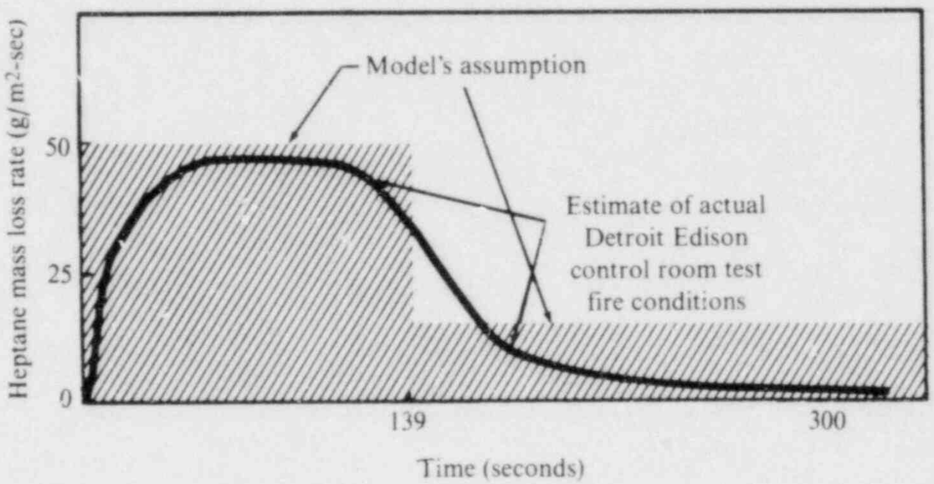
‡From Hottel and Sarofim (1967).

Table 3-1 summarizes the values used in the analysis. With a conservative mass loss rate of 50 g/m^2-sec, total combustion of 1 gallon of heptane in a 4-square-foot fire would be predicted to occur within 139 seconds, a duration supported by Pinkel (1978).

Despite predicted fuel exhaustion and self-extinguishment of a 1-gallon heptane fire at the end of such an intense burn, the burn time was conservatively extended to 5 minutes at a lower mass loss rate of approximately 23 g/m^2-sec (Figure 3-3). This has the effect of providing additional fuel to the postulated 1-gallon fire. Thus, although an efficient combustion of 1 gallon of heptane was modeled to burn within 139 seconds, a total quantity in excess of 1 gallon was actually considered to conservatively predict the thermal effects of a 5-minute fire on the benchboard and typical switches.

A final element of the analysis is related to the effects of flame impingement on the underside of the panel. Such impingement contributes to panel heatup as a result of conduction up along the panel. Flame impingement is conservatively taken to be full and direct. Using a model taken from Rohsenow and Choi (1961), an analysis of both realistic and artificially higher values of heat flux were considered. This, in turn, led to an exponential heatup of the panel's edge with time constants of 902 and 275 seconds for the realistic and worst cases, respectively. This aspect of the model is discussed in Appendix E.

Figure 3-3. Assumed heptane mass loss (burn) rate as a function of time.



In addition to the above-mentioned heating effects, three cooling effects are noted involving reradiation, convective cooling, and conduction to the heat sink at infinity. Each process was treated conservatively to ensure that the model adequately bounds the conditions on the panel.

As was previously discussed, despite the assumption that the upright switch and the control panel itself were treated as gray bodies with absorptivity of 95 percent, emissivity was taken to be only 10 percent. Thus, reradiation contributes only minimal cooling to the test switch and panel.

Conduction to an ultimate heat sink at 70°F was also postulated in order to provide a necessary boundary condition for the analysis. This condition was assumed to occur at an infinite distance and, therefore, was effectively removed as a cooling mechanism.

Convective heat transfer from the hot panel to the air space internal to the panel was considered for the sake of completeness. Simultaneously with fire initiation, total failure of any ventilation into that space was conservatively postulated for the purposes of analysis. Internal-panel air temperatures were assumed to be a uniform 200°F in the calculation of natural convection inside the panel. Credit was not taken for convective cooling to the control room air outside the panel. Appendix F discusses the turbulent free convection processes used in the model.

The assumptions used in the analysis as discussed above and in the appendixes are both bounding of substantiated data and conservative. A summary of some of the more limiting assumptions and considerations for the control room exposure fire model is provided below:

1. Panel and switches are treated as almost black bodies; essentially ignores reradiation.
2. The most intense (efficient) flame is assumed.
3. A fire of lower intensity (at lesser efficiency) is artificially extended to 5 minutes of burn (equivalent to a larger fuel volume).
4. The switch face is assumed to be perpendicular to the flame and assumed to have an unobstructed view of the entire fire.
5. The conduction model is one dimensional, ignoring radiation and lateral cooling effects.
6. Radiation and convection effects are assumed to be for an undisturbed free-burning vertical fire.
7. Enough oxygen to most efficiently fuel the fire is assumed, and the cooling effects of such ventilation are ignored.
8. Peak theoretical convective heat release rates are assumed.
9. The only cooling credited is by turbulent natural convection to air inside the panel assumed to be maintained at a uniform temperature of 200°F.

3.2 Results

The results of calculations for the most severe exposure fire involving in excess of 1 gallon of heptane in a confined 2-foot-square pan include the following:

1. Centerline temperatures above the fire (Table 3-2).
2. Temperatures out from the fire axis above the Stavrianidis critical height (Table 3-3).
3. Temperatures out from the fire axis above the Stavrianidis critical height using normalized distance from the fire axis (Table 3-4).
4. Switch temperature at the end of the intense portion of the fire due to radiation (Table 3-5).
5. "Realistic" worst-case control panel temperatures as a function of time and radial distance from the point of contact of the panel edge with the fire (Table 3-6).
6. "Conservative" worst-case control panel temperatures as a function of time and radial distance from the panel edge assuming arbitrarily a heat flux three times the calculated effects of flame impingement (Table 3-7).

The nature of these results is especially illuminating from the perspective of the effects of convective heating. Centerline temperatures using both the Stavrianidis and the Yokoi models are presented in Table 3-2. Yokoi presented two models: Yokoi-Tamb and Yokoi-Tgasc. The Yokoi-Tamb model correctly calculates centerline temperatures without modifying air density or specific heat as discussed in Pinkel (1978) and Lie (1972). The Yokoi-Tgasc model demonstrates a calculation as performed by Campbell (1979) for the NRC. It is provided to demonstrate the consistency of the Yokoi-Tamb model with the Stavrianidis model and to compare it with the Gage-Babcock calculational procedure, which appears to overestimate the magnitude of the risk of pool fires.

The Yokoi-Tamb model predicts thermal conditions consistent with the Stavrianidis model until the flame height is approached; at this point, the Stavrianidis model is more conservative in predicting higher temperatures. The Yokoi calculations are carried into the flame for comparison although this violates Yokoi's assumptions and invalidates the model. The Campbell (Gage-Babcock) approach becomes unstable at that point because of the attempt to modify the Yokoi parameter, and 5000°F is linearly projected at the point of instability.

In Tables 3-3 and 3-4, air temperatures from convective heating away from the fire axis (centerline) are presented. Above the Stavrianidis critical height, such heating must be considered in the analysis due to the divergence of the plume from the pan geometry. Below this height, however, the entrainment effects of the fire result in an air velocity component directed inward toward the fire axis, inhibiting any convective heating adjacent to the fire. Thus, below the critical height (5.63 feet) for the 1-gallon heptane fire analyzed, convective heat transfer need not be considered outside the fire gas plume.

Table 3-2. Centerline Temperatures Above the Fire

TEMPERATURES ALONG FIRE AXIS (F)

FIRE AREA = 576. IN2 FIRE HEAT RELEASE RATE = 2150. KW/M2 VIRTUAL SC..RCE HEIGHT = 10.0 IN AMBIENT TEMPERATURE = 70. F

ELEVATION ABOVE FIRE (IN)	YOKOI REGION/ PARAMETER	STAVRIANIDIS TGASC (F)	YOKOI TGASC(TAMB) (F)	YOKOI TGASC(TGASC) (F)	YOKOI ITERATIONS TGASC(TGASC)	YOKOI ERROR TGASC(TGASC) (F)
200.00	3/ 0.325	270.69	331.15	426.04	7	0.05682
196.00	3/ 0.336	277.94	340.09	442.20	5	0.04346
192.00	3/).348	285.61	349.54	459.57	5	0.05121
188.00	3/ 0.361	293.75	359.52	478.32	5	0.06085
184.00	3/ 0.374	302.39	370.09	498.57	5	0.07184
180.00	3/ 0.388	311.58	381.29	520.51	5	0.08569
176.00	3/ 0.402	321.36	393.17	544.37	6	0.02802
172.00	3/ 0.418	331.79	405.80	570.31	6	0.03479
168.00	3/ 0.435	342.93	419.23	598.63	6	0.04285
164.00	3/ 0.453	354.85	433.54	629.64	6	0.05273
160.00	3/ 0.472	367.63	448.82	663.68	6	0.06482
156.00	2/ 0.486	381.34	460.29	689.92	6	0.05493
152.00	2/ 0.499	396.10	470.56	713.89	6	0.05334
148.00	2/ 0.512	412.01	481.39	739.65	6	0.06201
144.00	2/ 0.527	429.20	492.82	767.41	6	0.07190
140.00	2/ 0.542	447.81	504.90	797.39	6	0.08325
136.00	2/ 0.558	468.01	517.69	829.85	6	0.09705
132.00	2/ 0.574	490.00	531.26	865.15	7	0.03943
128.00	2/ 0.592	514.00	545.67	903.56	7	0.04651
124.00	2/ 0.612	540.28	561.01	945.52	7	0.05640
120.00	2/ 0.632	569.13	577.38	991.53	7	0.06812
116.00	2/ 0.654	600.9_	594.88	1042.15	7	0.08240
112.00	2/ 0.677	636.08	613.62	1098.07	7	0.09898
108.00	2/ 0.702	675.12	633.76	1160.14	8	0.04614
104.00	2/ 0.729	718.65	655.44	1229.29	8	0.05811
100.00	2/ 0.758	767.42	678.86	1306.74	8	0.07446
96.00	2/ 0.790	822.33	704.23	1393.99	8	0.09473
92.00	2/ 0.824	884.49	731.80	1492.93	9	0.05029
88.00	2/ 0.862	955.31	761.88	1605.82	9	0.06763
84.00	2/ 0.903	1036.51	794.83	1735.70	9	0.09106
80.00	2/ 0.948	1130.32	831.07	1886.58	10	0.05615
76.00	2/ 0.998	1239.59	871.13	2063.68	10	0.08276
72.00	2/ 1.053	1368.07	915.63	2274.47	11	0.05884
68.00	2/ 1.115	1520.71	965.38	2529.58	11	0.09961
64.00	2/ 1.185	1704.24	1021.34	2345.72	12	0.09521
60.00	2/ 1.264	1763.00	1084.76	3251.18	14	0.06665
56.00	2/ 1.354	1763.00	1157.24	3802.93	16	0.09229
52.00	2/ 1.458	1763.00	1240.86	4668.56	23	0.09180
48.00	2/ 1.580	1763.00	1338.45	5000.00	*****	**********
44.00	2/ 1.723	1763.00	1453.77	5000.00	*****	**********
40.00	2/ 1.896	1763.00	1592.14	5000.00	*****	**********
36.00	2/ 2.106	1763.00	1761.27	5000.00	*****	**********
32.00	2/ 2.370	1763.00	1972.68	5000.00	*****	**********
28.00	2/ 2.708	1763.00	2244.49	5000.00	*****	**********
24.00	2/ 3.159	1763.00	2606.91	5000.00	*****	**********
20.00	2/ 3.791	1763.00	3114.29	5000.00	*****	**********
16.00	2/ 4.739	1763.00	3875.36	5000.00	*****	**********
12.00	1/ 5.080	1763.00	4149.02	5000.00	*****	**********

