ENCLOSURE 2

NUMARC

NUCLEAR MANAGEMENT AND RESOURCES COUNCIL

1776 Eye Street, N.W. • Suite 300 • Washington, DC 20006-2496
(202) 872-1280

December 3, 1990

Mr. Warren Minners, Director
Division of Safety Issue Resolution
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Mail Stop NLS007
Washington, DC 20555

Dear Mr. Minners:

Your letter of September 20, 1990, forwarded NRC Staff comments on the draft Fire Induced Vulnerability Evaluation (FIVE) methodology developed by EPRI in support of NUMARC. Included in the Staff comments was a request for NUMARC/EPRI to confirm the validity of the fire modeling techniques utilized in the FIVE methodology. As noted in our letter of November 14, 1990, which responded to the Staff's comments, the validation information would be forwarded at a later date. Enclosed for your information is an EPRI-sponsored comparison between the FIVE fire hazard analysis methodology and experimental data.

As noted in Dr. Sursock's transmittal letter to NUMARC, the results demonstrate an excellent performance of the analytical tools in reproducing data from experiments performed by Underwriters Laboratories and Factory Mutual Research under Sandia National Laboratory sponsorship. We believe this effort is sufficient confirmation of the validity of the FIVE fire modeling techniques.

Again, we appreciate Staff's cooperative efforts on this alternative methodology and its supporting information. Any questions Staff may have on the enclosed material should be directed to Dr. Sursock.

Sincerely,

William H. Rasin

William H. Rasin
Director, Technical Division

DJM/
Enclosure

cc: C. McCracken, NRC
C. Reed, CECo w/o enclosures
J. Sursock, EPRI w/o enclosures

9012310079 901217
PDR ORG NREA
PDR

EPRI
Electric Power
Research Institute

Leadership in Science and Technology

November 20, 1990

Mr. Dave Modeen
NUMARC
1776 Eye Street
Washington, DC 20006-2496

Dear Dave:

Please find enclosed a copy of the comparison between the FIV
analysis methodology and experimental data, performed b
University of Maryland.

The purpose of this work was to validate the
actual experiments performed by Underw
Mutual Research under Sandia Natio

The results demonstrate an excellent
reproducing the experimental data.

Sincerely,

Jean-Pierre Sursock
Manager
Safety Performance Program
Nuclear Power Division

Enclosures

cc: Doug Brandes
Dave Fan
Frank Garrett
Mike Kaminski
Alex Klein
Chris Ksobiech
Fred Mowrer

271L/JPS/CJS

Headquarters: 3412 Hillview Avenue, Post Office Box 10412, Palo Alto, CA 94303, USA • (415) 855-2000 • Telex: 82977 EPRI UF • Fax: (415)
Washington Office: 1019 Nineteenth Street, NW, Suite 1000, Washington, DC 20036, USA • (202) 872-9222 • Fax: (202) 296-5436

COMPARISONS WITH THE UL/SNL NATURA

A series of 4 experiments and
evaluate the 20 foot separatio
experiments used heptane pool
included heptane pools in c
cables. The 4 experiments
compared previously with th

Fire Source Characterizat

The fire source for the
of heptane in a 0.3 m
of the FIVE methodolo
heptane are:

ΔHc = 44.6
m'' = 0.10
b_p = 0.9
q = 41
ρ = 6

The total m
the heptan
(0.92 x 1
based on
burning
sugges

The
app
es

EPRI
Electric Power
Research Institute ________ *Leadership in Science and Technology*

November 20, 1990

Mr. Dave Modeen
NUMARC
1776 Eye Street
Washington, DC 20006-2496

Dear Dave:

Please find enclosed a copy of the comparison between the FIVE fire hazard analysis methodology and experimental data, performed by Fred Mowrer of University of Maryland.

The purpose of this work was to validate the FIVE hazard analysis using actual experiments performed by Underwriters Laboratories and Factory Mutual Research under Sandia National Lab sponsorship.

The results demonstrate an excellent performance of the analytical tools in reproducing the experimental data.

Sincerely,

Jean-Pierre Sursock
Manager
Safety Performance Program
Nuclear Power Division

Enclosures

cc: Doug Brandes
Dave Fan
Frank Garrett
Mike Kaminski
Alex Klein
Chris Ksobiech
Fred Mowrer

271L/JPS/CJS

Headquarters: 3412 Hillview Avenue, Post Office Box 10412, Palo Alto, CA 94303, USA • (415) 855-2000 • Telex: 82977 EPRI UF • Fax: (415) 855-2954
Washington Office: 1019 Nineteenth Street, NW, Suite 1000, Washington, DC 20036, USA • (202) 872-9222 • Fax: (202) 296-5436

COMPARISONS WITH THE UL/SNL NATURAL VENTILATION ENCLOSURE TESTS

A series of 4 experiments and 6 tests was conducted at UL to evaluate the 20 foot separation rule of Appendix R. The four experiments used heptane pools as the fire source; the 6 tests included heptane pools in conjunction with vertical electrical cables. The 4 experiments are analyzed here. They have been compared previously with the COMPBURN III model.

Fire Source Characterization

The fire source for the 4 experiments was 37.85 liters (10 gallons) of heptane in a 0.3 m (1 ft) by 1.5 m (5 ft) trough. From Table 2M of the FIVE methodology documentation, the relevant properties of heptane are:

ΔHc = 44.6 MJ/kg
m'' = 0.101 kg/s-m^2
b_ρ = 0.92
q'' = 4144 kW/m^2
ρ = 675 kg/m^3

The total mass of heptane is 25.5 kg. The total energy content of the heptane is 1140 MJ, with an effective energy content of 1050 MJ (0.92 x 1140). The heat release rate is calculated to be 1925 kW, based on large diameter pool fires. At this heat release rate, the burning duration is calculated to be 545 s. These are the values suggested for use by the FIVE basic screening methodology.

The actual burning duration measured during Experiments 2 and 3 was approximately 1300 s, which is approximately 2.4 times the estimated burning duration. Consequently, the actual average heat release rate during these experiments was likely to be approximately 800 kW (1925/2.4). The difference between the heat release rate suggested by the FIVE methodology and the measured heat release rate most likely can be attributed to the size and shape of the fire source. The heat release rate suggested by FIVE is a limit value based on large-diameter optically thick pool fires. The fire source used in these experiments was too small to achieve this limit burning rate.

A heat release rate of 800 kW is used for the detailed comparisons developed here. This should provide a reasonably accurate basis for comparison of the FIVE calculation methods with the experimental data. The 1925 kW heat release rate that would be estimated by the FIVE method results in higher calculated temperatures and therefore yields more conservative estimates of hazard. The primary goal here is to develop the most accurate comparisons, so the 800 kW heat release rate is used for the primary comparisons. Results of calculations using a 1925 kW heat release rate are also provided to demonstrate that the basic FIVE screening methodology yields conservative temperature estimates.

