VERIFICATION OF NUREG-1805 BY HAND CALCULATIONS

Purpose: Verification of spreadsheets from NUREG-1805 (FDT^S) using hand calculations.

Design Input: Most inputs for calculations were from Benchmark Exercise #2 ("Experimental Study of the Localized Room Fires," NFDC2 Test Series, VTT Research Notes 2104) and Benchmark Exercise #3 (*Report of Experimental Results for the International Fire Model Benchmarking and Validation Exercise #3*, NUREG/CR-6905, NIST Special Publication 1013-1).

Assumptions: For one test (Heskestad's Flame Height Correlation), heptane was used as the fuel to determine the flame height.

Documentation for Assumptions: The properties of heptane used for the hand calculations and FDT^S spreadsheet are from the SFPE handbook.

Procedure: A total of nine hand calculations were performed to verify their respective spreadsheets.

Spreadsheets used in Calculation

Calculation	Excel File Name
Natural Ventilation: Method of McCaffrey, Quintiere, and Harkleroad (MQH)	02.1_Temperature_NV.xls (v. 1805.0)
Natural Ventilation: (Smoke Filling): The Non-Steady State Yamana and Tanaka Method	02.1_Temperature_NV.xls (v. 1805.0)
Forced Ventilation: Method of Foote, Pagni, and Alvares (FPA)	02.2_Temperature_FV.xls (v. 1805.0)
Forced Ventilation: Method of Deal and Beyler	02.2_Temperature_FV.xls (v. 1805.0)
Natural Ventilation (Compartment Closed): Method of Beyler	02.3_Temperature_CC.xls (v. 1805.1)
Heskestad's Flame Height Correlation	03_HRR_Flame_Height_Burning_Duration_Calculations.xls (v. 1805.0)
Point Source Radiation Model	05.1_Heat_Flux_Calculations_Wind_Free.xls (v. 1805.0)
Solid Flame Radiation Models (Above Ground)	05.1_Heat_Flux_Calculations_Wind_Free.xls (v. 1805.0)
Heskestad's Plume Temperature Correlation	09_Plume_Temperature_Calculations.xls (v. 1805.0)

Calculation: The calculation of each spreadsheet was performed with a methodical process. All of the inputs were listed first, followed by the applicable equations and description of variables. Lastly, the calculation was performed and the results for comparison are presented in a table.

Summary: All of the spreadsheets used in the verification exercise were within 1% of the hand calculation, except the spreadsheet pertaining to Natural Ventilation: (Smoke Filling): The Non-Steady State Yamana and Tanaka Method, which had a large difference in output. However, this discrepancy is due to FDT^s calculating the layer height only until the smoke starts to exit through the vent. In performing the hand calculations, an error was discovered for the Forced Ventilation: Method of Deal and Beyler. An errata and updated/revised excel spreadsheet to NUREG-1805 is in the process of completion.

Conclusions: All of the spreadsheets tested have been verified by hand calculations. This supports NUREG-1824.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Hot Gas Layer Temperature

Process: Natural Ventilation: Method of McCaffrey, Quintiere, and Harkleroad (MQH)

Design Input:
$T_{\infty,air} = 27.8^{\circ}C = 300.8K$
$\rho_{\infty,air} = 1.2\ kg/m^3$
$g = 9.81\ m/s^2$

Room size:
Width (m) = 7.04
Length (m) = 21.7
Height (m) = 3.82

Wall properties:
Interior lining thermal inertia [$(kW/m^2\text{-}K)^2$-sec] = 0.11
Interior lining thermal conductivity (kW/m-K) = 0.00012
Interior lining specific heat (kJ/kg-K) = 1.26
Interior lining density (kg/m^3) = 737
Interior lining thickness (m) = 0.0254

Ventilation:
Vent width (m) = 2
Vent height (m) = 2
Top of vent from floor (m) = 2