Table 3-3. Temperatures as a Function of Distance frcm the Fire Axis at Heights Above the Stavrianidis Critical Height

TEMPERATURES OUT FROM FIRE AXIS ABOVE CRITICAL HEIGHT (F)

CRITICAL HEIGHT = 67.7 (IN)

ELEV (IN)	DISTANCE FROM FIRE AXIS (IN) 0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.
200.	271.	270.	269.	268.	265.	262.	258.	254.	249.	244.	238.	232.	225.	219.	212.	205.	197.	190.
196.	278.	278.	276.	275.	272.	269.	265.	260.	255.	249.	243.	236.	229.	222.	215.	207.	200.	192.
192.	286.	285.	284.	282.	279.	275.	271.	266.	261.	254.	248.	241.	233.	226.	218.	210.	202.	194.
188.	294.	293.	292.	290.	287.	283.	278.	273.	267.	260.	253.	245.	238.	229.	221.	212.	204.	195.
184.	302.	302.	300.	298.	295.	291.	285.	280.	273.	266.	258.	250.	242.	233.	224.	215.	206.	197.
180.	312.	311.	309.	307.	303.	299.	293.	287.	280.	272.	264.	255.	246.	237.	227.	218.	208.	198.
176.	321.	321.	319.	316.	312.	307.	301.	295.	287.	279.	270.	260.	251.	241.	230.	220.	210.	200.
172.	332.	331.	329.	326.	322.	317.	310.	303.	295.	286.	276.	266.	255.	245.	234.	223.	212.	201.
168.	343.	342.	340.	337.	332.	326.	319.	311.	302.	293.	282.	271.	260.	248.	237.	225.	213.	202.
164.	355.	354.	352.	348.	343.	337.	329.	320.	311.	300.	289.	277.	265.	252.	240.	227.	215.	203.
160.	368.	367.	364.	360.	355.	348.	339.	330.	319.	308.	296.	283.	270.	256.	243.	229.	216.	204.
156.	381.	380.	378.	373.	367.	359.	350.	340.	328.	316.	303.	288.	275.	260.	246.	231.	218.	204.
152.	396.	395.	392.	387.	380.	372.	362.	351.	338.	324.	310.	295.	279.	264.	249.	233.	218.	204.
148.	412.	411.	408.	402.	395.	385.	374.	362.	348.	333.	317.	301.	284.	268.	251.	235.	219.	204.
144.	429.	428.	424.	418.	410.	400.	388.	374.	359.	342.	325.	307.	289.	271.	254.	236.	220.	204.
140.	448.	446.	442.	436.	427.	415.	402.	386.	370.	352.	333.	314.	294.	275.	256.	237.	219.	203.
136.	468.	466.	462.	454.	444.	432.	417.	400.	381.	362.	341.	320.	299.	278.	258.	238.	219.	201.
132.	490.	488.	483.	475.	463.	449.	433.	414.	394.	372.	349.	327.	304.	281.	259.	238.	218.	199.
128.	514.	512.	506.	497	484.	468.	450.	429.	406.	383.	358.	333.	308.	283.	260.	237.	216.	197.
124.	540.	[illegible]	532.	521.	507.	489.	468.	445.	420.	394.	366.	339.	312.	285.	260.	236.	214.	194.
120.	569.	567.	559.	547.	531.	511.	488.	462.	434.	405.	375.	345.	315.	287.	260.	235.	211.	190.
116.	601.	598.	590.	576.	558.	535.	509.	480.	449.	[illegible]	383.	350.	318.	288.	259.	232.	208.	186.
112.	636.	633.	623.	608.	587.	561.	532.	499.	464.	428.	391.	355.	321.	287.	257.	228.	203.	180.
108.	675.	671.	661.	643.	618.	590.	556.	519.	480.	440.	399.	360.	322.	286.	254.	224.	197.	174.
104.	719.	714.	702.	681.	654.	620.	582.	540.	496.	451.	406.	363.	322.	284.	249.	218.	191.	167.
100.	767.	762.	748.	724.	693.	654.	610.	562.	513.	462.	413.	365.	321.	280.	243.	211.	183.	160.
96.	822.	817.	799.	772.	735.	691.	640.	586	529.	473.	418.	366.	318.	275.	236.	203.	175.	151.
92.	884.	878.	858.	825.	782.	730.	672.	610.	546.	483.	422.	365.	313.	267.	227.	193.	[illegible]	142.
88.	955.	947.	923.	885.	835.	774.	706.	635.	562.	491.	424.	362.	306.	[illegible]	217.	183.	155.	133.
84.	1037.	1027.	998.	953.	893.	822.	743.	660.	578.	498.	423.	356.	297.	246.	204.	170.	144.	123.
80.	1130.	1119.	1084.	1030.	958.	874.	781.	686.	591.	502.	420.	347.	285.	[illegible]	191.	157.	132.	113.
76.	1240.	1225.	1183.	1117.	1031.	930.	821.	710.	603.	502.	412.	334.	269.	216.	175.	144.	120.	104.
72.	1369.	1350.	1299.	1218.	1113.	992.	863.	734.	610.	498.	400.	318.	251.	198.	153.	130.	109.	95.
68.	1521.	1499.	1434.	1333.	1205.	1058.	905.	754.	613.	488.	382.	295.	229.	178.	142.	116.	98.	87.

Table 3-4. Normalized Temperatures as a Function of Distance from the Fire Axis at Heights Above the Stavrianidis Critical Height

TEMPERATURES OUT FROM FIRE AXIS ABOVE CRITICAL HEIGHT (F)

CRITICAL HEIGHT = 67.7 (IN)

ELEV (IN)	(DISTANCE FROM FIRE AXIS)/ELEVATION 0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34
200.	271.	265.	248.	225.	197.	169.	142.	120.	103.	90.	82.	76.	73.	72.	71.	70.	70.	70.
196.	278.	272.	256.	231.	202.	172.	145.	122.	104.	91.	82.	77.	73.	72.	71.	70.	70.	70.
192.	286.	280.	262.	237.	207.	176.	148.	124.	105.	92.	83.	77.	74.	72.	71.	70.	70.	70.
188.	294.	287.	270.	243.	212.	180.	150.	126.	106.	52.	83.	77.	74.	72.	71.	70.	70.	70.
184.	302.	296.	277.	250.	218.	184.	154.	128.	108.	93.	84.	77.	74.	72.	71.	70.	70.	70.
180.	312.	305.	286.	257.	223.	189.	157.	130.	109.	94.	84.	79.	74.	72.	71.	70.	70.	70.
176.	321.	314.	294.	265.	[illegible]	194.	160.	133.	111.	95.	85.	78.	74.	72.	71.	70.	70.	70.
172.	332.	324.	304.	273.	236.	199.	164.	135.	113.	96.	85.	78.	74.	72.	71.	70.	70.	70.
168.	343.	335.	314.	281.	243.	204.	168.	138.	114.	97.	86.	79.	75.	72.	71.	70.	70.	70.
164.	355.	347.	324.	291.	251.	210.	172.	141.	116.	99.	87.	79.	75.	72.	71.	70.	70.	70.
160.	368.	359.	336.	300.	259.	218.	177.	144.	118.	100.	87.	80.	75.	72.	71.	70.	70.	70.
156.	381.	373.	348.	311.	268.	223.	182.	147.	121.	101.	88.	80.	75.	73.	71.	71.	70.	70.
152.	396.	387.	361.	323.	277.	230.	187.	151.	123.	103.	88.	80.	75.	73.	71.	71.	70.	70.
148.	412.	402.	375.	335.	287.	238.	193.	155.	126.	104.	90.	81.	76.	73.	71.	71.	70.	70.
144.	429.	419.	391.	348.	298.	247.	199.	159.	128.	106.	91.	82.	76.	73.	71.	71.	70.	70.
140.	448.	437.	407.	363.	310.	256.	206.	164.	131.	108.	92.	82.	76.	73.	71.	71.	70.	70.
136.	468.	457.	425.	378.	323.	266.	213.	169.	135.	110.	93.	83.	77.	73.	72.	71.	70.	70.
132.	490.	478.	445.	395.	337.	276.	221.	174.	138.	112.	95.	84.	77.	73.	72.	71.	70.	70.
128.	514.	502.	466.	414.	352.	288.	230.	180.	142.	114.	96.	84.	77.	74.	72.	71.	70.	70.
124.	540.	527.	490.	434.	369.	301.	239.	187.	146.	117.	97.	85.	78.	74.	72.	71.	70.	70.
120.	569.	555.	516.	457.	387.	315.	250.	194.	151.	120.	99.	86.	78.	74.	72.	71.	70.	70.
116.	601.	586.	544.	481.	407.	331.	261.	202.	156.	123.	101.	87.	79.	74.	72.	71.	70.	70.
112.	636.	620.	575.	508.	428.	348.	274.	211.	162.	127.	103.	88.	79.	75.	72.	71.	70.	70.
108.	675.	658.	610.	539.	454.	368.	288.	220.	168.	131.	105.	89.	80.	75.	72.	71.	70.	70.
104.	719.	700.	649.	572.	482.	389.	303.	231.	175.	135.	108.	91.	81.	75.	72.	71.	70.	70.
100.	767.	748.	683.	610.	513.	413.	321.	243.	183.	140.	111.	92.	82.	76.	73.	71.	70.	70.
96.	822.	801.	742.	653.	548.	440.	341.	257.	192.	145.	114.	94.	83.	76.	73.	71.	71.	70.
92.	884.	862.	797.	701.	587.	470.	363.	273.	202.	152.	118.	96.	84.	77.	73.	71.	71.	70.
88.	955.	931.	860.	756.	632.	505.	388.	290.	214.	159.	122.	98.	85.	77.	73.	71.	71.	70.
84.	1037.	1009.	933.	819.	684.	545.	418.	310.	227.	167.	126.	101.	86.	78.	74.	72.	71.	70.
80.	1130.	1101.	1016.	881.	743.	591.	451.	334.	242.	176.	132.	104.	88.	79.	74.	72.	71.	70.
76.	1240.	1207.	1114.	976.	812.	645.	491.	361.	260.	187.	138.	108.	90.	80.	74.	72.	71.	70.
72.	1368.	1332.	1229.	1075.	894.	708.	537.	393.	281.	200.	146.	112.	92.	81.	75.	72.	71.	70.
68.	1521.	1480.	1365.	1194.	991.	783.	592.	431.	306.	215.	155.	117.	94.	82.	76.	72.	71.	70.