Mass Flow Estimates

A simple closed-form method for evaluating the mass flow balance in naturally ventilated enclosure fires has been developed recently for the FIVE methodology. This method uses linearized forms of the mass efflux and plume entrainment equations.

Based on application of Bernoulli's Equation, the mass efflux rate through a vertical rectangular opening can be expressed as:

$$\dot{m}_e = \frac{2}{3} C_d W_o \rho_f \sqrt{2g\left(\frac{\rho_o}{\rho_f} - 1\right)}\,(H_o - H_L)^{3/2} \tag{1}$$

where

C_d = Orifice flow coefficient
W_o = Opening width (m)
ρ = gas density (ambient and fire) (kg/m3)
H_o = Opening height (m)
H_L = Height of layer above bottom of opening (m)

The flow coefficient, C_d, accounts for differences between theoretical and actual flows due to friction and flow contraction at an orifice. A value of 0.7 is representative for flows through rectangular wall openings. Equation 42 appears to depend strongly on the smoke layer temperature, but in fact this dependence is weak over the temperature range of interest because as the temperature goes up, the density goes down. This causes a greater pressure difference across the opening, which in turn causes the gas velocity to increase. The decreased density and increased gas velocity tend to balance each other, resulting in a fairly constant mass flux. Consequently, Equation 1 can be simplified to:

$$\dot{m}_e = 1.20\ W_o H_o^{3/2} (1 - H_L/H_o)^{3/2} \quad (kg/s) \tag{2}$$

In compartments with single rectangular openings in one wall, the single opening serves both for air inflow to and for smoke outflow from the enclosure. The maximum rate of mass exchange is limited by the opening size and shape and can be estimated, in units of kg/s, as:

$$\dot{m}_{max} = 0.5 A_o \sqrt{H_o} \tag{3}$$

where A_o is the opening area (m^2) and H_o is the opening height (m). This is known as the ventilation limit of air flow.

Equations 2 and 3 can be equated to estimate the height of the layer in the opening when the ventilation limit is reached:

$$\left(\frac{H_L}{H_o}\right)_{@V.L.} = 0.44 \tag{4}$$

This suggests that the ventilation limit of air flow is achieved when the hot gas layer descends to fill the upper 56% of the opening. As a consequence, Equation 2 only applies over the range $0.44 < H_L/H_o < 1$. Over this range, Equation 2 can be linearized by noting that:

$$(1-H_L/H_o)^{3/2} = 0.9(0.9-H_L/H_o) \tag{5}$$

With this simplification, the mass efflux term can be expressed as a linear function of the hot gas layer height above the bottom of the opening:

$$\dot{m}_e = A_o\sqrt{H_o}\,(0.97-1.08H_L/H_o) \tag{6}$$

Under quasi-steady conditions, this mass efflux term must be balanced with the plume entrainment rate to evaluate the location of the hot gas layer interface and, consequently, the mass flow rate. Heskestad suggests that the rate of entrainment into fire plumes can be treated as a linear function of the height, z, in the region near the fire source:

$$\dot{m}_l = 0.0054\ \dot{Q}_c\ z/z_L \tag{7}$$

where

$$z_L = z_o + 0.166\ \dot{Q}_c^{2/5}$$

For fires along walls and in corners, the method of reflection is used to estimate the effect on entrainment. This method suggests that a fire burning along a wall can be treated as a fire burning with twice the actual intensity that entrains air around only one-half its perimeter. A fire burning in a corner is treated as a fire with four times the intensity of the actual fire that entrains air around only one-quarter of its perimeter. Consequently, Equations 7 and 8 can be rewritten to treat fires along walls and in corners as:

$$\dot{m}_l = 0.0054 \frac{(k\dot{Q}_c)}{k} \frac{z}{z_L} \tag{9}$$

$$z_L = z_o + 0.166 \, (k\dot{Q}_c)^{2/5} \tag{10}$$

Because of the linear dependence of the entrainment rate on the heat release rate expressed by Equation 7, Equation 9 reduces to be identical to Equation 7. Equation 10 can be used in place of Equation 8 by using k = 1 for fires in the center of rooms, k = 2 for fires located along walls, and k = 4 for fires in corners.

Assuming that the virtual origin location, z_o, can be located at the top of the fire source and that the convective heat release rate, Q_c, is approximately 70 percent of the actual heat release, Q_a, the expression for plume entrainment in the near fire region can be expressed as:

$$\dot{m}_l = 0.026 \frac{\dot{Q}_a^{3/5}}{k^{2/5}} \, z \tag{11}$$

where $z = H_L + H_b + H_f$. H_f is the fire source height relative to the floor level and H_b is the distance from the floor to the bottom of the opening.

For regions far above the fire source, Heskestad and other investigators suggest the entrainment rate will follow the form suggested by classical plume theory:

$$\dot{m}_l = k \, \dot{Q}^{1/3} \, z^{5/3} \tag{12}$$

For most room fire scenarios, it is expected that the near region equation expressed by Equation 11 will be appropriate because the hot gas layer is likely to equilibrate near or below the flame region, particularly for scenarios that represent the most significant hazard. Any errors that might occur due to extension of Equation 11 to the far region should be conservative in view of the much more rapid entrainment rate, and consequent temperature decay, expressed by Equation 12.

Equations 6 and 11 can be equated to solve for the layer height:

$$\frac{H_L}{H_o} = \frac{0.97 A_o \sqrt{H_o} + 0.026 (H_f - H_b) \dot{Q}_a^{3/5} / k^{2/5}}{0.026 H_o \dot{Q}_a^{3/5} / k^{2/5} + 1.08 A_o \sqrt{H_o}} \qquad \textbf{(13)}$$

For the case where the fire height, H_f, is at the same elevation as the bottom of the wall opening, H_b, such as for a floor-based fire in a room with an open door, Equation 13 simplifies slightly to:

$$\frac{H_L}{H_o} = \frac{0.97 A_o \sqrt{H_o}}{0.026 H_o \dot{Q}_a^{3/5} / k^{2/5} + 1.08 A_o \sqrt{H_o}} \qquad \textbf{(14)}$$

Finally, once the layer height is calculated from Equation 13 or 14, the quasi-steady mass flow rate for naturally ventilated enclosure fires can be expressed as:

$$\dot{m} = A_o \sqrt{H_o} \times MIN[0.5, 0.97 - 1.08 H_L / H_o] \qquad \textbf{(15)}$$

This is the approach used to evaluate the mass flows and temperatures in the naturally ventilated UL/SNL experiments.

UL/SNL Experiment #1 - 800 kW in center - 2.4 m x 2.4 m opening

This experiment was conducted in a room with dimensions of 9.1 m (30 ft) long x 4.3 m (14 ft) wide x 3.0 m (10 ft) high. The fire source was located 6.1 m (20 ft) from a set of horizontal cable trays located near the single wall opening and approximately 2 m (6.5 ft) from the rear wall. This opening had dimensions of 2.4 m (8 ft) high x 2.4 m (8 ft) wide, with the base of the opening located at floor level.