Heat Release Rate: 1190 kW

Calculation: Natural Ventilation: Method of McCaffrey, Quintiere, and Harkleroad (MQH)

$$\Delta T_g = 6.85\left(\frac{\dot{Q}^2}{\left(A_v\sqrt{h_v}\right)\left(A_T h_k\right)}\right)^{1/3} \qquad (1)$$

Where:
ΔT_g = upper layer gas temperature rise above ambient ($T_g - T_a$) (K)
$\dot{Q}$ = heat release rate of the fire (kW)
A_v = total area of ventilation opening(s) (m^2)
h_v = height of ventilation opening (m)
h_k = heat transfer coefficient (kW/m^2-K)
A_T = total area of compartment enclosing surfaces (m^2), excluding area of vent opening(s).

Compartment interior surface area

$$A_t = [2(w_c \text{ x } l_c) + 2(h_c \text{ x } w_c) + 2(h_c \text{ x } l_c)] - A_v$$

$$A_t = 2(7.04 \text{ m x } 21.7 \text{ m}) + 2(3.82 \text{ m x } 7.04 \text{ m}) + 2(3.82 \text{ m x } 21.7 \text{ m}) - 4 \text{ m}^2 = 521.11\text{m}^2$$

Thermal penetration time

$$t_p = \left(\frac{\rho c}{k}\right)\left(\frac{\delta}{2}\right)^2$$

Where:

ρ = density of interior lining (kg/m^3)

c = thermal capacity of interior lining (kJ/kg-K)

k = thermal conductivity of the interior lining (kW/m-K)

δ = thickness of the interior lining (m)

Heat Transfer Coefficient

$$h_k = \sqrt{\frac{k\rho c}{t}} \quad \text{for} \quad t < t_p \qquad \text{or} \qquad h_k = \frac{k}{\delta} \quad \text{for} \quad t > t_p$$

h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia [(kW/m^2-K)^2-sec]

δ = thickness of the interior lining (m)

t = time after ignition in seconds (characteristic burning time)

<u>Calc</u>:

$$t_p = \left(\frac{\left(737 \,{}^{\text{kg}}\!/\!_{\text{m}^3}\right)\left(1.26 \,{}^{\text{kJ}}\!/\!_{\text{kg}\cdot\text{K}}\right)}{0.00012 \,{}^{\text{kW}}\!/\!_{\text{m}\cdot\text{K}}}\right)\left(\frac{0.0254\text{m}}{2}\right)^2 = 1248.14\,\text{sec}$$

<u>60 sec</u>:

$$t < t_p\text{, where } \quad h_k = \sqrt{\frac{0.11\left({}^{\text{kW}}\!/\!_{\text{m}^2\cdot\text{K}}\right)^2\cdot\text{sec}}{60 \text{ sec}}} = 0.0428 \,{}^{\text{kW}}\!/\!_{\text{m}^2\cdot\text{K}}$$

$$T_g = 6.85\left(\frac{(1190 \text{ kW})^2}{\left(4 \text{ m}\sqrt{2 \text{ m}}\right)\left(521.11 \text{ m}^2\right)\left(0.0428 \,{}^{\text{kW}}\!/\!_{\text{m}^2\cdot\text{K}}\right)}\right)^{1/3} + 300.8 \text{ K} = 454.17 \text{ K}$$

300 sec:

$$t < t_p\text{, where}\quad h_k = \sqrt{\frac{0.11\left(\mathrm{kW}/\mathrm{m^2\cdot K}\right)^2\cdot \mathrm{sec}}{300\ \mathrm{sec}}} = 0.01914\ \mathrm{kW}/\mathrm{m^2\cdot K}$$

$$T_g = 6.85\left(\frac{(1190\ \mathrm{kW})^2}{\left(4\ \mathrm{m}\sqrt{2\ \mathrm{m}}\right)\left(521.11\ \mathrm{m^2}\right)\left(0.01914\ \mathrm{kW}/\mathrm{m^2\cdot K}\right)}\right)^{1/3} + 300.8\ \mathrm{K} = 501.36\ \mathrm{K}$$