Table 3-5. Switch Temperature due to Radiation at the End of the Intense Portion of the Fire

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RADIATION HEAT FLUX FROM FIRE ABOVE EDGE ONTO CONSOLE SURFACE AT VARIOUS DISTANCES FROM EDGE.
AND TEMPERATURE OF PLASTIC SWITCH PLATE AT END OF BURN FOR VARIOUS POSITIONS AND MATERIAL EMISSIVITY

HEAT FLUX IN UNITS OF B/S.FT2
TEMPERATURES IN DEGREES FAHRENHEIT

FIRE DIAMETER =  27.0 IN.      FLAME HEIGHT =  43.0 IN.      FLAME GAS TEMPERATURE = 1763.0 F.      BURN TIME = 139.0 S.
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DISTANCE FROM EDGE (IN.)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
GRAD	3.474	3.252	2.881	2.758	2.581	2.438	2.319	2.218	2.129	2.050	1.879	1.915	1.855	1.800	1.749	1.702	1.657	1.614	1.574	1.536	1.500
EMISS 0.10	780.	745.	688.	643.	606.	577.	552.	531.	513.	496.	482.	468.	456.	445.	434.	424.	415.	406.	398.	390.	382.

Table 3-6. Control Panel Temperatures as a Function of Time and Radial Distance from the Panel Edge in the Fire

TRANSIENT CONSOLE TEMPERATURE AT VARIOUS DISTANCES FROM EDGE ALONG CONSOLE SURFACE.
CONSIDERING FIRE RADIATION ABOVE EDGE AND CONDUCTION THROUGH CONSOLE

CONSOLE TEMPERATURES IN DEGREES FAHRENHEIT

FIRE DIAMETER = 27.0 IN. FLAME HEIGHT ABOVE EDGE = 43.0 IN. FLAME GAS TEMPERATURE = 1763.0 F. BURN TIME = 300.0 S.
TIME OF FLAME ABOVE CONSOLE EDGE = 139.0 S.
FLAME IMPINGEMENT HEAT FLUX = 18. KW/M2 CONSOLE HEAT UP TIME CONSTANT = 902. S.
LOCAL CONSOLE COOL DOWN TIME CONSTANT BASED ON TURBULENT FREE CONVECTION

TIME\DISTANCE FROM EDGE (IN.) (S.)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
0.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.
30.	125.	135.	139.	139.	138.	136.	135.	133.	131.	130.	128.	127.	125.	124.	123.	122.	121.	119.	118.	117.	116.
60.	179.	194.	202.	205.	204.	202.	199.	196.	193.	190.	187.	184.	181.	178.	176.	174.	171.	169.	167.	165.	163.
90.	231.	251.	262.	267.	268.	266.	262.	258.	254.	249.	245.	241.	237.	233.	229.	225.	222.	219.	216.	212.	210.
120.	281.	305.	320.	327.	329.	328.	325.	320.	315.	309.	303.	298.	292.	287.	282.	277.	273.	268.	264.	260.	256.
150.	329.	337.	351.	360.	365.	365.	363.	358.	353.	347.	341.	335.	328.	322.	317.	311.	306.	301.	296.	291.	286.
180.	376.	358.	353.	354.	356.	358.	357.	354.	350.	345.	339.	333.	327.	322.	316.	310.	305.	300.	295.	290.	286.
210.	422.	387.	368.	359.	355.	354.	352.	350.	346.	342.	337.	332.	326.	321.	315.	310.	305.	300.	295.	290.	286.
240.	466.	419.	390.	371.	361.	354.	350.	347.	343.	339.	335.	330.	325.	319.	314.	309.	304.	299.	294.	290.	285.
270.	508.	452.	413.	387.	370.	359.	351.	346.	341.	337.	333.	328.	323.	318.	313.	308.	303.	298.	294.	289.	285.
300.	549.	485.	439.	405.	382.	366.	355.	347.	341.	336.	331.	326.	322.	317.	312.	307.	302.	298.	293.	289.	284.
330.	544.	499.	458.	423.	396.	376.	361.	350.	342.	336.	330.	325.	320.	316.	311.	306.	302.	297.	292.	288.	284.
360.	539.	501.	465.	434.	407.	385.	368.	355.	345.	337.	330.	325.	320.	315.	310.	305.	301.	296.	292.	287.	283.
390.	534.	501.	469.	440.	414.	392.	374.	360.	348.	339.	331.	325.	319.	314.	309.	304.	300.	295.	291.	287.	283.
420.	530.	499.	470.	443.	419.	397.	379.	364.	351.	341.	333.	325.	319.	314.	309.	304.	299.	295.	290.	286.	282.
450.	525.	497.	471.	445.	422.	401.	383.	368.	354.	343.	334.	326.	320.	314.	308.	303.	299.	294.	290.	286.	282.
480.	520.	495.	470.	446.	424.	404.	386.	371.	357.	346.	336.	327.	320.	314.	308.	303.	298.	294.	289.	285.	281.
510.	516.	492.	469.	446.	425.	406.	389.	373.	359.	348.	337.	329.	321.	314.	308.	303.	298.	293.	289.	285.	281.
540.	512.	489.	467.	446.	426.	407.	390.	375.	361.	349.	329.	330.	322.	315.	309.	303.	298.	293.	289.	284.	280.
570.	507.	486.	465.	445.	426.	408.	392.	376.	363.	351.	340.	331.	323.	315.	309.	303.	298.	293.	288.	284.	280.
600.	503.	483.	463.	444.	426.	408.	392.	378.	364.	352.	341.	332.	323.	316.	309.	303.	298.	293.	288.	284.	280.
630.	499.	480.	461.	443.	425.	408.	393.	378.	365.	353.	342.	333.	324.	317.	310.	303.	298.	293	288.	284.	279.
660.	495.	477.	459.	441.	424.	408.	393.	379.	366.	354.	343.	334.	325.	317.	310.	304.	298.	293	288.	283.	279.
690.	491.	473.	456.	439.	423.	407.	393.	378.	366.	355.	344.	334.	325.	318.	310.	304.	298.	293.	288.	283.	279.
720.	487.	470.	454.	437.	422.	407.	392.	379.	367.	355.	344.	335.	326.	318.	311.	304.	298.	293.	288.	283.	279.
750.	483.	467.	451.	435.	420.	406.	392.	379.	367.	355.	345.	335.	326.	318.	311.	305.	298.	293.	[illegible]	283.	279.
780.	479.	464.	448.	433.	419.	405.	391.	379.	367.	355.	345.	336.	327.	319.	311.	305.	299.	293.	288.	283.	279.
810.	476.	461.	446.	431.	417.	404.	391.	378.	366.	355.	345.	336.	327.	319.	312.	305.	299.	293.	288.	283.	279.
840.	472.	457.	443.	429.	416.	402.	390.	378.	366.	355.	345.	336.	327.	319.	312.	305.	299.	293.	288.	283.	278.
870.	468.	454.	441.	427.	414.	401.	389.	377.	366.	355.	345.	336.	327.	319.	312.	305.	299.	293.	288.	283.	278.
900.	465.	451.	438.	425.	412.	400.	388.	376.	365.	355.	345.	336.	327.	319.	312.	305.	299.	293.	288.	283.	278.
930.	461.	448.	435.	423.	410.	398.	386.	375.	364.	354.	345.	336.	327.	319.	312.	305.	299.	293.	288.	283.	278.
960.	458.	445.	433.	420.	408.	397.	385.	374.	364.	354.	344.	336.	327.	319.	312.	305.	299.	293.	298.	283.	278.
990.	455.	442.	430.	418.	407.	395.	384.	373.	363.	353.	344.	335.	327.	319.	312.	305.	299.	293.	288.	283.	278.
1020.	451.	439.	428.	416.	405.	394.	383.	372.	362.	353.	344.	335.	327.	319.	312.	305.	299.	293.	288.	283.	278.
1050.	448.	437.	425.	414.	403.	392.	381.	371.	361.	352.	343.	335.	327.	319.	312.	305.	299.	293.	288.	283.	278.
1080.	445.	434.	423.	412.	401.	390.	380.	370.	360.	351.	343.	334.	320.	319.	312.	365.	299.	293.	288.	283.	278.
1110.	442.	431.	420.	409.	399.	389.	379.	368.	360.	351.	342.	334.	326.	319.	312.	305.	299.	293.	288.	283.	278.
1140.	439.	428.	418.	407.	397.	387.	377.	368.	359.	350.	341.	333.	326.	318.	311.	305.	299.	293.	288.	283.	278.
1170.	436.	425.	415.	405.	395.	385.	376.	366.	358.	349.	341.	333.	325.	318.	311.	305.	299.	293.	288.	283.	278.
1200.	433.	423.	413.	403.	393.	384.	374.	365.	356.	348.	340.	332.	325.	318.	311.	305.	299.	293.	288.	283.	278.
1230.	430.	420.	410.	401.	391.	382.	373.	364.	355.	347.	339.	331.	324.	317.	311.	304.	298.	293.	287.	282.	278.
1260.	427.	417.	408.	399.	389.	380.	371.	363.	354.	346.	338.	331.	324.	317.	310.	304.	298.	292.	287.	282.	278.
1290.	424.	415.	406.	396.	387.	379.	370.	361.	353.	345.	338.	330.	323.	316.	310.	304.	298.	292.	287.	282.	277.
1320.	421.	412.	403.	394.	386.	377.	368.	360.	352.	344.	337.	329.	322.	316.	309.	303.	298.	292.	287.	282.	277.
1350.	419.	410.	401.	392.	384.	375.	367.	359.	331.	343.	336.	329.	322.	315.	309.	303.	297.	292.	287.	282.	277.
1380.	416.	407.	399.	390.	382.	374.	365.	358.	350.	342.	335.	328.	321.	315.	309.	303.	297.	292.	286.	281.	277.
1410.	413.	405.	396.	388.	380.	372.	364.	356.	349.	341.	334.	327.	321.	314.	308.	302.	297.	291.	286.	281.	277.
1440.	411.	402.	394.	386.	378.	370.	363.	355.	347.	340.	333.	326.	320.	314.	308.	302.	296.	291.	286.	281.	276.
1470.	408.	400.	392.	384.	376.	369.	361.	354.	346.	339.	332.	326.	319.	313.	307.	301.	296.	291.	286.	281.	276.
1500.	406.	398.	390.	382.	375.	367.	360.	352.	345.	338.	331.	325.	318.	312.	306.	301.	295.	290.	283.	280.	276.