The basic screening methodology, which assumes an unventilated enclosure, was used to evaluate this experiment. The results of this analysis are not physically meaningful for two reasons: they neglect the oxygen limitation on combustion in unventilated room fires and they neglect the important role the natural ventilation played in this experiment. The analysis appropriate for an unventilated space is discussed in more detail for Experiment 4, in which the ventilation opening was closed.

For this experiment, the ventilation factor is calculated as:

$$A_o\sqrt{H_o} = 2.4 \times 2.4^{3/2} = 8.92\ m^{5/2} \qquad \textbf{(16)}$$

The maximum mass flow rate is therefore calculated to be 4.5 kg/s.

For a heat release rate of 800 kW and a ventilation factor of 8.92 $m^{5/2}$, with H_b = 0 and H_f = 0.3 m (1 ft), the height of the layer interface is calculated, using Equation 13, as:

$$\frac{H_L}{H_o} = \frac{0.97(8.92)+(.026)(0.3-0)(800)^{3/5}/1^{2/5}}{(.026)(2.4)(800)^{3/5}/1^{2/5}+(1.08)(8.92)} = 0.70 \qquad \textbf{(17)}$$

Using Equation 15, the mass flow rate is calculated to be:

$$\dot{m} = 8.92 \times MIN[0.5, 0.97-1.08(0.70)] = 2.0\ kg/s \qquad \textbf{(18)}$$

The average gas temperature is calculated as:

$$\Delta T_{AVG} = \frac{\dot{Q}_n}{\dot{m}c_p} = \frac{(1-0.7)(800kW)}{(2.0kg/s)(1.0kJ/kg\text{-}K)} = 120K \qquad \textbf{(19)}$$

The plume temperature rise at the ceiling is calculated as:

$$\Delta T_{pl} = 25\ \dot{Q}^{2/3}/z^{5/3} = 25(800)^{2/3}/2.7^{5/3} = 412K \qquad \textbf{(20)}$$

Temperatures beneath the ceiling were measured a distance r/H=2 from the plume centerline. The ceiling jet temperature rise therefore is calculated as:

$$\Delta T_{cj} = \Delta T_{pl} \times \frac{0.3}{(r/H)^{2/3}} = \frac{(0.3)(412)}{2^{2/3}} = 78K \tag{21}$$

The total temperature rise is calculated to be:

$$\Delta T_{TOT} = \Delta T_{AVG} + \Delta T_{pl} = 120 + 78 = 198\ K\ (C) \tag{22}$$

The measured temperature in this experiment was approximately 245C at the target. Assuming an ambient temperature of 20C, the calculated temperature at the target is 218C. This is a difference of approximately 27C, or approximately 11%, with respect to the measured temperature. For the heat release rate of 1925 kW suggested by the FIVE screening methodology, the calculated temperature at the target would be 366C, which is 121C higher than the measured temperature at the target.

UL/SNL Experiment #2 - 800 kW along wall - 2.4 m x 2.4 m opening

Experiment 2 was conducted with the same fire source as Experiment 1, but the compartment was reduced from 9.1 m (30 ft) to 7.6 m (25 ft) in length and the burner was placed against the wall opposite the door opening, rather than in the middle of the room. The room opening size remained the same and consequently the ventilation factor and the maximum air flow rate remained unchanged.

For these conditions the normalized layer interface height is calculated as:

$$\frac{H_L}{H_o} = \frac{0.97(8.92)+(.026)(0.3-0)(800)^{3/5}/2^{2/5}}{(.026)(2.4)(800)^{3/5}/2^{2/5}+(1.08)(8.92)} = 0.73 \tag{23}$$

Using Equation 15, the mass flow rate is calculated to be:

$$\dot{m} = 8.92 \times MIN[0.5, 0.97-1.08(0.73)] = 1.6\ kg/s \tag{24}$$

The average gas temperature is calculated, using a heat loss fraction of 70%, as:

$$\Delta T_{AVG} = \frac{\dot{Q}_n}{\dot{m}c_p} = \frac{(1-0.7)\,(800kW)}{(1.6kg/s)\,(1.0kJ/kg\text{-}K)} = 151K \qquad \textbf{(25)}$$

The plume temperature rise at the ceiling is calculated as:

$$\Delta T_{pl} = 25\ (k\dot{Q})^{2/3}/z^{5/3} = 25(2\times 800)^{2/3}/2.7^{5/3} = 653K \qquad \textbf{(26)}$$

Temperatures beneath the ceiling were measured a distance r/H=2 from the plume centerline. The ceiling jet temperature rise therefore is calculated as:

$$\Delta T_{cj} = \Delta T_{pl} \times \frac{0.3}{(r/H)^{2/3}} = \frac{(0.3)\,(653)}{2^{2/3}} = 123K \qquad \textbf{(27)}$$

The total temperature rise is calculated to be:

$$\Delta T_{TOT} = \Delta T_{AVG} + \Delta T_{pl} = 151 + 123 = 274\ K\ (C) \qquad \textbf{(28)}$$

The measured temperature in this experiment was approximately 325C at the target. Assuming an ambient temperature of 20C, the calculated temperature at the target is 294C. This is a difference of approximately 31C, or approximately 10%, with respect to the measured temperature. Using the heat release rate of 1925 kW suggested by the basic FIVE methodology, the calculated temperature at the target would be 489C, which is 164C higher than the measured temperature.

UL/SNL Experiment #3 - 800 kW along wall - 2.4 m x 1.2 m opening

Experiment 3 was essentially the same as Experiment 2, except the compartment opening was reduced from 2.4 m (8 ft) high x 2.4 m (8 ft) wide to 2.4 m (8 ft) high x 1.2 m (4 ft) wide. This reduces the ventilation factor to 4.46 $m^{5/2}$ and the maximum air flow rate to 2.23 kg/s.

For these conditions the normalized layer interface height is calculated as:

$$\frac{H_L}{H_o}=\frac{0.97(4.46)+(.026)(0.3-0)(800)^{3/5}/2^{2/5}}{(.026)(2.4)(800)^{3/5}/2^{2/5}+(1.08)(4.46)}=0.63 \qquad (29)$$

From this, the mass flow rate is calculated to be:

$$\dot{m}=4.46\times MIN[0.5,0.97-1.08(0.63)]=1.3\ kg/s \qquad (30)$$

The average gas temperature is calculated, using a heat loss fraction of 70%, as:

$$\Delta T_{AVG}=\frac{\dot{Q}_n}{\dot{m}c_p}=\frac{(1-0.7)(800kW)}{(1.3kg/s)(1.0kJ/kg\text{-}K)}=183K \qquad (31)$$

The ceiling jet temperature rise therefore is calculated as for Experiment 2 to be 123 K. The total temperature rise is calculated to be:

$$\Delta T_{TOT}=\Delta T_{AVG}+\Delta T_{pl}=183+123=306\ K\ (C) \qquad (32)$$

The measured temperature in this experiment was approximately 355C at the target. Assuming an ambient temperature of 20C, the calculated temperature at the target is 326C. This is a difference of approximately 29C, or approximately 10%, with respect to the measured temperature. Using the heat release rate of 1925 kW suggested by the basic FIVE screening methodology, the calculated temperature at the target would be 566C, which is 211C higher than the measured temperature.