600 sec:

$$t < t_p\text{, where}\quad h_k = \sqrt{\frac{0.11\left(\mathrm{kW}/\mathrm{m^2\cdot K}\right)^2\cdot \mathrm{sec}}{600\ \mathrm{sec}}} = 0.01354\ \mathrm{kW}/\mathrm{m^2\cdot K}$$

$$T_g = 6.85\left(\frac{(1190\ \mathrm{kW})^2}{\left(4\ \mathrm{m}\sqrt{2\ \mathrm{m}}\right)\left(521.11\ \mathrm{m^2}\right)\left(0.01354\ \mathrm{kW}/\mathrm{m^2\cdot K}\right)}\right)^{1/3} + 300.8\ \mathrm{K} = 525.89\ \mathrm{K}$$

900 sec:

$$t < t_p\text{, where}\ h_k = \sqrt{\frac{0.11\left(\mathrm{kW}/\mathrm{m^2\cdot K}\right)^2\cdot \mathrm{sec}}{900\ \mathrm{sec}}} = 0.011055\ \mathrm{kW}/\mathrm{m^2\cdot K}$$

$$T_g = 6.85\left(\frac{(1190\ \mathrm{kW})^2}{\left(4\ \mathrm{m}\sqrt{2\ \mathrm{m}}\right)\left(521.11\ \mathrm{m^2}\right)\left(0.011055\ \mathrm{kW}/\mathrm{m^2\cdot K}\right)}\right)^{1/3} + 300.8\ \mathrm{K} = 541.62\ \mathrm{K}$$

1200 sec:

$$t < t_p\text{, where}\ h_k = \sqrt{\frac{0.11\left(\mathrm{kW}/\mathrm{m^2\cdot K}\right)^2\cdot \mathrm{sec}}{1200\ \mathrm{sec}}} = 0.00957\ \mathrm{kW}/\mathrm{m^2\cdot K}$$

$$T_g = 6.85\left(\frac{(1190\ \mathrm{kW})^2}{\left(4\ \mathrm{m}\sqrt{2\ \mathrm{m}}\right)\left(521.11\ \mathrm{m^2}\right)\left(0.00957\ \mathrm{kW}/\mathrm{m^2\cdot K}\right)}\right)^{1/3} + 300.8\ \mathrm{K} = 553.49\ \mathrm{K}$$

1500 sec:

$$t > t_p\text{, where}\quad h_k = \left(\frac{0.00012\,{}^{kW}\!/\!_{m \cdot K}}{0.0254\text{ m}}\right) = 0.00472\,{}^{kW}\!/\!_{m^2 \cdot K}$$

$$T_g = 6.85\left(\frac{(1190\text{ kW})^2}{\left(4\text{ m}\sqrt{2\text{ m}}\right)\left(521.11\text{ m}^2\right)\left(0.00472\,{}^{kW}\!/\!_{m^2 \cdot K}\right)}\right)^{1/3} + 300.8\text{ K} = 620.62\text{ K}$$

For $t > 1500$ sec, T_g will be constant at 620.62 K

Results:

Time (sec)	FDT (K)	Calculation (K)	Temp. Difference (K)
60	454.15	454.17	0.02
300	501.33	501.36	0.03
600	525.89	525.89	0.00
900	541.62	541.62	0.00
1200	553.45	553.49	0.04
1500	620.52	620.62	0.10

Summary/Conclusions:
Spreadsheet (02.1_Temperature_NV.xls) for Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire With Natural Ventilation Compartment (v. 1805.0) is valid against hand calculations.