Table 3-7. Control Panel Temperatures as a Function of Time and Radial Distance from the Panel Edge in the Fire Assuming Flame Impingement Heat Flux Three Times Calculated (60 kW/m^2)

TRANSIENT CONSOLE TEMPERATURE AT VARIOUS DISTANCES FROM EDGE ALONG CONSOLE SURFACE,
CONSIDERING FIRE RADIATION ABOVE EDGE AND CONDUCTION THROUGH CONSOLE

CONSOLE TEMPERATURES IN DEGREES FAHRENHEIT

FIRE DIAMETER = 27.0 IN. FLAME HEIGHT ABOVE EDGE = 43.0 IN. FLAME GAS TEMPERATURE = 1763.0 F. BURN TIME = 300.0 S.
TIME OF FLAME ABOVE CONSOLE EDGE = 139.0 S.
FLAME IMPINGEMENT HEAT FLUX = 60. KW/M2 CONSOLE HEAT UP TIME CONSTANT = 275. S.
LOCAL CONSOLE COOL DOWN TIME CONSTANT BASED ON TURBULENT FREE CONVECTION

TIME\DISTANCE FROM EDGE (IN.) (S.)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
0.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.
30.	245.	188.	159.	146.	140.	137.	135.	133.	131.	130.	128.	127.	125.	124.	123.	122.	121.	119.	118.	117.	116.
60.	402.	323.	271.	239.	220.	208.	201.	197.	193.	190.	187.	184.	181.	178.	176.	174.	171.	169.	167.	165.	163.
90.	543.	453.	386.	340.	308.	287.	273.	263.	256.	250.	245.	241.	237.	233.	229.	225.	222.	219.	216.	212.	210.
120.	669.	574.	500.	443.	401.	370.	349.	333.	321.	312.	305.	299.	293.	287.	282.	278.	273.	268.	264.	260.	256.
150.	782.	665.	582.	518.	469.	432.	404.	383.	367.	355.	345.	337.	329.	323.	317.	311.	306.	301.	296.	291.	286.
180.	883.	737.	630.	551.	493.	450.	417.	393.	374.	359.	347.	338.	330.	323.	317.	311.	305.	300.	295.	291.	286.
210.	974.	811.	687.	594.	524.	472.	433.	404.	382.	364.	351.	340.	331.	323.	317.	311.	305.	300.	295.	290.	286.
240.	1056.	882.	746.	640.	560.	499.	453.	418.	392.	371.	356.	343.	333.	324.	317.	311.	305.	299.	294.	290.	285.
270.	1129.	948.	802.	687.	598.	528.	475.	435.	404.	380.	362.	347.	336.	326.	318.	311.	305.	299.	294.	289.	285.
300.	1194.	1008.	856.	734.	636.	559.	499.	453.	418.	390.	369.	352.	339.	328.	319.	312.	305.	299.	294.	289.	285.
330.	1174.	1029.	894.	774.	673.	591.	525.	474.	433.	402.	378.	358.	343.	331.	321.	313.	306.	300.	294.	289.	284.
360.	1155.	1029.	909.	798.	701.	618.	550.	494.	450.	415.	388.	366.	349.	335.	324.	315.	307.	300.	294.	289.	284.
390.	1136.	1023.	914.	813.	721.	640.	571.	514.	467.	429.	398.	374.	355.	340.	327.	317.	308.	301.	295.	289.	284.
420.	1117.	1014.	915.	821.	734.	656.	589.	531.	482.	442.	409.	383.	362.	345.	331.	320.	310.	302.	296.	290.	284.
450.	1099.	1004.	912.	825.	743.	669.	603.	545.	496.	455.	420.	392.	369.	350.	335.	323.	313.	304.	297.	290.	285.
480.	1081.	994.	908.	826.	749.	678.	614.	557.	508.	466.	431.	401.	377.	356.	340.	326.	315.	306.	298.	291.	285.
510.	1064.	982.	902.	825.	752.	684.	622.	567.	518.	476.	440.	409.	384.	363.	345.	330.	318.	308.	300.	292.	286.
540.	1047.	971.	895.	822.	753.	688.	629.	575.	527.	485.	449.	417.	391.	369.	350.	334.	322.	311.	302.	294.	287.
570.	1031.	959.	888.	819.	753.	691.	634.	582.	535.	493.	456.	425.	398.	375.	355.	339.	325.	313.	304.	295.	288.
600.	1015.	947.	880.	814.	752.	693.	637.	587.	541.	500.	463.	431.	404.	380.	360.	343.	328.	316.	306.	297.	289.
630.	1000.	935.	871.	809.	750.	693.	640.	591.	546.	503.	469.	437.	410.	386.	365.	347.	332.	319.	308.	299.	291.
660.	985.	923.	863.	804.	747.	692.	641.	594.	550.	510.	475.	443.	415.	390.	369.	351.	335.	322.	311.	301.	292.
690.	970.	912.	854.	798.	743.	691.	642.	596.	553.	514.	479.	448.	420.	395.	374.	355.	339.	325.	313.	303.	294.
720.	956.	900.	845.	791.	739.	689.	641.	597.	556.	518.	483.	452.	424.	399.	378.	359.	342.	328.	316.	305.	296.
750.	942.	889.	836.	785.	734.	686.	641.	598.	557.	520.	486.	456.	428.	403.	381.	362.	345.	331.	318.	307.	298.
780.	928.	877.	827.	778.	730.	683.	639.	598.	559.	522.	489.	459.	431.	407.	385.	366.	348.	334.	321.	309.	299.
810.	915.	866.	818.	771.	725.	680.	637.	597.	559.	524.	491.	461.	434.	410.	388.	369.	351.	336.	323.	311.	301.
840.	902.	855.	809.	764.	719.	676.	635.	596.	559.	525.	493.	464.	437.	413.	391.	371.	354.	339.	325.	313.	303.
870.	889.	844.	800.	756.	714.	672.	633.	595.	559.	526.	494.	466.	439.	415.	394.	374.	357.	341.	327.	315.	305.
900.	877.	834.	791.	749.	709.	668.	630.	593.	559.	526.	495.	467.	441.	418.	396.	376.	359.	343.	330.	317.	306.
930.	865.	823.	782.	742.	702.	664.	627.	591.	558.	526.	496.	468.	443.	419.	398.	379.	361.	346.	332.	319.	308.
960.	853.	813.	774.	735.	697.	660.	624.	589.	557.	526.	496.	469.	444.	421.	400.	381.	363.	348.	334.	321.	310.
990.	841.	803.	765.	728.	691.	655.	620.	587.	555.	525.	497.	470.	445.	422.	402.	382.	365.	349.	335.	323.	311.
1020.	830.	793.	757.	720.	685.	650.	617.	584.	553.	524.	496.	470.	446.	424.	403.	384.	367.	351.	337.	324.	313.
1050.	819.	784.	748.	713.	679.	645.	613.	582.	552.	523.	496.	470.	447.	425.	404.	385.	368.	353.	339.	326.	314.
1080.	808.	774.	740.	706.	673.	641.	609.	579.	549.	522.	495.	470.	447.	425.	405.	387.	370.	354.	340.	327.	316.
1110.	798.	765.	732.	699.	667.	636.	605.	576.	547.	520.	494.	470.	447.	426.	406.	388.	371.	355.	341.	329.	317.
1140.	788.	756.	724.	692.	661.	631.	601.	573.	545.	519.	493.	470.	447.	426.	407.	389.	372.	357.	343.	330.	318.
1170.	778.	747.	716.	685.	655.	626.	597.	569.	542.	517.	492.	469.	447.	426.	407.	389.	373.	358.	344.	331.	319.
1200.	768.	736.	708.	679.	649.	621.	593.	566.	540.	515.	491.	468.	447.	427.	408.	390.	374.	359.	345.	332.	320.
1230.	758.	729.	700.	672.	644.	616.	589.	563.	537.	513.	490.	467.	446.	426.	408.	390.	374.	359.	346.	333.	321.
1260.	749.	721.	693.	665.	638.	611.	585.	559.	535.	511.	488.	466.	446.	426.	408.	391.	375.	360.	346.	334.	322.
1290.	740.	713.	686.	659.	632.	606.	581.	556.	532.	509.	486.	465.	445.	426.	408.	391.	375.	361.	347.	334.	323.
1320.	731.	705.	678.	652.	626.	601.	576.	552.	529.	506.	485.	464.	444.	425.	408.	391.	376.	361.	348.	335.	324.
1350.	722.	697.	671.	646.	621.	596.	572.	549.	526.	504.	483.	462.	443.	425.	407.	391.	376.	361.	348.	336.	324.
1380.	714.	689.	664.	640.	615.	591.	568.	545.	523.	501.	481.	461.	442.	424.	407.	391.	376.	362.	349.	336.	325.
1410.	705.	681.	657.	633.	610.	587.	564.	542.	520.	499.	479.	459.	441.	423.	407.	391.	376.	362.	349.	337.	325.
1440.	697.	674.	650.	627.	604.	582.	560.	538.	517.	497.	477.	458.	440.	422.	406.	391.	376.	362.	349.	337.	326.
1470.	689.	666.	644.	621.	598.	577.	555.	534.	514.	494.	475.	456.	439.	422.	405.	390.	376.	362.	349.	337.	326.
1500.	681.	659.	637.	615.	594.	572.	551.	531.	511.	491.	473.	455.	437.	421.	405.	390.	375.	362.	349.	338.	327.

The radiation model results for the test switch are shown in Table 3–5. As may be seen from the results, switch temperatures do not exceed 600°F past 2 inches from the fire panel-edge interface. These temperatures indicate that a switch may be exposed to a worst-case heptane fire for short durations with little chance for significant damage.