Temperature measurements were also reported for a distance of 1.2 m (4 ft) radially from the plume centerline. This represents a value of r/H = 0.45. At this location, the ceiling jet temperature rise is calculated to be:

$$\Delta T_{cj}=\frac{(0.3)(653)}{(0.45)^{2/3}}=333K \qquad (33)$$

The total temperature rise therefore is calculated as:

$$\Delta T_{TOT} = 333 + 183 = 516K \tag{34}$$

The measured temperature 0.3 m (1 ft) below the ceiling at this radial distance was approximately 510C. Assuming an ambient temperature of 20C, the calculated temperature at this location is 536C. This is a difference of approximately 26C, or about 5%.

UL/SNL Experiment #4 - 800 kW along wall - No opening

Experiment 4 was conducted in the same size compartment with the same fire source size and location as Experiments 2 and 3, but for this experiment the door opening was closed. In this experiment, the fire burned out before all the fuel was consumed, apparently due to oxygen depletion. A method has been developed to analyze the average gas temperature rise in an unventilated enclosure fire under conditions of oxygen depletion.

This method has not been described in the basic FIVE screening methodology documentation because it is considered unlikely that reliance could be placed on oxygen depletion as an effective means of fire control. Even if the oxygen-limited temperature remains below the critical damage temperature, eventually the compartment must be ventilated, for example to permit firefighting access or damage assessment. A description of this oxygen limitation on heat release, and consequently on the average temperature rise, in an unventilated enclosure fire follows.

Oxygen limitation on temperature rise in an unventilated enclosure

The rate of change of the mass fraction of oxygen, Y_{O2}, in an unventilated enclosure fire is related directly to the rate of heat release as:

$$m\frac{dY_{O2}}{dt} = -\frac{\dot{Q}_f}{(\Delta H_c/r_{O2})} \tag{35}$$

Assuming the enclosure remains at constant pressure, the total mass, m, of air in the enclosure changes as:

$$m = m_o \exp(Q_o/Q_n) \tag{36}$$

Equations 35 and 36 can be combined to yield:

$$-m_o(\Delta H_c/r_{O2})\int_{Y_{amb}}^{Y_{O2}} dY_{O2} = \int_0^{Q_f} \exp[(1-\chi_L)Q_f/Q_o]\,dQ_f \tag{37}$$

Equation 37 can be integrated directly to yield:

$$\frac{Q_o}{(1-\chi_L)}[e^{(Qn/Qo)}-1] = m_o Y_{amb}(\Delta H_c/r_{O2})\chi_{O2} = m_o(\Delta H_c/r_{air})\chi_{O2} \tag{38}$$

where

$$\chi_{O2} = [Y_{amb} - Y_{O2}]/Y_{amb} \tag{39}$$

and

$$Q_n = (1-\chi_L)Q_f = (1-\chi_L)\int_0^t \dot{Q}_f\,dt \tag{40}$$

Equation 38 can be solve for the net energy that can be added to an unventilated enclosure, normalized per unit volume of the space:

$$Q_n/V = Q_o/V\times\ln\left[1+\frac{\rho_o(\Delta H_c/r)\chi_{O2}(1-\chi_L)}{Q_o/V}\right] \tag{41}$$

For typical ambient conditions Equation 41 reduces to:

$$Q_n/V = 353\times\ln\left[1+\frac{3600\chi_{O2}(1-\chi_L)}{353}\right] \tag{42}$$

Equation 42 shows the functional dependence of the net heat release rate on the heat loss fraction and on the fraction of oxygen that can be consumed before the limiting oxygen index is reached.

Finally, this limit can be expressed in terms of the average temperature rise in the space:

$$\frac{\Delta T}{T_o} = e^{(Q_e/Q_o)} - 1 = \left[\frac{\rho_o (\Delta H_c / r) \chi_{O2} (1 - \chi_L)}{Q_o / V} \right] \qquad (43)$$

Assuming a heat loss fraction of 70%, an oxygen consumption fraction of 50% and an ambient temperature of 293K (20C), Equation 41 evaluates to ΔT = 448K, or T = 468C. Assuming a heat loss fraction of 85% and an oxygen consumption fraction of 50 %, the calculated temperature rise would be ΔT = 224K, or T = 244C. The same results occur for a heat loss fraction of 70% and an oxygen consumption fraction of 25%. The reported temperature for this experiment was approximately 250C. Since the actual oxygen consumption fraction was likely to be between 25% and 50% when the fire extinguished itself, this would suggest that the actual heat loss fraction was probably between 70% and 85%. While it is difficult to establish values of either of these parameters with absolute precision, this analysis does help explain the reasons for the observed temperatures in Experiment 4.

Summary of UL/SNL Experiments

Measured and calculated temperatures have been compared for three naturally ventilated enclosure fire experiments and one unventilated experiment conducted at UL under the direction of SNL. A method has been developed for inclusion in the FIVE methodology to estimate in closed form the mass flow rate in naturally ventilated enclosure fires with a single rectangular wall opening. A method also has been developed to evaluate the oxygen limitation on energy release and average temperature rise in an unventilated enclosure fire. This method is not suggested for inclusion in the screening methodology, but it is useful for evaluating an upper physical bound on calculated temperature rises in unventilated enclosure fires. Neglect of this coupling between heat release and the consumption and availability of oxygen can yield nonphysical results.

For the three ventilated experiments, the calculated temperatures at the target located a radial distance r/H=2 from the fire source were consistently about 10% lower than the maximum measured temperatures when a reasonable estimate for the actual heat release rate is used. The exact reasons for these systematic differences have not been discerned. They may be attributable to relatively small errors in the assumed heat release rate, in the mass entrainment rate, in the heat loss fraction, or in the model of ceiling jet temperature decay. Errors in each of these parameters may account for part of the difference, or they may tend to offset each other.

The fact that the calculated temperatures are within 90% of the measured temperatures for each of these naturally ventilated experiments suggests the FIVE calculations are able to consider with reasonable accuracy the influences of ventilation opening size and shape, fire location, and target location on temperatures in naturally ventilated fires. When the more conservative estimate of heat release rate suggested by the basic FIVE screening methodology is used, the calculated temperatures are consistently higher than the maximum measured temperatures.

FIVE FIRE HAZARD ANALYSIS METHODOLOGY
COMPARISON WITH EXPERIMENTAL DATA

Temperatures calculated with the fire hazard analysis methodology developed for the FIVE methodology are compared with measured experimental temperatures from the FM/SNL test series. In this test series, experiments were conducted in a 18.3 m by 12.2 m by 6.1 m high enclosure with forced ventilation. The FM/SNL test series is described in NUREG/CR-4681.