Reference:
1)McCaffrey, B.J., J.G. Quintiere, and M.F. Harkleroad, "Estimating Room Temperature and Likelihood of Flashover Using Fire Test Data Correlation," *Fire Technology*, Volume 17, No. 2, pp. 98-119, 1981.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Smoke Layer Temperature

Process: Natural Ventilation (Smoke Filling): The Non-Steady State Yamana and Tanaka Method

Design Input:

$T_{\infty,air} = 27.8^{\circ}C = 300.8K$

$\rho_{\infty,air} = 1.2 \text{ kg/m}^3$

$g = 9.81 \text{ m/s}^2$

$c_p = 1 \text{ kJ/kg-K}$

Room size:
Width (m) = 7.04
Length (m) = 21.7
Height (m) = 3.82

Wall properties:
Interior lining thermal inertia [(kW/m^2-K)^2-sec] = 0.11
Interior lining thermal conductivity (kW/m-K) = 0.00012
Interior lining specific heat (kJ/kg-K) = 1.26
Interior lining density (kg/m^3) = 737
Interior lining thickness (m) = 0.0254

Ventilation:
Vent width (m) = 2
Vent height (m) = 2
Top of vent from floor (m) = 2

Heat Release Rate: 1190 kW

Calculation: Natural Ventilation (Smoke Filling): The Non-Steady State Yamana and Tanaka Method

$$z = \left(\frac{2\,k\,\dot{Q}^{1/3}\,t}{3\,A_c} + \frac{1}{h_c^{2/3}} \right)^{-3/2} \qquad (1)$$

Where:
z = height (m) of the smoke later interface above the floor
$\dot{Q}$ = heat release rate of the fire (kW)
t = time after ignition (sec)
A_c = compartment floor area (m^2)
h_c = compartment height (m)

Compartment floor area

$$A_c = l_c \text{ x } w_c = (21.7 \text{ m})(7.04 \text{ m}) = 152.768 \text{ m}^2$$

And:
k = a constant given by the following equation

$$k = \frac{0.21}{\rho_g}\left(\frac{\rho_a{}^2 g}{c_p T_a}\right)^{1/3}$$

Where:
ρ_g = hot gas density (kg/m^3)
ρ_a = ambient density (kg/m^3)
g = acceleration of gravity (m/s^2)
c_p = specific heat of air (kJ/kg-K)
T_a = ambient air temperature

Where density of the hot gas (p_g), layer is given by:

$$\rho_g = \frac{353}{T_g}$$

Where:
T_g = hot gas layer temperature (k) calculated from Method of McCaffrey, Quintiere, and Harkleroad (MQH)

Calc:

Time (sec)	(T_g) Input from MQH method (K)
60	454.17
300	501.36

60 sec:

$$p_g = \frac{353}{454.17\ K} = 0.777\ {kg}/{m^3}$$

$$k = \frac{0.21}{0.777\ {kg}/{m^3}}\left(\frac{\left(1.2\ {kg}/{m^3}\right)^2\left(9.81\ {m}/{s^2}\right)}{\left(1\ {kJ}/{kg \cdot K}\right)(300.8\ K)}\right)^{1/3} = 0.0975$$

$$z = \left(\frac{2(0.0975)(1190\ kW)^{1/3}(60\ \sec)}{3(152.768\ m^2)} + \frac{1}{(3.82\ m)^{2/3}} \right)^{-3/2} = 1.78\ m$$

300 sec:

$$p_g = \frac{353}{501.36\ K} = 0.704\ kg/m^3$$

$$k = \frac{0.21}{0.704\ kg/m^3} \left(\frac{\left(1.2\ kg/m^3\right)^2 \left(9.81\ m/s^2\right)}{\left(1\ kJ/kg \cdot K\right)(300.8\ K)} \right)^{1/3} = 0.1076$$

$$z = \left(\frac{2(0.1076)(1190\ kW)^{1/3}(300\ \sec)}{3(152.768\ m^2)} + \frac{1}{(3.82\ m)^{2/3}} \right)^{-3/2} = 0.38\ m$$

Results:

Time (sec)	FDT (m)	Calculation (m)	Height Difference (m)
60	2	1.78	0.22
300	2	0.38	1.62

The discrepancy in results is due to FDT^s calculating the layer height only until the smoke starts to exit through the vent.

Summary/Conclusions:
Spreadsheet (02.1_Temperature_NV.xls) for Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire With Natural Ventilation Compartment (v. 1805.0) is valid against hand calculations.