Table 3–6 shows the effects of radiation and conduction through the 3/16-inch steel plate. The results show that panel temperatures do not exceed 600°F past 3.5 inches from the fire panel-edge interface. At the time of fire self-extinguishment, radiation and conduction effects on the panel are consistent with the effects of radiation to the switch at the same location. The model in postulating only minimal cooling highlights the redistribution of energy through the panel resulting in a transient temperature effect.

Table 3–6 presents realistic, worst-case results that indicate that the radiation effects of the fire dominate the effects of flame impingement on the panel underside. This may be seen in the lower console temperatures beneath the switch, a condition that results from the conduction processes redistributing energy away from the fire. Thus, although isolated switch temperatures are predicted to be higher, in reality switch temperatures may be expected to approach the underlying console temperatures.

In Table 3–7, the effects of flame impingement are arbitrarily and conservatively increased threefold. The principal impact of this assumption is that switch and panel temperatures at fire extinguishment are closer. As in the case of Table 3–6, panel and switch cooling is essentially ignored and the subsequent thermal transient resulting from energy redistribution from the panel edge is evident after the fire self-extinguishes at 300 seconds.

In reality, the magnitude of this thermal transient would be expected to be significantly less. One reason is that thermal energy redistribution is conservatively forced up the panel because of the one-dimensional nature of the model, and lateral heat sinks are ignored. Another reason for an expected lower thermal transient after 300 seconds is related to the fact that natural convection in one direction only to an ambient gas at 200°F is assumed for the duration of the model. Thus, the effects of control room ventilation and the normal room temperature of 70°F are entirely ignored. The postulated fire, in effect, is allowed to burn for 5 minutes without any intervention by operating personnel. The combined effects of these conservative assumptions lead to panel-edge temperatures of 406°F and 681°F for the realistic and the threefold heat flux cases, respectively, 20 minutes after the fire self-extinguishes. In reality, one would expect significantly lower temperatures, indicating the conservative nature of the cooldown portion of Tables 3–6 and 3–7.

3.3 Conclusions

The analysis of the effects of exposure fires adjacent to the control panels inside the control room has been previously discussed. These results indicate that peak temperatures may be determined both at fire extinguishment and subsequent transient peaks resulting from the conduction of energy from then panel's edge. These temperatures are conservative for heatup and in the resultant cooldown.

In the worst-case 1-gallon heptane fire in a control room, console switches located approximately 3 to 3.5 inches from the panel edge may be expected to survive intact with any such fire that is immediately adjacent.

These conclusions should be viewed as bounding due to the conservatisms taken in the modeling process. In order to confirm that the model is indeed bounding, the conclusions may be reviewed against the actual experimental data obtained from the Detroit Edison control room fire test (Colbert, 1981). A review of the photographs indicates that paint on the control panels was not blackened at distances beyond approximately 1 to 2 inches from the panel edge in contact with the fire. On this basis, and from a review of the thermocouple data, it is apparent that panel temperatures of 600°F were not exceeded at distances greater than 2 inches and that temperatures were around 400°F at 1 inch. Furthermore, thermocouple data indicate that at approximately 4 inches from the panel edge, the temperature of the test-switch body never exceeded 125.5°F. The analytical model conservatively represents the worst-case conditions of the postulated 1-gallon heptane fire and confirms experimental evidence indicating the survivability of control panel switches in the Fermi 2 control room.

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4.0 Conclusions

Throughout the NRC's review of the fire protection features of the Fermi 2 plant, Detroit Edison has agreed to implement those modifications required by the NRC that could reasonably be incorporated at this late stage in the construction of the plant. Detroit Edison is convinced that the Fermi 2 fire protection features ensure adequate protection of the public health and safety. The control panel fire test reported earlier and the oven test and calculations presented here confirm the validity of Detroit Edison's position and confirm the adequacy of the remote-shutdown capabilities of the Fermi 2 plant.

Appendix A

Calibration of Data Logger Used in the Oven Test of the CMC and Pushbutton Switches

CERTIFICATE NUMBER 6618

FLUKE

JOHN FLUKE MFG. CO., INC.

CENTRAL REGION

☐ Central Tech. Ctr. 14400 Midway Road Dallas, Texas 75240	☐ Central Tech. Ctr. 10800 Lyndale Ave. South Minneapolis, Mn. 55420 (612) 884-4541	☒ Central Tech. Ctr. 1400 Hicks Rd. Rolling Meadows, Ill. 60008 (312) 398-5800	☐ Central Tech. Ctr. 13955 Farmington Road Livonia, Michigan 48154

CERTIFICATE OF CALIBRATION

SUBMITTED BY:
Detroit Edison
Attn: Bob Pitman
6100 W. Warren
Detroit, MI 48210

MANUFACTURER	MODEL	SERIAL NO.
	2240B	800008

RECEIVED →
☐ WITHIN TOLERANCE ☒ OPERATIONAL FAILURE
☐ SCHEDULE RECALL ☐ PHYSICAL DAMAGE
☐ OUT OF TOLERANCE ☐ OTHER

RETURNED →
☒ WITHIN TOLERANCE ☐ RECALL DATE
☐ LIMITED
TEMP. 23 °C HUM. 40 %

The John Fluke Mfg. Co., Inc. does hereby certify the above listed instrument meets or exceeds all published specifications and has been calibrated using standards whose accuracies are traceable to the National Bureau of Standards within the limitations of the Bureau's Calibration Services, or have been derived from accepted values of natural physical constants, or have been derived by the ratio type of self-calibration techniques. Our "Calibration System Requirements" satisfy MIL-C-45662A.

Applicable NBS Test Report Numbers

DC Voltage	216868
AC Voltage	807675
Resistance	214691
Temperature	211875
Inductance	
Capacitance	
Frequency	WWBB VLF TRANSMISSION

WM 10/24/78
CERTIFIED BY DATE

Barbara L. Hunt
SERVICE MANAGER

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

April 15, 1980

In reply refer to:
522/222456

Detroit Edison Company
Engineering Research 019
7940 Livernois, Building H-100
Detroit, Michigan 48210

Attention: Bob Pitman

Subject : Thermometric Test
Order No: E 016408

Gentlemen:

Enclosed are results of the test which you requested in the above reference. Please refer to the above file number in any later communication, and if you have any questions concerning this test, contact William R. Bigge, telephone number (301) 921-2757.

Sincerely yours,

James F. Schooley
Chief, Temperature Measurements
and Standards Division
Center for Absolute Physical Quantities

Material tested:

1 Platinum Resistance Thermometer

Enclosures:

1 Report of Calibration
1 Notes to Supplement Resistance
Thermometer Reports

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
NATIONAL MEASUREMENT LABORATORY
WASHINGTON D.C. 20234

REPORT OF CALIBRATION

PLATINUM RESISTANCE THERMOMETER
SERIAL NO. 1875628

SUBMITTED BY
DETROIT EDISON COMPANY, ENGINEERING RESEARCH DIVISION
DETROIT, MICHIGAN

THIS THERMOMETER WAS CALIBRATED FOR USE WITH CONTINUOUS CURRENT OF 1.0 MA. THROUGH THE THERMOMETER.

THE FOLLOWING VALUES WERE FOUND FOR THE CONSTANTS IN THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE(1968) FORMULAS:

ALPHA = 3.926237-03 A4 = 2.700-07
DELTA = 1.496288 *C4 = 2.654-14

THE PERTINENT INTERNATIONAL PRACTICAL TEMPERATURE FORMULAS ARE GIVEN IN THE DISCUSSION ON THE FOLLOWING PAGES.

THE RESISTANCE AT 0 DEGREES C WAS FOUND TO BE 25.5535 ABSOLUTE OHMS. DURING CALIBRATION, THIS RESISTANCE CHANGED BY THE EQUIVALENT OF .0004 DEG C.

THIS THERMOMETER IS SATISFACTORY AS A DEFINING STANDARD IN ACCORDANCE WITH THE TEXT OF THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968.

* THIS VALUE WAS ASSUMED.

FOR THE DIRECTOR,
NATIONAL MEASUREMENT LABORATORY

JAMES F. SCHOOLEY
CHIEF, TEMPERATURE MEASUREMENTS
AND STANDARDS DIVISION
CENTER FOR ABSOLUTE PHYSICAL QUANTITIES

TEST NO. 222456
COMPUTED 8 APRIL 1980
JLR/UNIVAC

THE DETROIT EDISON COMPANY

CERTIFICATE OF TEST

June 26, 1980

TEST MADE FOR Engineering Research

THEIR ORDER NO.

APPARATUS L & N 8067 Mueller Bridge

NUMBER 1011421

RATING

TEST: This instrument has been tested under conditions and with results as follows:

		Decade Corrections			
Step	1	0.1	0.01	0.001	0.0001
0	+.00005				
1	+.0002	+.0001	.0000	.0000	.0000
2	-.0002	+.0001	.0000	.0000	.0000
3	-.0002	+.0001	.0000	.0000	.0000
4	-.0003	-.0001	.0000	.0000	.0000
5	-.0004	-.0001	.0000	.0000	.0000
6	-.0006	.0000	.0000	.0000	.0000
7	-.0006	-.0001	.0000	.0000	.0000
8	-.0006	-.0001	-.0001	.0000	.0000
9	-.0006	-.0002	.0000	.0000	.0000
X	-.0004	-.0004	.0000	.0000	.0000
		C Resistors			
C10	-.0008	C40	-.0021	C70	-.0022
C20	-.0015	C50	-.0020	C25	+.0001
C30	-.0021	C60	-.0016	C25.5	+.0005

DE FORM ME162 7-62

REMARKS Traceable to National Bureau of Standards through Standard Resistors Serial 838,035 and 1,805,636

METER DEPARTMENT B-121 WARREN SERVICE CENTER

E. V. Kelly

IN CHARGE OF TEST

WS/ma

Detroit Edison 81D75-4

CALIBRATION CERTIFICATE

ENGINEERING RESEARCH—ELECTRICAL EQUIPMENT & INSTRUMENTATION

CALIBRATION OF Fluke 2240B Data Logger P.O. NO.