Sandia has previously used some results of the FM/SNL test series for preliminary comparisons with the FIVE methodology. Based on this comparison, the Sandia review was critical of the results demonstrated by the fire hazard analysis component of the FIVE methodology. However, the Sandia comparison neglected the effects of the hot gas layer on the overall temperature rise in the ceiling jet. These effects are included in the present comparison. Inclusion of the hot gas layer effects makes the calculated ceiling jet temperatures much more consistent with the measured temperatures.

The basic screening procedure of the FIVE methodology suggests that analyses based on unventilated enclosures will yield the most conservative results. Here, the term unventilated means that the only ventilation is due to the expansion of gases from the enclosure volume. The present comparisons confirm this premise, but they can yield either overly conservative predictions or nonphysical predictions if extended beyond the actual conditions being represented. Overly conservative predictions arise when the actual ventilation significantly exceeds the ventilation due to gas expansion. Nonphysical predictions can occur when the oxygen limit on combustion within an unventilated enclosure is neglected.

Methods to analyze ventilated enclosures have been developed as part of the FIVE methodology. These methods are used as appropriate for the present comparisons. They are identified when they are used.

COMPARISONS WITH THE FM/SNL FORCED VENTILATION ENCLOSURE TESTS

A total of 22 tests using a simple propylene-fired gas burner, heptane pool, methanol pool and PMMA solid fires was conducted in the 18.3 m (60 ft.) by 12.2 m (40 ft.) by 6.1 m (20 ft.) high enclosure. Parameters varied among tests included the nominal fire intensity, the nominal enclosure ventilation rate and the fire location.

Nominal fire intensities included 500 kW, 1000 kW and 2000 kW. For some experiments, transient fire growth histories were used. These transient histories are described in NUREG/CR-4681. For other experiments, the nominal heat release rate was maintained steady for a period of approximately 10 minutes. A duration of 10 minutes was assumed for calculations involving steady fires.

Nominal ventilation rates varied from 1 air change per hour to 10 air changes per hour. The present analysis suggests that in some cases the nominal ventilation rate in fact may have been inadequate to exhaust the expanding gases from the enclosure. For these situations, an unventilated enclosure analysis was used for the present comparisons. Otherwise, a ventilated enclosure analysis was used, in which case the nominal ventilation rate was taken as the rate of air inflow to the enclosure (ie., a push- type ventilation system was assumed).

The effects of fire location have not been analyzed for the present comparison. The correction factors suggested for use by the FIVE methodology in situations where a fire is located along a wall or in a corner apply when the fire is located tight along the wall or corner. It is not clear how close to the walls the experimental fires actually were in those tests where the fire was located along a wall or in a corner.

FM/SNL Experiments 1&2 - 500 kW steady - 10 ch/hr - Center

A ventilated space analysis applies for these experiments because the nominal ventilation rate of 10 changes per hour (3.8 m^3/s) exceeds the ventilation rate due to expansion, which is calculated as:

$$\dot{V}_{exp} = \frac{\dot{Q}_n}{Q_o/V}$$

where $Q_n = (1-X_L)\ Qf$
Q_f = Nominal fire heat release rate (kW)
$Q_o/V = 353\ kJ/m^3$
X_L = 0.7 for these calculations

For these experiments, V_{exp} is calculated to be 0.4 m^3/s.

The average gas temperature rise is calculated as:

$$\Delta T_{AVG} = \frac{\dot{Q}_n}{\dot{m}c_p} = \frac{\dot{Q}_n}{\rho \dot{V} c_p}$$

This evaluates to 33K, assuming a constant specific heat capacity of 1.0 kJ/kg-K.

The plume temperature rise at the ceiling is calculated as:

$$\Delta T_{pl} = 25\frac{\dot{Q}^{2/3}}{z^{5/3}} = 25\frac{(500)^{2/3}}{6^{5/3}} = 80K$$

The ceiling jet temperature rise is then calculated as:

$$\Delta T_{cj}=\Delta T_{pl} \times \frac{0.3}{(r/H)^{2/3}}$$

Results for calculations as a function of r/H are tabulated below:

r/H	dT_{Avg}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	33	80	113
0.5	33	38	71
1.0	33	24	57
1.5	33	28	51
2.0	33	15	48

The reported peak measured nonflame temperatures were 120C during Experiment #1 and 123C during Experiment #2. Assuming an ambient temperature of 20C, the peak calculated temperature would be 133C. The measured values are within 13C of the calculated temperature.

FM/SNL Experiment 3 - 2000 kW steady - 10 ch/hr - Center

The ventilation rate due to expansion for this experiment is calculated to be:

$$\dot{V}_{\text{exp}}=\frac{\dot{Q}_n}{(Q_o/V)}=\frac{(1-0.7)\ 2000kW}{353kJ/m^3}=1.7m^3/s$$

This is less than the nominal ventilation rate of 3.8 m^3/s, so a ventilated enclosure analysis is appropriate. The average temperature rise is calculated as:

$$\Delta T_{AVG}=\frac{\dot{Q}_n}{\rho \dot{V} c_p}=\frac{(1-0.7)\ 2000kW}{(1.2kg/m^3)\,(3.78m^3/s)\,(1.0kJ/kg\text{-}K)}=132K$$

The plume temperature rise at the ceiling is calculated as:

$$\Delta T_{pl} = 25 \frac{Q^{2/3}}{z^{5/3}} = 25 \frac{2000^{2/3}}{6^{5/3}} = 200K$$

Consequently, the total temperature rise as a function of r/H can be tabulated as:

r/H	dT_{avg}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	132	200	332
0.5	132	95	227
1.0	132	60	192
1.5	132	46	178
2.0	132	38	170

The peak non-flame temperature measured during Experiment #3 was 368C. Assuming an ambient temperature of 20C, peak calculated temperature would be 352C. This value is within 16C of the peak measured value.

An unventilated space analysis was also performed for this experiment. For this analysis, the average temperature rise is calculated as:

$$\Delta T_{AVG} = T_o[\exp(Q_n / Q_o) - 1]$$

The total energy release for this experiment is 1200 MJ (2000 kW for 10 minutes). For a heat loss fraction of 70%, the net combustion energy added to the enclosure volume is 360 MJ. The ambient energy in the enclosure volume is 480 MJ (353 kJ/m^3 x 1362 m^3). Therefore, the average gas temperature rise is calculated as:

$$\Delta T_{AVG} = 293[\exp(360/481) - 1] = 327K$$

These are added to the plume/ceiling jet temperature rise to yield the calculated total temperature rise:

r/H	dT_{avg}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	327	200	527
0.5	327	95	422
1.0	327	60	387
1.5	327	46	373
2.0	327	38	365

These values are considerably higher than the measured peak non-flame temperatures reported for any of the 2000 kW experiments. The reported peak temperatures were 368C, 332C and 304C for experiments 3, 12 and 13, respectively. This suggests that an unventilated analysis would be very conservative for these experiments.