Reference:
1) Yamana, T., and T. Tanaka, "Smoke Control in Large Spaces, Part 1: Analytical Theories for Simple Smoke Control Problems," *Fire Science and Technology*, Volume 5, No. 1, 1985.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Hot Gas Layer Temperature

Process: Forced Ventilation: Method of Foote, Pagni, and Alvares (FPA)

Design Input:

$T_{\infty,air} = 20^\circ C = 293$ K

$\rho_{\infty,air} = 1.2$ kg/m^3

$c_p = 1$ kJ/kg-K

Room size:
Width (m) = 27.0
Length (m) = 13.8
Height (m) = 15.8

Wall properties:
Interior lining thermal inertia [(kW/m^2-K)^2-sec] = 0.015
Interior lining thermal conductivity (kW/m-K) = 0.0002
Interior lining specific heat (kJ/kg-K) = 0.15
Interior lining density (kg/m^3) = 500
Interior lining thickness (m) = 0.05

Ventilation: 23,500 cfm = 11.0907 m^3/sec

Heat Release Rate: 3640 kW

Calculation: Forced Ventilation: Method of Foote, Pagni, and Alvares (FPA)

$$\frac{\Delta T_g}{T_a} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_pT_a}\right)^{0.72}\left(\frac{h_kA_T}{\dot{m}c_p}\right)^{-0.36} \qquad (1)$$

Where:
ΔT_g = hot gas layer temperature rise above ambient ($T_g - T_a$) (K)
T_a = ambient air temperature (K)
$\dot{Q}$ = heat release rate of the fire (kW)
$\dot{m}$ = mass of the gas in the compartment (kg)
c_p = specific heat of air (kJ/kg-k)
h_k = heat transfer coefficient (kW/m^2-K)
A_T = total area of compartment enclosing surfaces (m^2)

$\dot{m} = p_{\infty,air}$ x ventilation

$$\dot{m} = \left(1.2\,{}^{kg}\!/\!_{m^3}\right)\left(11.0907\,{}^{m^3}\!/\!_{s}\right) = 13.309\,{}^{kg}\!/\!_{s}$$

Compartment interior surface area

$$A_t = 2(w_c \text{ x } l_c) + 2(h_c \text{ x } w_c) + 2(h_c \text{ x } l_c)$$

$$A_t = 2(15.8 \text{ m x } 27 \text{ m}) + 2(15.8 \text{ m x } 13.8 \text{ m}) + 2(27 \text{ m x } 13.8 \text{ m}) = 2034.48\text{m}^2$$

Thermal penetration time

$$t_p = \left(\frac{\rho c}{k}\right)\left(\frac{\delta}{2}\right)^2$$

Where:

t_p = thermal penetration time (sec)
ρ = interior construction density (kg/m^3)
c = interior construction heat capacity (kJ/kg-K)
k = interior construction thermal conductivity (kW/m-K)
δ = interior construction thickness (m)

Heat Transfer Coefficient

$$h_k = \sqrt{\frac{k\rho c}{t}} \quad \text{for} \quad t < t_p \qquad \text{or} \qquad h_k = \frac{k}{\delta} \quad \text{for} \quad t > t_p$$

h_k = heat transfer coefficient (kW/m^2-K)
$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec
t = time after ignition (sec)

Calc:

$$t_p = \left(\frac{\left(500\, {}^{kg}/_{m^3}\right)\left(0.15\, {}^{kJ}/_{kg \cdot K}\right)}{0.0002\, {}^{kW}/_{m \cdot K}}\right)\left(\frac{0.05m}{2}\right)^2 = 234.37 \sec$$