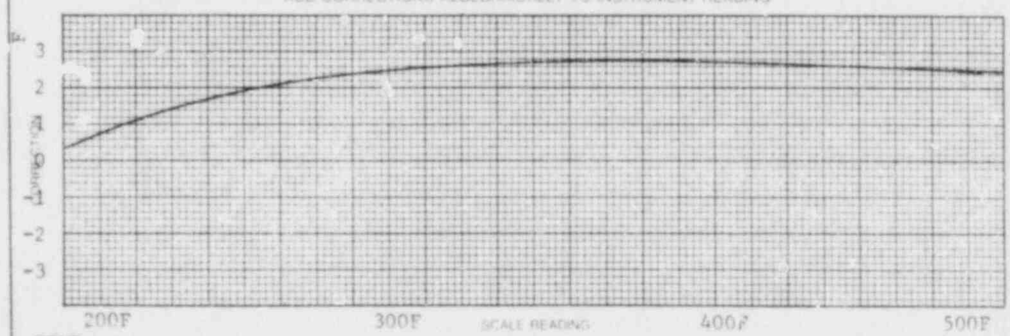
USED FOR Fermi II CMC Switch Test (at 600 F)

MANUFACTURER'S NO. 800008 CALIBRATED BY T. Booker/J. Sabo DATE 10-16-81

RANGE 0-4V TYPE APPROVED BY DATE

Platinum Res. Thermometer	Mueller Bridge Corr.	Corrected Resistance	Standard Temperature	Data Logger Temperature	Correction
34.9992 ohms	-0.0029 ohms	34.9963 ohms	201.88 F	201.11 F	+0.77 F
42.7922 ohms	-0.0024 ohms	42.7898 ohms	345.5 F	342.80 F	+2.70 F
50.7087 ohms	-0.0022 ohms	50.7065 ohms	495.28 F	492.73 F	+2.55 F

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING



TEMP.

RECEIVED FROM Property of ERD

STANDARDS USED L&N 8067 Mueller Bridge, SN 1011421; L&N Platinum Resistance Thermometer SN1875628; Thermotrol Constant Temperature (Oil) Bath Model 1398, SN15423

COMMENTS Overall Calibration of Fluke Data Logger, Thermocouple Wire (Type K, Premium Grade), and Isothermal Block.

RECALIBRATION DUE DATE ERD PROJECT NO. 81D75

Detroit Edison

CALIBRATION CERTIFICATE

ENGINEERING RESEARCH—
ELECTRICAL EQUIPMENT
& INSTRUMENTATION

CALIBRATION OF Fluke 2240 B Data Logger R.C. NO

USED FOR Fermi II CMC Switch Test

MANUFACTURER'S NO S/N 800008 CALIBRATED BY T. Booker DATE 10-16-81

RANGE 0-4V TYPE APPROVED BY [signature] DATE

Channel	Input In MV	Output In MV	Corr. (MV)		
0	10.000	9.983	+0.017		
1		9.982	+0.018		
2		9.980	+0.020		
3		9.981	+0.019		
4		9.980	+0.020		
5		9.981	+0.019		
6		9.981	+0.019		
7		9.980	+0.020		
8		9.982	+0.018		
9		9.981	+0.019		
0	20.000	19.981	+0.019		
1		19.981	+0.019		
2		19.978	+0.022		
3		19.983	+0.017		
4		19.984	+0.016		
5		19.984	+0.016		
6		19.983	+0.017		
7		19.983	+0.017		
8		19.983	+0.017		
9		19.982	+0.018		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING

CORRECTION

SCALE READING

RECEIVED FROM Property of ERD

STANDARDS USED L&N K-5 1745012

COMMENTS Calibration of Individual Channels

RECALIBRATION DUE DATE ERD PROJECT NO 81D75

Detroit Edison **CALIBRATION CERTIFICATE**

ENGINEERING RESEARCH—ELECTRICAL EQUIPMENT & INSTRUMENTATION

CALIBRATION OF Fluke 2240B Data Logger R.C. NO

USED FOR Fermi II CMC Switch Test

MANUFACTURER'S NO. S/N 800008 CALIBRATED BY T. Booker DATE 10-16-81

RANGE 0-4V TYPE APPROVED BY [signature] DATE

Channel	Input In MV	Output In MV	Corr. In MV		
10	10.000	9.981	+0.019		
11		9.982	+0.018		
12		9.981	+0.019		
13		9.982	+0.018		
14		9.981	+0.019		
15		9.980	+0.020		
16		9.981	+0.019		
17		9.981	+0.019		
18		9.981	+0.019		
19		9.981	+0.019		
10	20.000	19.983	+0.017		
11		19.981	+0.019		
12		19.981	+0.019		
13		19.983	+0.017		
14		19.983	+0.017		
15		19.982	+0.018		
16		19.981	+0.019		
17		19.982	+0.018		
18		19.983	+0.017		
19		19.982	+0.018		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING

CORRECTION

SCALE READING

RECEIVED FROM Property of ERD

STANDARDS USED L&N K-5 1745012

COMMENTS Calibration of Individual Channels

RECALIBRATION DUE DATE ERD PROJECT NO. 81D75

Detroit Edison

CALIBRATION CERTIFICATE

ENGINEERING RESEARCH—
ELECTRICAL EQUIPMENT
& INSTRUMENTATION

CALIBRATION OF: Fluke 2240B Data Logger   R.L. NO.

USED FOR: Fermi II CMC Switch Test

MANUFACTURER'S NO.: S/N 800008   CALIBRATED BY: T. Booker   DATE: 10-16-81

RANGE: 0-4 V   TYPE: APPROVED BY: [illegible]   DATE:

Channel	Input In MV	Output In MV	Corr. (MV)		
20	10.000	9.981	+0.019		
21		9.981	+0.019		
22		9.982	+0.018		
23		9.981	+0.019		
24		9.981	+0.019		
25		9.982	+0.018		
26		9.980	+0.020		
27		9.981	+0.019		
28		9.981	+0.019		
29		9.981	+0.019		
20	20.000	19.982	+0.018		
21		19.979	+0.021		
22		19.978	+0.022		
23		19.983	+0.017		
24		19.982	+0.018		
25		19.982	+0.018		
26		19.982	+0.018		
27		19.983	+0.017		
28		19.982	+0.018		
29		19.983	+0.017		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING

CORRECTION

SCALE READING

RECEIVED FROM: Property of ERD

STANDARDS USED: L&N K-5 1745012

COMMENTS: Calibration of Individual Channels

RECALIBRATION DUE DATE: ERD PROJECT NO.: 81D75-4

Detroit Edison **CALIBRATION CERTIFICATE**

ENGINEERING RESEARCH—ELECTRICAL EQUIPMENT & INSTRUMENTATION

CALIBRATION OF: Fluke 2240B Data Logger R.C. NO.

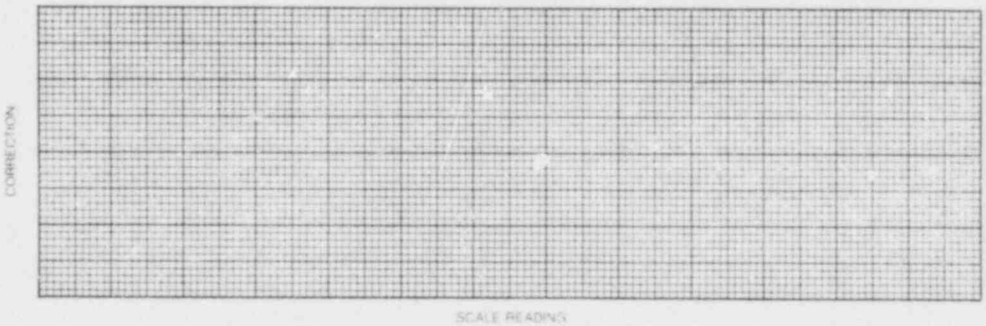
USED FOR: Fermi II CMC Switch Test

MANUFACTURER'S NO.: S/N 800008 CALIBRATED BY: T. Booker DATE: 10-16-81

RANGE: 0-4V TYPE: APPROVED BY: [signature] DATE:

Channel	Input In MV	Output In MV	Corr. (MV)		
30	10.000	9.977	+0.023		
31		9.975	+0.025		
32		9.975	+0.025		
33		9.975	+0.025		
34		9.976	+0.024		
3[illegible]		9.976	+0.024		
36		9.976	+0.024		
37		9.976	+0.024		
38		9.976	+0.024		
39		9.976	+0.024		
30	20.000	19.977	+0.023		
31		19.976	+0.024		
32		19.975	+0.025		
33		19.977	+0.023		
34		19.977	+0.023		
35		19.977	+0.023		
36		19.978	+0.022		
37		19.978	+0.022		
38		19.977	+0.023		
39		19.977	+0.023		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING



RECEIVED FROM: Property of ERD

STANDARDS USED: L&N K-5 1745012

COMMENTS: Calibration of Indivicual Channels

RECALIBRATION DUE DATE: ERD PROJECT NO.: 81D75

Appendix A

Detroit Edison **CALIBRATION CERTIFICATE**

ENGINEERING RESEARCH—
ELECTRICAL EQUIPMENT
& INSTRUMENTATION

CALIBRATION OF Fluke 2240B Data Logger R.C. NO

USED FOR Fermi II CMC Switch Test

MANUFACTURER'S NO S/N 800008 CALIBRATED BY T. Booker DATE 10-16-81

RANGE 0-4 V TYPE APPROVED BY DATE

Channel	Input In MV	Output In MV	Corr. (MV)		
40	10.000	9.977	+0.023		
41		9.976	+0.024		
42		9.975	+0.025		
43		9.976	+0.024		
44		9.976	+0.024		
45		9.976	+0.024		
46		9.976	+0.024		
47		9.976	+0.024		
48		9.976	+0.024		
49		9.976	+0.024		
40	20.000	19.976	+0.024		
41		19.975	+0.025		
42		19.975	+0.025		
43		19.977	+0.023		
44		19.978	+0.022		
45		19.977	+0.023		
46		19.977	+0.023		
47		19.978	+0.022		
48		19.978	+0.022		
49		19.977	+0.023		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING

CORRECTION

SCALE READING

RECEIVED FROM Property of ERD

STANDARDS USED L&N K-5 1745012

COMMENTS Calibration of Individual Channels

RECALIBRATION DUE DATE ERD PROJECT NO 81D75

Appendix A

Detroit Edison **CALIBRATION CERTIFICATE**

ENGINEERING RESEARCH—
ELECTRICAL EQUIPMENT
& INSTRUMENTATION

CALIBRATION OF Fluke 2240B Data Logger R.C. NO

USED FOR Fermi II CMC Switch Test

MANUFACTURER'S NO. S/N 800008 CALIBRATED BY T. Booker DATE 10-16-81

RANGE 0-4 V TYPE APPROVED BY [signature] DATE

Channel	Input In MV	Output In MV	Corr. (MV)		
50	10.000	9.976	+0.024		
51		9.975	+0.025		
52		9.976	+0.024		
53		9.977	+0.023		
54		9.977	+0.023		
55		9.977	+0.023		
56		9.977	+0.023		
57		9.977	+0.023		
58		9.977	+0.023		
59		9.977	+0.023		
50	20.000	19.977	+0.023		
51		19.976	+0.024		
52		19.975	+0.025		
53		19.978	+0.022		
54		19.978	+0.022		
55		19.979	+0.021		
56		19.978	+0.022		
57		19.979	+0.021		
58		19.979	+0.021		
59		19.978	+0.022		