FM/SNL Experiment 4 - 500 kW transient - 1 ch/hr - Center

The ventilation rate due to expansion for this experiment is calculated to be:

$$\dot{V}_{exp} = \frac{\dot{Q}_n}{(Q_o/V)} = \frac{(1-0.7)\ 500kW}{353kJ/m^3} = 0.43m^3/s$$

This is comparable to the nominal ventilation rate of 0.38 m^3/s, so an unventilated enclosure analysis is appropriate. For this analysis, the average temperature rise is calculated as:

$$\Delta T_{AVG} = T_o[\exp(Q_n\ /\ Q_o)-1]$$

The total energy release for this experiment is 230 MJ. For a heat loss fraction of 70%, the net combustion energy added to the enclosure volume is 69 MJ. The ambient energy in the enclosure volume is 480 MJ (353 kJ/m^3 x 1362 m^3). Therefore, the average gas temperature rise is calculated as:

$$\Delta T_{AVG} = 293[\exp(69/481)-1] = 45K$$

The plume temperature rise at the ceiling is calculated as it was for Experiments 1 and 2. Consequently, the total temperature rise as a function of r/H can be tabulated as:

r/H	dT_{avg}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	45	80	125
0.5	45	38	83
1.0	45	24	69
1.5	45	18	63
2.0	45	15	60

The peak non-flame temperature measured during Experiment #4 was 133C. Assuming an ambient temperature of 20C, the peak calculated temperature would be 145C. This value is within 12C of the measured value.

FM/SNL Experiment 5 - 500 kW transient - 10 ch/hr - Center

This experiment is the same as Experiments 1 and 2, except that a transient fire growth history was used for this experiment. This does not alter the analysis, however, because a ventilated space analysis applies for the 10 change per hour ventilation rate. Consequently, the analysis used for Experiments 1 and 2 also applies for Experiment 5.

The peak non-flame temperature measured during Experiment 5 was 115C. Assuming an ambient temperature of 20C, the peak temperature calculated for this experiment is 133C, a difference of 18C.

FM/SNL Experiment 7 - 500 kW steady - 1 ch/hr - Center

This experiment is the same as Experiment 4, except the fire was steady rather than transient. The only difference this makes in the analysis is that the total heat release in this experiment was approximately 300 MJ (500 kW for 10 minutes), compared to 230 MJ for Experiment 4. Using an unventilated space analysis, this results in an average temperature rise calculated as:

$$\Delta T_{AVG}=293[\exp(90/481)-1]=60K$$

This is 15 K higher than the Experiment 4 analysis. The plume/ceiling jet temperature rises remain the same, so the temperature rise as a function of r/H can be tabulated as:

r/H	dT_{avg}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	60	80	140
0.5	60	38	98
1.0	60	24	84
1.5	60	18	78
2.0	60	15	75

The peak reported temperature for Experiment 7 was 146C. Assuming an ambient temperature of 20C, the peak calculated temperature would be 160C, a difference of 14C.

FM/SNL Experiment 8 - 1000 kW transient - 1 ch/hr - Center

The ventilation due to expansion for this experiment is calculated as:

$$\dot{V}_{exp} = \frac{\dot{Q}_n}{(Q_o\ /\ V)} = \frac{(1-0.7)1000kW}{353kJ/m^3} = 0.85m^3/s$$

This is approximately twice the nominal forced ventilation rate of 0.38 m^3/s, so this experiment is treated with an unventilated space analysis.

The total heat release during the experiment was 460 MJ. For a heat loss fraction of 70%, this yields a net energy addition to the space of 138 MJ. The average temperature rise is calculated as:

$$\Delta T_{AVG} = 293[\exp(138/481)-1] = 97K$$

The plume temperature rise at the ceiling for this heat release rate is calculated to be:

$$\Delta T_{pl} = 25\frac{\dot{Q}^{2/3}}{z^{5/3}} = 25\frac{1000^{2/3}}{6^{5/3}} = 126K$$

The total temperature rise calculated as a function of r/H is tabulated as:

r/H	dT_{AVG}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	97	126	223
0.5	97	60	157
1.0	97	38	135
1.5	97	29	126
2.0	97	24	121

The peak non-flame temperature measured for this experiment was 290C. Assuming an ambient temperature of 20C, the peak calculated temperature would be 243C. Thus, the measured temperature is 47C higher than the calculated temperature. The reason for this difference has not been determined. The calculated temperatures do fall within the range of measured temperatures, however.

FM/SNL Experiment 9 - 1000 kW transient - 8 ch/hr - Center

This experiment was the same as experiment 8, except the ventilation rate was changed from 1 to 8 air changes per hour. The forced ventilation for this experiment was nominally 3.0 m^3/s, while the ventilation due to expansion was 0.85 m^3/s. As a consequence, a ventilated space analysis is appropriate for Experiment 9.

The average temperature rise is calculated as:

$$\Delta T_{AVG}=\frac{\dot{Q}_n}{\rho \dot{V} c_p}=\frac{(1-0.7)1000kW}{(1.2kg/m^3)(3.0m^3/s)(1.0kJ/kg\text{-}K)}=83K$$

This is 14K less than calculated for Experiment 8 for the unventilated case. The plume/ceiling jet temperature calculations remain the same as for Experiment 8, so the total temperature rise can be tabulated as:

r/H	dT_{AVG}(K)	dT_{cj}(K)	dT_{tot}(K)
0.0	83	126	209
0.5	83	60	143
1.0	83	38	121
1.5	83	29	112
2.0	83	24	107

All these values are within the range of experimental data reported by Sandia. The peak non-flame temperature reported for this experiment was 229C. Assuming an ambient temperature of 20C, this is the same as the calculated value.