60 sec:

$$t < t_p \text{, where } \quad h_k = \sqrt{\frac{0.015\left({}^{kW}/_{m^2 \cdot K}\right)^2 \cdot \sec}{60 \text{ sec}}} = 0.0158\, {}^{\text{kW}}/_{\text{m}^2 \cdot K}$$

$$T_g = \left[0.63\left(\frac{3640\ kW}{\left(13.309\, {}^{kg}/_{s}\right)\left(1\, {}^{kJ}/_{kg \cdot s}\right)(293K)}\right)^{0.72}\left(\frac{\left(0.0158\, {}^{kW}/_{m^2 \cdot K}\right)\left(2034.48\ m^2\right)}{\left(13.309\, {}^{kJ}/_{s}\right)\left(1\, {}^{kJ}/_{kg \cdot s}\right)}\right)^{-0.36}\right]293K + 293K$$

$$T_g = 420.88K$$

120 sec:

$t < t_p$, where $h_k = \sqrt{\dfrac{0.015\left(kW/m^2 \cdot K\right)^2 \cdot \sec}{120 \text{ sec}}} = 0.01118 \text{ kW}/\text{m}^2 \cdot K$

$$T_g = \left[0.63\left(\frac{3640\ kW}{\left(13.309\,kg/s\right)\left(1\,kJ/kg \cdot s\right)(293K)}\right)^{0.72}\left(\frac{\left(0.01118\,kW/m^2 \cdot K\right)\left(2034.48\ m^2\right)}{\left(13.309\,kJ/s\right)\left(1\,kJ/kg \cdot s\right)}\right)^{-0.36}\right]293K + 293K$$

$T_g = 437.74K$

180 sec:

$t < t_p$, where $h_k = \sqrt{\dfrac{0.015\left(kW/m^2 \cdot K\right)^2 \cdot \sec}{180 \text{ sec}}} = 0.00913 \text{ kW}/\text{m}^2 \cdot K$

$$T_g = \left[0.63\left(\frac{3640\ kW}{\left(13.309\,kg/s\right)\left(1\,kJ/kg \cdot s\right)(293K)}\right)^{0.72}\left(\frac{\left(0.00913\,kW/m^2 \cdot K\right)\left(2034.48\ m^2\right)}{\left(13.309\,kJ/s\right)\left(1\,kJ/kg \cdot s\right)}\right)^{-0.36}\right]293K + 293K$$

$T_g = 448.8K$

240 sec:

$t > t_p$, where $h_k = \left(\dfrac{0.0002\,kW/m \cdot K}{0.05\ m}\right) = 0.004 \text{ kW}/\text{m}^2 \cdot K$

$$T_g = \left[0.63\left(\frac{3640\ kW}{\left(13.309\,kg/s\right)\left(1\,kJ/kg \cdot s\right)(293K)}\right)^{0.72}\left(\frac{\left(0.004\,kW/m^2 \cdot K\right)\left(2034.48\ m^2\right)}{\left(13.309\,kJ/s\right)\left(1\,kJ/kg \cdot s\right)}\right)^{-0.36}\right]293K + 293K$$

$T_g = 502.7K$

Any time above 240 seconds will be constant at 502.7 K

Results:

Time (sec)	FDT (K)	Calculation (K)	Temp. Difference (K)
60	420.66	420.88	0.22
120	437.63	437.74	0.11
180	448.58	448.8	0.22
240	502.39	502.7	0.31

Summary/Conclusions:
Spreadsheet (02.2_Temperature_FV.xls) for Predicting Hot Gas Layer Temperature in a Room Fire With Forced Ventilation Compartment (v. 1805.0) is valid against hand calculations.

Reference:
1) Foote, K.L., P.J. Pagni, and N.L. Alvares, "Temperatures Correlations for Forced-Ventilated Compartment Fires," Fire Safety Science-Proceedings of the First International Symposium, International Association of Fire Safety Science (IAFSS), Grant and Pagni, Editors, Hemisphere Publishing Corporation, New York, pp. 139–148, 1985.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Hot Gas Layer Temperature

Process: Forced Ventilation: Method of Deal and Beyler

Design Input:

$T_{\infty,air} = 20^{\circ}C = 293$ K

$\rho_{\infty,air} = 1.2$ kg/m^3

$c_p = 1$ kJ/kg-K

Room size:
Width (m) = 27.0
Length (m) = 13.8
Height (m) = 15.8

Wall properties:
Interior lining thermal inertia [(kW/m^2-K)^2-sec] = 0.015
Interior lining thermal conductivity (kW/m-K) = 0.0002
Interior lining specific heat (kJ/kg-K) = 0.15
Interior lining density (kg/m^3) = 500
Interior lining thickness (m) = 0.05