ADD CORRECTIONS ALGEBRAICALLY TO INSTRUMENT READING

CORRECTION

SCALE READING

RECEIVED FROM Property of ERD

STANDARDS USED L&N K-3 1745012

COMMENTS Calibration of Individual Channels

RECALIBRATION DUE DATE ERD PROJECT NO. 81D75

Appendix B

Plume Equations

Buoyant diffusion plumes are caused by gravitational forces acting on the difference in density between the source fluid and its ambient environment. Batchelor (1954) proposed that turbulent buoyant plumes may be described by

$$U_0 = (Fa^{1/3} Z^{-1/3} f_1)(r/Z)$$

$$g' = (Fa^{2/3} Z^{-5/3} f_2)(r/Z)$$

$$Fa = 2\pi \int_0^\infty U_0 g' r dr$$

$$g' = g \frac{\Delta\rho}{\Delta\rho a}$$

Rouse, Yih, and Humphrey (1952) conducted a series of experiments that indicated that both mean temperature and velocity profiles were essentially Gaussian.

$$U_0 = 4.7\ Fa^{1/3} Z^{-1/3} \exp(-96\ r^2/Z^2)$$

$$g' = 11\ Fa^{1/3} Z^{-5/3} \exp(-71\ r^2/Z^2)$$

Stavrianidis (1980) modified the plume laws and obtained meaningful and generalized correlations of experimental data from three different fuels for the mean temperature and velocity profiles and the actual convective heat release rates. This work led to the rewriting of the plume laws as follows:

$$\overline{\Delta T_0} = 0.092\ Q_c^{2/3} (Z - Z_0)^{-5/3}$$

and

$$U_0 = 1.20\ Q_c^{1/3} (Z - Z_0)^{-1/3}$$

The critical height, that is, the height where divergence from the correlation is noted, is given by

$$\frac{Z_c - Z_0}{Q_c^{2/5}} = 0.13$$

Finally, Stavrianidis developed a flame height correlation to observed, videotaped flames with a basis derived from Heskestad (1980). This relation is given by

$$\frac{Z_f}{D} = 7.54\ F \left(\frac{\dot{m}^2 S^3}{\alpha_c H_c D^5} \right)^{1/5}$$

From this, the virtual source height (the height at which the fire is equivalently derived from) is described by

$$Z_0 = 7.54\,F^{1/5}\left(\frac{\dot{m}^2 S^3}{\alpha_c H_c}\right)^{1/5} - 0.15\,Q_c^{2/5}$$

The modeling of the source fire requires that several conservative assumptions be considered. As discussed in Tewarson (1980), the convective heat release rate is strongly influenced by the fuel's mass loss rate and stoichiometric fuel-to-air ratio. These parameters will in turn affect both the combustion efficiency and the actual heat of combustion. For the purposes of modeling, the maximum values for the heat of combustion of heptane were used. These values were taken from experimental data reported in Tewarson (1980), Figures 3(a) and 3(b). These values are as follows:

Total heat of combustion is 43 kJ/g.
Convective heat of combustion is 23 kJ/g.

Tewarson reports on experimental data discussed by Blinov and Khudiakov (1961), where the maximum mass loss rate of 50 g/m^2-sec was used.

With this information, the virtual source height was calculated as follows:

$$Z_0 = 7.54\,F^{1/5}\left(\frac{Q_c^2 S^3}{\alpha_c^3 H_c^3}\right)^{1/5} - 0.15\,Q_c^{2/5}$$

where

$$F = \frac{c_p T_a}{\rho_a^2 g} = 21.73$$

$$Q_c = \text{convective heat release rate} = (1150\ \text{kW/m}^2)(0.3716\ \text{m}^2) = 427\ \text{kW}$$

$$\alpha_c = \frac{Q_c}{Q_{th}} = \frac{Q_c}{\dot{m} H_c} = \frac{427}{(50)(0.3716)(45.1)} = 0.51$$

$$S = \text{stochiometric ratio} = \frac{\text{g air}}{\text{g fuel}} = 15.16$$

$$H_c = 45.1\ \text{kJ/g}$$

Substituting into the original expression,

$$Z_0 = 9.88 \text{ in.}$$

Knowing the virtual source height, the critical fire height is given by

$$Z_c - Z_0 = 0.13\ Q_c^{2/5}$$

which yields

$$Z_c = 1.717 \text{ m} = 5.63 \text{ ft}$$

References

Batchelor, G. K. 1954. "Heat Convection and Buoyancy Effects in Fluids." *Quarterly Journal of the Royal Meteorologic Society*, Vol. 80, pp. 339-358.

Blinov, V. I., and G. N. Khudiakov. 1961. *Diffusion Burning of Liquids*. Research Information Service, U.S. Army Engineer Research and Development Laboratory, Fort Belvoir, Va.

Heskestad, G. 1980. *Peak Gas Velocities and Flame Heights of Buoyancy-Controlled Turbulent Diffusion Flames*. Presented at the Eighteenth International Symposium on Combustion.

Rouse, M., C. S. Yih, and H. W. Humphreys. 1952. "Gravitational Convection from a Boundary Source." *Tellus*, Vol. 4, pp. 201-210.

Stavrianidis, P. 1980. *The Behavior of Plumes Above Pool Fires*. Thesis, Department of Mechanical Engineering, Northeastern University, Boston.

Tewarson, A. 1980. "Heat Release Rate in Fires." *Fire and Materials*, Vol. 4, Issue 4.

Appendix C

Switch Radiation Model

The test switch that was analyzed was composed of a polymeric body and plate. The body contained within the panel was ignored for the purposes of analysis and only that portion located above the console was considered. The model effectively rotated the switch to the vertical position so that the full face viewed the entire fire. The properties of the switch were considered to be composed primarily of bakelite with values derived from Rohsenow and Choi (1961). As a gray body, absorptivity was taken to be 0.95 with the emissivity assumed to be only 0.10.

The model used a right cylinder defined by the critical height and assumed the following form:

$$\frac{dT}{dt} = \frac{1}{c_p \rho \delta}(\dot{q}_r'' - \epsilon \sigma T^4)$$

where

$c_p = 0.38$ B/lbm·°F (Rohsenow and Choi, 1961)

$\rho = 0.046$ lbm/in.^{3} (Rohsenow and Choi, 1961)

$\epsilon = 0.10$

σ = Boltzmann Constant = 3.3044×10^{-15} B/sec·in.^{2}·R^4

This equation was solved using a Runge-Kutta integration where

$$T_{n+1} = T_n + (1/6)(K_1 + 2K_2 + 2K_3 + K_4)$$

$$K_1 = \frac{\Delta t}{c_p \rho \delta}(\dot{q}_r'' - \epsilon \sigma (T_n)^4)$$

$$K_2 = \frac{\Delta t}{c_p \rho \delta}[\dot{q}_r'' - \epsilon \sigma (T_n + 1/2\, K_1)^4]$$

$$K_3 = \frac{\Delta t}{c_p \rho \delta}[\dot{q}_r'' - \epsilon \sigma (T_n + 1/2\, K_2)^4]$$

$$K_4 = \frac{\Delta t}{c_p \rho \delta}[\dot{q}_r'' - \epsilon \sigma (T_n + K_3)^4]$$

$\dot{q}_r''$ is taken to be a gray gas. Emissivity is taken to be that associated with soot, carbon dioxide, and water.

$$\epsilon_{gas} = 10(-0.1807 - 2.341 \times 10^{-4}\ T_{gas})$$

$$\epsilon_{soot} = 0.10$$

$$\sigma = 3.3044 \times 10^{-15}\ \text{B/sec}\cdot\text{in.}^2\cdot\text{R}^4$$

Therefore,

$$\dot{q}_r'' = \text{configuration factor} \cdot (\epsilon_{gas} + \epsilon_{soot})\ \sigma\, T_{gas}^4$$

where

$$T_{gas} = 1763°\text{F} = 2223°\text{R (Stavrianidis, 1980)}$$

At the cylinder surface, the configuration factor equals 1. Therefore

$$\dot{q}_r'' = 1(0.2 + 0.1)(0.0807)$$

$$\dot{q}_r'' = 0.02413\ \text{B/sec}\cdot\text{in.}^2$$

Burn time for the radiation model may be calculated from the most intensive burn in order to maximize the impact of radiation. Such an assumption corresponds with a mass loss rate of 50 g/m^2-sec. A 4-ft^2 fire area is equivalent to 0.3716 m^2 yielding a mass loss rate of

$$(50\ \text{g/m}^2\cdot\text{sec})(0.3716\ \text{m}^2) = 18.58\ \text{g/sec}$$

With a density of 68 g/cm^3, the burn time is given by

$$\frac{(0.68\ \text{g/cm}^3)(1\ \text{gal})(3785.4\ \text{cm}^3/\text{gal})}{18.58\ \text{g/sec}} = 138.5\ \text{sec}$$

The radiation flux visible to the switch at any point is partially obscured by the panel. With a critical height of 68 in. and a panel height of 25 in., the unobstructed component of the cylinder is, therefore, 43 in. clearly visible to the switch.