FM/SNL Experiment 21 - 500 kW transient - 1 ch/hr - Center

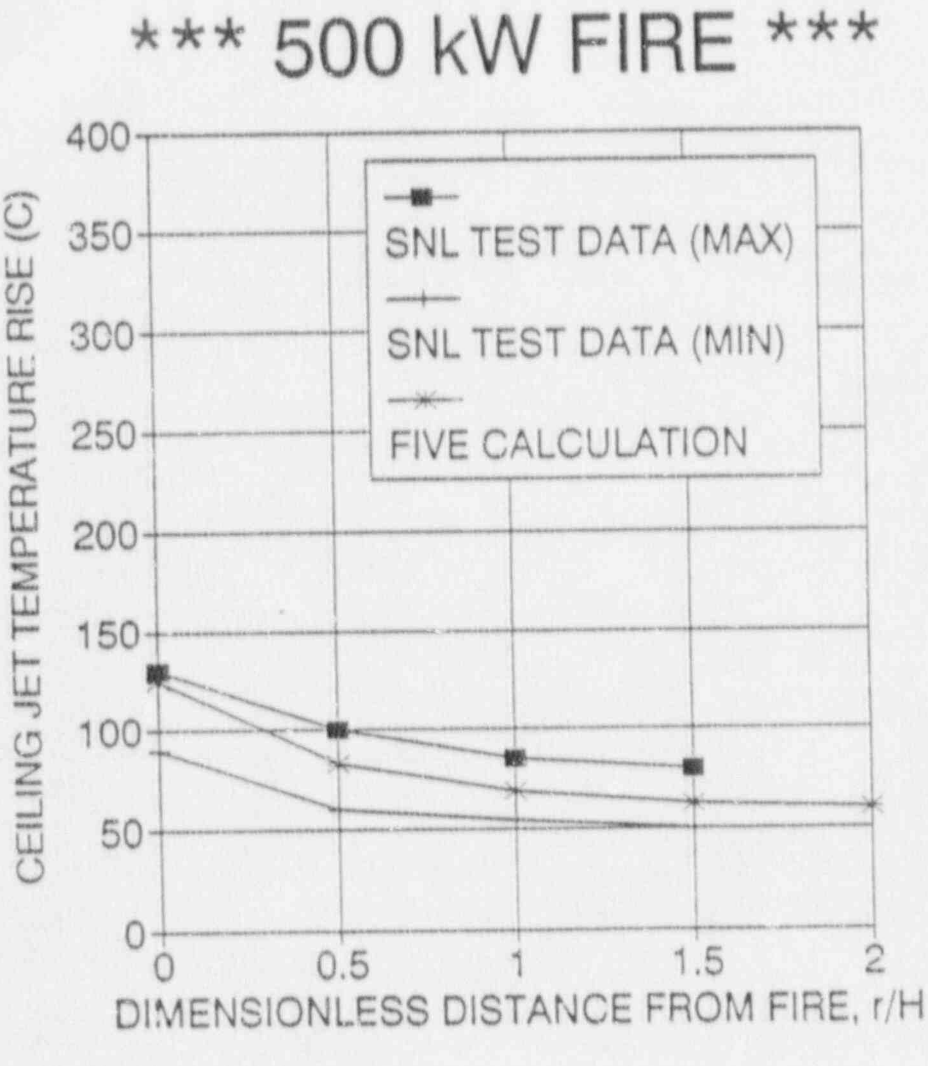
Experiment 21 was the same as Experiment 4, except the fire source was placed within a benchboard cabinet (Model A). The peak measured temperature for this experiment was 146C, while the peak calculated temperature is 145C (See Experiment 4 analysis), assuming an ambient temperature of 20C. For comparison, the peak temperature measured in Experiment 4 was 133C.

The peak temperature may have been higher in Experiment 21 than in Experiment 4 due to confinement of the fire source in the cabinet enclosure. This likely reduced the ventilation to the plume, resulting in a higher plume temperature. The effects do not appear to be too significant, however, and the calculation results seem reasonably valid for both experiments.

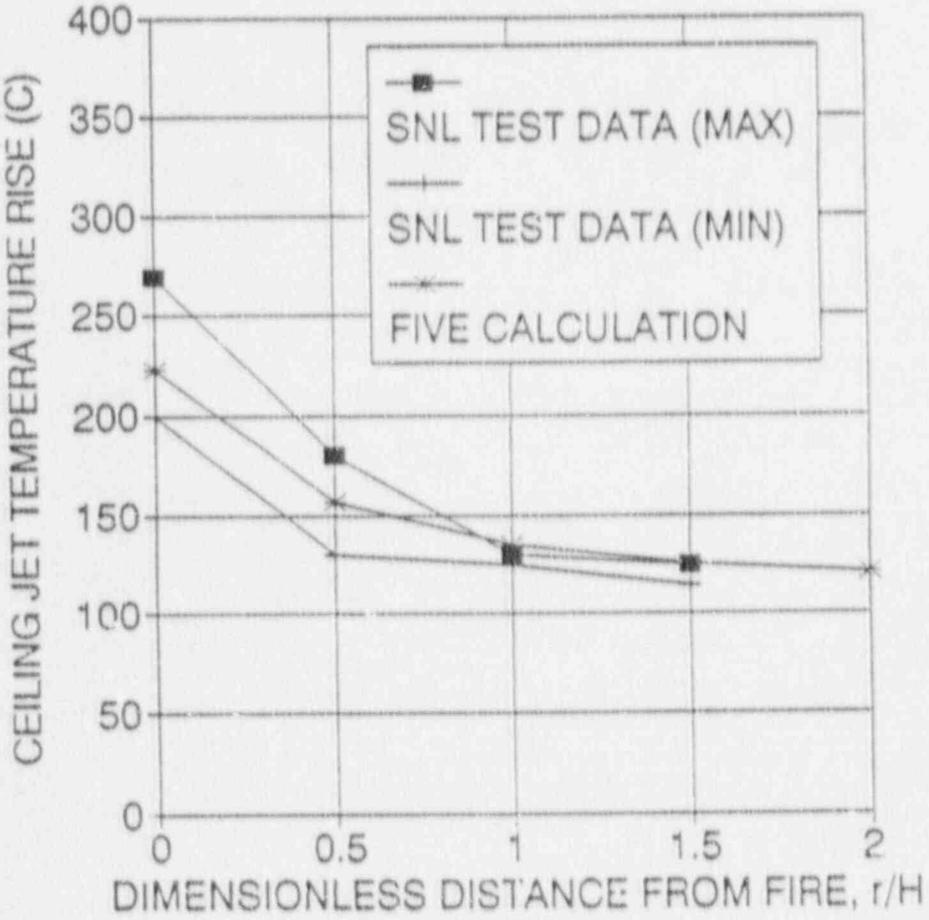
Summary of FM/SNL Experiments

Measured and calculated temperatures are illustrated graphically as functions of r/H in Figures 1 to 3 for the three nominal heat release rates of 500, 1000 and 2000 kW, respectively. Peak measured and calculated temperatures are illustrated in Figure 4 for the experiments analyzed.