Ventilation: 23,500 cfm = 11.0907 m^3/sec

Heat Release Rate: 3640 kW

Calculation: Forced Ventilation: Method of Deal and Beyler

$$\Delta T_g = T_g - T_a = \left(\frac{\dot{Q}}{\dot{m} c_p + h_k A_t}\right) \quad (1)$$

Where:
ΔT_g = hot gas layer temperature rise above ambient ($T_g - T_a$) (K)
T_a = ambient air temperature (K)
$\dot{Q}$ = heat release rate of the fire (kW)
$\dot{m}$ = mass of the gas in the compartment (kg)
c_p = specific heat of air (kJ/kg-k)
h_k = convective heat transfer coefficient (kW/m^2-K)
A_t = total area of compartment enclosing surfaces (m^2)

$$\dot{m} = \rho_{\infty,air} \text{ x ventilation}$$

$$\dot{m} = \left(1.2\,\mathrm{kg}/\mathrm{m}^3\right)\left(11.0907\,\mathrm{m}^3/\mathrm{s}\right) = 13.309\,\mathrm{kg}/\mathrm{s}$$

Compartment interior surface area

$$A_t = 2(w_c \text{ x } l_c) + 2(h_c \text{ x } w_c) + 2(h_c \text{ x } l_c)$$

$$A_t = 2(15.8 \text{ m x } 27 \text{ m}) + 2(15.8 \text{ m x } 13.8 \text{ m}) + 2(27 \text{ m x } 13.8 \text{ m}) = 2034.48\text{m}^2$$

Thermal penetration time

$$t_p = \left(\frac{\rho c}{k}\right)(\delta)^2$$

Where:

t_p = thermal penetration time (sec)
ρ = interior construction density (kg/m^3)
c = interior construction heat capacity (kJ/kg-K)
k = interior construction thermal conductivity (kW/m-K)
δ = interior construction thickness (m)

Heat Transfer Coefficient

$$h_k = 0.4\sqrt{\frac{k\rho c}{t}} \quad \text{for} \quad t < t_p \qquad \text{or} \qquad h_k = 0.4\left(\frac{k}{\delta}\right) \quad \text{for} \quad t > t_p$$

Where:

h_k = heat transfer coefficient (kW/m^2-K)
$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec
t = time after ignition (sec)

<u>Calc</u>:

$$t_p = \left(\frac{\left(500 \, {}^{kg}\!/\!_{m^3}\right)\left(0.15 \, {}^{kJ}\!/\!_{kg \cdot K}\right)}{0.0002 \, {}^{kW}\!/\!_{m \cdot K}}\right)(0.05m)^2 = 937.5 \sec$$

<u>60 sec</u>:

$$t < t_p \text{, where} \quad h_k = 0.4\sqrt{\frac{0.015\left({}^{kW}\!/\!_{m^2 \cdot K}\right)^2 \cdot \sec}{60 \sec}} = 0.00632 \, {}^{\text{kW}}\!/\!_{\text{m}^2 \cdot K}$$

$$T_g = \left(\frac{3640 \, kW}{\left(13.309 \, {}^{kg}\!/\!_{s}\right)\left(1 \, {}^{kJ}\!/\!_{kg \cdot s}\right) + \left(0.00632 \, {}^{kW}\!/\!_{m^2 \cdot K}\right)\left(2034.48 \, m^2\right)}\right) + 293 \, K = 432.06 \, K$$

180 sec:

$$t < t_p \text{, where} \quad h_k = 0.4\sqrt{\frac{0.015\left(kW/m^2 \cdot K\right)^2 \cdot \text{sec}}{180 \text{ sec}}} = 0.00365\ \text{kW}/\text{m}^2 \cdot K$$

$$T_g = \left(\frac{3640\ kW}{\left(13.309\ kg/s\right)\left(1\ kJ/kg \cdot s\right) + \left(0.00365\ kW/m^2 \cdot K\right)\left(2034.48\ m^2\right)}\right) + 293\ K = 468.52\ K$$