References

Rohsenov, W. M., and H. Choi. 1961. *Heat, Mass and Momentum Transfer*. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Stavrianidis, P. 1980. *The Behavior of Plumes Above Pool Fires*. Thesis, Department of Mechanical Engineering, Northeastern University, Boston

Appendix D

Numerical Solution

Finite-difference methods for solving differential equations provide numerical solutions for problems that may not be easily treated analytically. A typical problem from mathematical physics that may be successfully approached in such a manner is Poisson's equation:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \frac{\partial \phi}{\partial t}$$

An analytical solution to this equation may be demonstrated for the Direchlet Problem, where the equation assumes the form of the Laplacian $(\partial\phi/\partial t \rightarrow 0)$ and where boundary conditions are stated

$$\phi\,(X,O) = \phi\,(X,b) = \phi\,(O,y) = 0$$

$$\phi\,(a,y) = f\,(y)$$

In this case, an analytical solution may be obtained through a separation of variables technique and a Fourier series representation

$$\phi(x,y) = \sum_{n=1}^{\infty} \phi_n(x,y) = \sum_{n=1}^{\infty} C_n \sinh \frac{n\pi x}{b} \sin \frac{n\pi y}{b}$$

$$\phi(a,y) = f(y) = \sum_{n=1}^{\infty} C_n \sin \frac{n\pi a}{b} \sin \frac{n\pi y}{b}$$

$$C_n = \frac{2}{b \sin \frac{\pi a}{b}} \int_0^b f(y) \sin \frac{\pi y}{b}\, dy$$

A finite-difference solution may be derived as follows:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \frac{(\phi_{n+\Delta x} - \phi_n) - (\phi_n - \phi_{n-\Delta x})}{(\Delta x)^2} + \frac{(\phi_{n+\Delta y} - \phi_n) - (\phi_n - \phi_{n-\Delta y})}{(\Delta y)^2}$$

For $\Delta x = \Delta y$

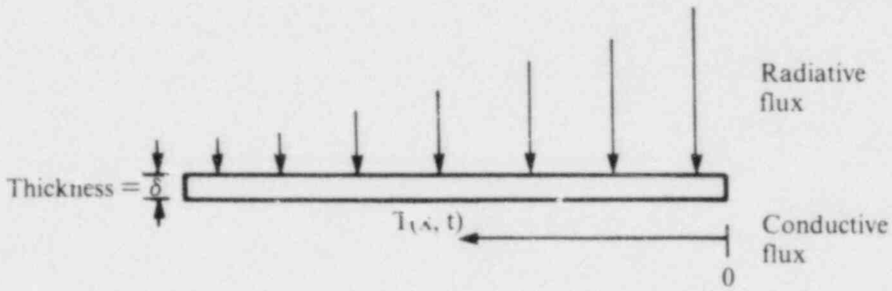
$$\frac{\phi_{n+\Delta x} + \phi_{n-\Delta x} + \phi_{n+\Delta y} + \phi_{n-\Delta y}}{(\Delta x)^2} = 0$$

$$\phi_n = \frac{\phi_{n+\Delta x} + \phi_{n-\Delta x} + \phi_{n+\Delta y} + \phi_{n-\Delta y}}{4(\Delta x)^2}$$

Finite-difference algorithms are extremely useful where equations assume complex forms or where boundary conditions impose difficult conditions. For the problem relating to console temperatures, finite-difference methods seemed appropriate. The console panel was considered as a one-dimensional problem in order to effectively bound the outcome. The following two processes were assumed to occur simultaneously:

1. Radiative flux that varied with position.
2. Conduction of energy deposited on the console underside as a result of direct flame impingement.

These two processes may be visualized as follows:



Based on a similar development in El-Wakil (1971)

$$\frac{\partial T}{\partial t} = \alpha_c \frac{\partial^2 T}{\partial x^2} + \frac{\alpha_c \dot{q}_r'' \alpha_r}{k\delta}$$

where

α_c = thermal diffusivity = 0.01808

α_r = radiation absorptivity = 0.95 (for pointed steel, Rohsenow and Choi, 1961)

δ = 0.1875 in.

Transposing into a finite-difference form,

$$\frac{T_{i_{n+1}} - T_{i_n}}{\Delta t} = \alpha_c \left[\frac{\left(T_{(i+1)_n} - T_{i_n}\right) - \left(T_{i_n} - T_{(i-1)_n}\right)}{(\Delta x)^2} \right] + \left(\frac{\alpha_c \alpha_r}{k\delta} \right) \dot{q}_{r_i}''$$

With Fourier modules

$$F_0 = \frac{\alpha_c \Delta \tau}{(\Delta x)^2}$$

and temperature increment due to radiation absorption is

$$\Delta T_{r_i} = \frac{(\Delta x)^2 \; \dot{q}''_{r_i} \, \alpha_r}{2K\delta}$$

$$T_{i_{n+1}} = (1 - 2F_0)\, T_{i_n} + F_0 \left(T_{(i-1)_n} + T_{(i+1)_n}\right) + 2F_0 \Delta T_{r_i}$$

where

$$F_0 \leqslant 1/2 \text{ for stability, or } t \leqslant \frac{(\Delta x)^2}{2\alpha}$$

References

El-Wakil, M. M. 1971. *Nuclear Heat Transport*. International Textbook Company, Scranton, Penn.
Rohsenow, W. M., and H. Choi. 1961. *Heat, Mass and Momentum Transfer*. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Appendix E

Panel Heatup

A significant contribution to console heatup is provided by flame impingement on the underside portion of the control panel. The heat-flux incident on the control panel leads to an exponential heatup of the panel edge and subsequent conduction toward cooler regions of the control panel. Because of the intense nature of the effects of flame impingement, this phenomenon has the potential of being a dominant contributor to the heating of components in proximity to an exposure fire.

The approach followed in the model treats the process of flame impingement essentially as a convective heat transfer problem. The mechanism for heat transfer in this case is turbulent forced convection of hot fire gases in direct and continuous contact with a 3/16-in. steel plate. Since the panel underside makes approximately a 20 degree angle with the vertical axis, stagnation of the fire plume leading to the development of a completely horizontal jet is not assumed. This view is supported by the Detroit Edison control room fire test (Colbert, 1981), which clearly demonstrates partially deflected flames without evidence of stagnation.

From Rohsenow and Choi (1961), the film heat transfer coefficient along a plate with predominantly parallel turbulent flow is given by

$$\frac{Pr^{2/3} h}{c_p \rho V} = 0.0296 \left(\frac{\nu}{LV}\right)^{1/5}$$

for air at approximately 500°F where 500°F air is conservatively assumed to be representative of the Newton film temperature adjacent to the plate.

V = vertical component of the fire gas velocity vector
ρ = plate density = 0.0413 lbm/ft^3 (air)
c_p = plate specific heat = 0.248 B/lbm·°F (air)
Pr = Prandtl number = 0.68 (steel) (air)
ν = kinematic viscosity = 1.63 ft^2/hr
L = length along the plate

The above-listed thermophysical properties were taken from Rohsenow and Choi (1961).

The vertical velocity component is given by the Stavrianidis (1980) critical velocity as follows:

$$u_0 = 1.20\, Q_c^{1/3} (z_c - z_0)^{-1/3}$$

$$u_0 = 1.20(427\text{ kW})^{1/3} (1.717\text{ m} - 0.251\text{ m})^{-1/3}$$

$$u_0 = 7.954\text{ m/sec} = 26.1\text{ ft/sec}$$

To artificially and conservatively increase the effect of heating, the vertical gas velocity used in this analysis was reduced to 25 ft/sec.

The plate length is conservatively taken to be the vertical height of the panel itself, a distance of approximately 25 in. With these assumptions, the film heat transfer coefficient is solved as follows:

$$h = 0.0296\left(\frac{\nu}{LV}\right)^{1/5} \frac{c_p \rho V}{Pr^{2/3}}$$

$$h = 3.43\ B/hr \cdot ft^2 \cdot {}^\circ F = 0.01082\ kW/m^2 \cdot {}^\circ F$$

For the fire gas temperature of 1763°F and assuming the panel to be initially at 70°F, the maximum convection heat flux at model fire initiation is given by

$$\dot{q}''_{convection} = 0.01082(1763^\circ F - 70^\circ F) = 18.32\ kW/m^2$$

Assuming uniform panel temperatures from the floor to the panel edge and complete insulation to the floor and in either direction off the fire centerline, edge heatup may be calculated as follows:

$$\frac{dT_{edge}}{dt} = \left(\frac{1}{c_p \rho \delta}\right) h \left(T_{gas} - T_{edge}\right)$$

$$\int_{T_{amb}}^{T} \frac{-dT_{edge}}{T_{gas} - T_{edge}} = \int_0^t \frac{-h}{\rho c_p \delta} dt$$

$$T_{edge} = T_{gas} - (T_{gas} - T_{amb}) e^{-\frac{t}{\tau}}$$

where

$$\tau = \frac{\rho c_p \delta}{h}$$

A best-estimate calculation using these conservative assumptions yields a $\tau = 902$ sec with the one-dimensional panel temperature results documented in Table 3–6. To be even more conservative, an additional assumption is arbitrarily made whereby the flame impingement heat flux is increased by a factor of 3 to 60 kW/m^2. The new time constant is given as follows:

$$h = \left(\frac{60\ kW/m^2}{18.32\ kW/m^2}\right)\left(3.43\right) = 11.23\ B/hr \cdot ft^2 \cdot {}^\circ F$$

which yields

$$\tau = \frac{\rho c_p \delta}{h} = 275\ sec$$

The results of arbitrarily increasing the incident flame impingement heat flux to 60 kW/m^2, a factor of 3 higher than the heat flux calculated with conservative assumptions, are shown in Table 3-7.

References

Colbert, W. F., Detroit Edison. 1981. "Control Panel Fire Test." Letter EF2-54205 to L. L. Kintner, NRC, July 31.

Rohsenow, W. M., and H. Choi. 1961. *Heat, Mass and Momentum Transfer.* Prentice-Hall, Inc., Englewood Cliffs, N.J.

Stavrianidis, P. 1980. *Behavior of Plumes Above Pool Fires.* Thesis, Department of Mechanical Engineering, Northeastern University, Boston.

Appendix F

Convection

In the course of the postulated fire, both the console and the switch continuously receive energy through conduction and radiation. A constant emissivity of 0.10 is assumed for the switch for the purpose of reradiation, although both the switch and the console are considered to be gray bodies in terms of absorption (95 percent). The only other mechanism for cooling which the model takes credit for is that associated with turbulent convection.

The approach followed is taken from Kreith (1973). The console is assumed for cooling purposes to have a rectangular face 2 by 2 ft in size. Convection is provided as follows:

$$Nu_L = \frac{h_c L}{k} = 0.14(Gr_L Pr)^{1/3}$$

where convection is assumed to occur with air at a uniform temperature of 200°F, and where

$$L = 2 \text{ ft}$$

$$h_c = 0.2122\ (T - 200)^{1/3}\ \text{B/ft}^2\cdot\text{hr}\cdot{}^\circ\text{F}$$

$$k = 0.018\ \text{B/ft}\cdot\text{hr}\cdot{}^\circ\text{F}$$

$$Pr = \text{Prandtl number} = 0.694$$

$$Gr_L = 688 \times 10^6\ (T - 200)$$

The resultant cooldown process assumes an exponential form that may be characterized by a time constant.

$$\frac{dT}{dt} = -\left(\frac{h_c}{c_p \rho \delta}\right)\left(T - 200\right)$$

$$\int_{T_o}^{T} \left(\frac{dT}{T - 200}\right) = \int_0^t -\left(\frac{h_c}{c_p \rho \delta}\right) dt$$

$$T = 200 + (T_o - 200)\exp\left(\frac{h_c t}{c_p \rho \delta}\right)$$

$$\text{defining } \tau = \frac{c_p \rho \delta}{h_c} = \frac{3095.5}{h_c} \text{ sec}$$

Reference

Kreith, F. 1973. *Principles of Heat Transfer*. Intext Press, Inc., New York.