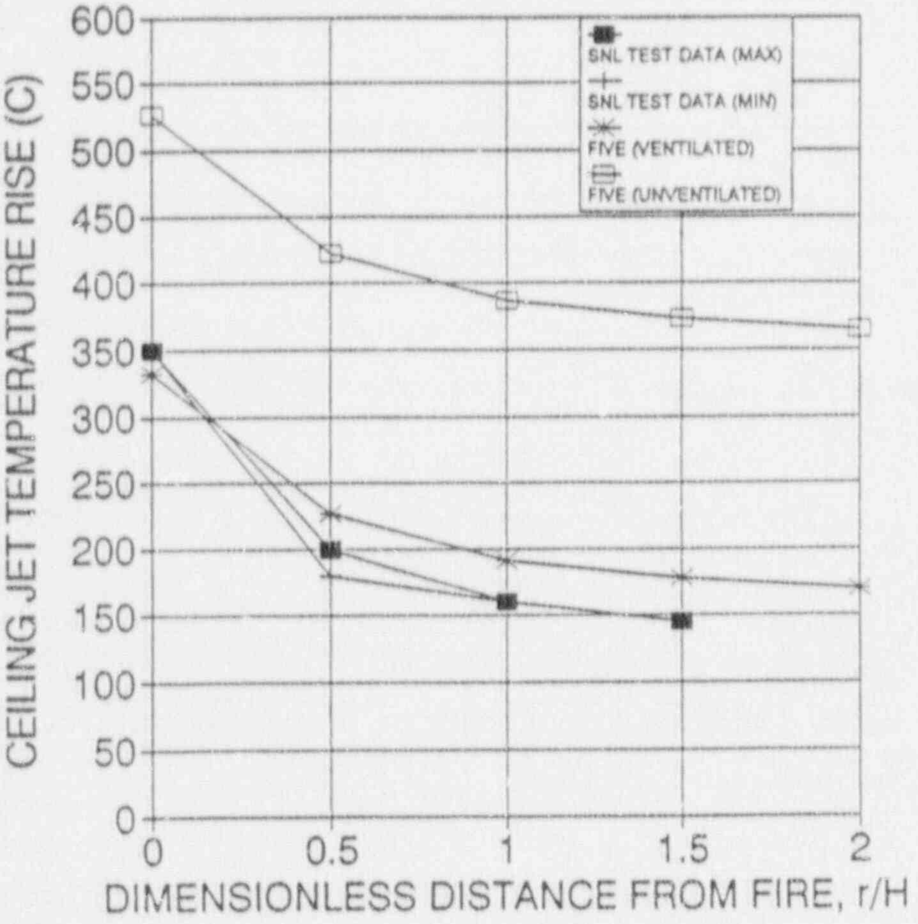
The calculated temperatures demonstrate reasonable agreement with the measured temperatures when an appropriate analysis is performed. The previous comparisons by Sandia, which have been used as a basis for criticism of the FIVE methodology, neglected to consider the average hot gas layer temperature effects and consequently yielded predicted temperatures significantly lower than the measured values. As illustrated in Figures 1 to 4, these comparisons become much better when the average temperature rise is considered.


*** 500 kW FIRE ***
CEILING JET TEMPERATURE RISE (C)
400
350
300
250
200
150
100
50
0
SNL TEST DATA (MAX)
SNL TEST DATA (MIN)
FIVE CALCULATION
0
0.5
1
1.5
2
DIMENSIONLESS DISTANCE FROM FIRE, r/H

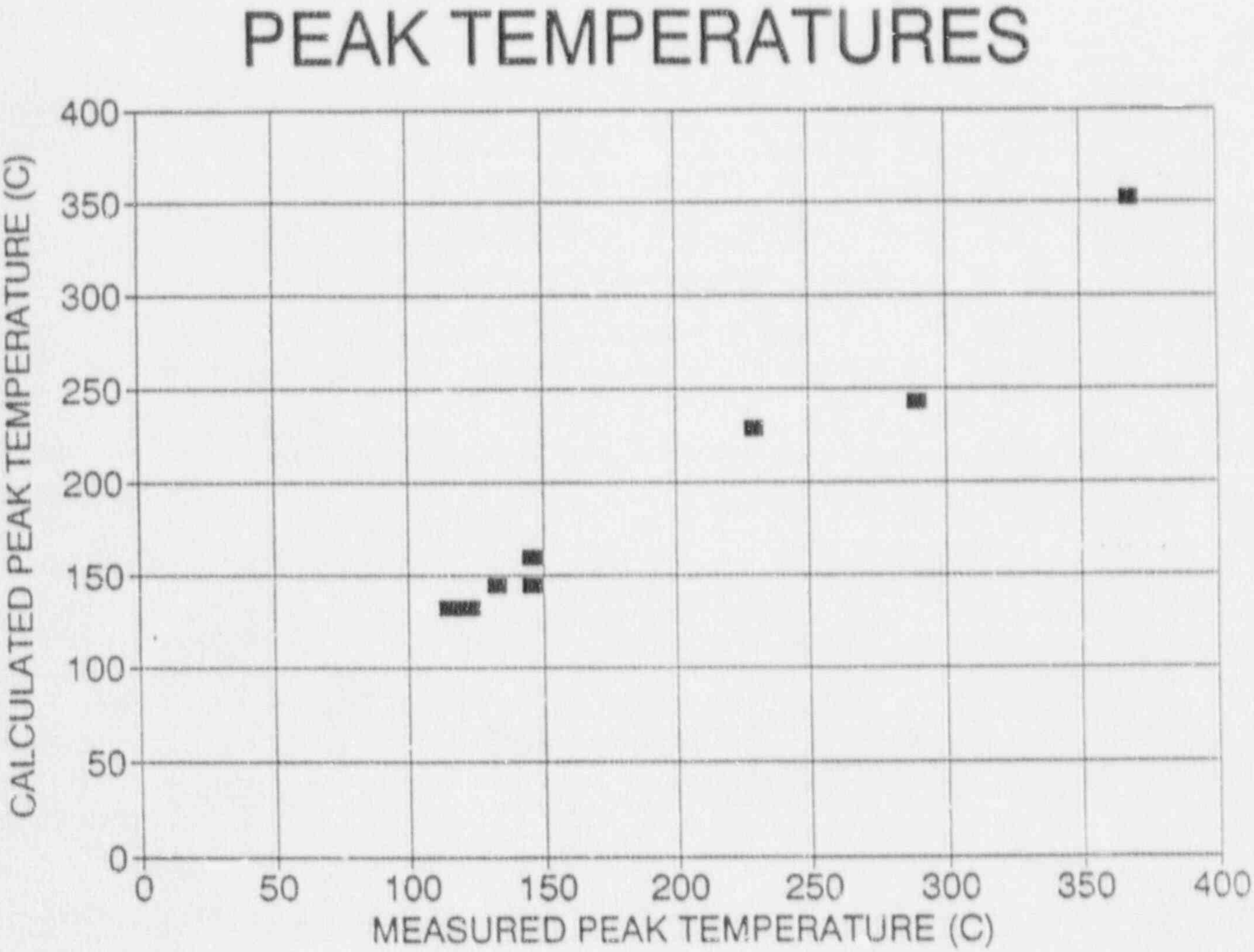
*** 1000 kW FIRE ***


CEILING JET TEMPERATURE RISE (C)
400
350
300
250
200
150
100
50
0
SNL TEST DATA (MAX)
SNL TEST DATA (MIN)
FIVE CALCULATION
0
0.5
1
1.5
2
DIMENSIONLESS DISTANCE FROM FIRE, r/H

*** 2000 kW FIRE ***



SNL TEST DATA (MAX)
SNL TEST DATA (MIN)
FIVE (VENTILATED)
FIVE (UNVENTILATED)
CEILING JET TEMPERATURE RISE (C)
0
50
100
150
200
250
300
350
400
450
500
550
600
0
0.5
1
1.5
2
DIMENSIONLESS DISTANCE FROM FIRE, r/H


PEAK TEMPERATURES
CALCULATED PEAK TEMPERATURE (C)
MEASURED PEAK TEMPERATURE (C)
0
50
100
150
200
250
300
350
400