1200 sec:

$$t > t_p \text{, where} \quad h_k = 0.4\left(\frac{0.0002\ kW/m \cdot K}{0.05m}\right) = 0.0016\ \text{kW}/\text{m}^2 \cdot K$$

$$T_g = \left(\frac{3640\ kW}{\left(13.309\ kg/s\right)\left(1\ kJ/kg \cdot s\right) + \left(0.0016\ kW/m^2 \cdot K\right)\left(2034.48\ m^2\right)}\right) + 293\ K = 512.75\ K$$

Any time above 1200 seconds, the temperature will be constant at 512.75 K

Results:

Time (sec)	FDT (K)	Calculation (K)	Temp. Difference (K)
60	431.78	432.06	0.28
180	468.08	468.52	0.44
1200	512.05	512.75	0.70

Summary/Conclusions:
In performing the hand calculations, an error was discovered for the Forced Ventilation: Method of Deal and Beyler. An errata and updated/revised excel spreadsheet to NUREG-1805 is in the process of completion. Based on revision, spreadsheet (02.2_Temperature_FV.xls) for Predicting Hot Gas Layer Temperature in a Room Fire With Forced Ventilation Compartment (v. 1805.0) is valid against hand calculations.

Reference:
1) Deal, S., and C.L. Beyler, "Correlating Preflashover Room Fire Temperatures," *SFPE Journal of Fire Protection Engineering*, Volume 2, No. 2, pp. 33–48, 1990.
Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Hot Gas Layer Temperature

Process: Natural Ventilation (Compartment Closed): Method of Beyler

Design Input:
$T_{\infty,air} = 20^{\circ}C = 293$ K
$\rho_{\infty,air} = 1.2$ kg/m^3
$c_p = 1$ kJ/kg-K

Room size:
Width (m) = 27.0
Length (m) = 13.8
Height (m) = 15.9

Wall properties:
Interior lining thermal inertia [(kW/m^2-K)^2-sec] = 0.015
Interior lining thermal conductivity (kW/m-K) = 0.0002
Interior lining specific heat (kJ/kg-K) = 0.15
Interior lining density (kg/m^3) = 500
Interior lining thickness (m) = 0.05

Heat Release Rate

Time (sec)	HRR (kW)
0	0
13.2	1251
90	1706
288	1858
327	1782
409.2	1365
438	0

Calculation: Natural Ventilation (Compartment Closed): Method of Beyler

$$\Delta T_g = T_g - T_a = \frac{2K_2}{K_1^2}\left(K_1\sqrt{t} - 1 + e^{-K_1\sqrt{t}}\right) \qquad (1)$$

Where:

$$K_1 = \frac{2\left(0.4\sqrt{k\rho c}\right)A_T}{mc_p} \qquad K_2 = \frac{\dot{Q}}{mc_p}$$

And:
ΔT_g = upper layer gas temperature rise above ambient ($T_g - T_a$) (K)
A_T = total area of internal compartment boundaries (m^2)
k = thermal conductivity of the interior lining (kW/m-K)
ρ = density of the interior lining (kg/m^3)
c = thermal capacity of the interior lining (kJ/kg-K)

$\dot{Q}$ = heat release rate of the fire (kW)
m = mass of the gas in the compartment (kg)
c_p = specific heat of air (kJ/kg-k)
t = exposure time (sec)

$$V = L \cdot W \cdot H$$
$$V = (27\text{m})(13.8\text{m})(15.9\text{m}) = 5{,}924.34\text{m}^3$$

$$m = \rho_{\infty,\text{air}} \cdot V$$
$$m = (1.2\,\text{kg}/\text{m}^3)(5{,}924.34\text{m}^3) = 7{,}109.208\ \text{kg}$$

Compartment interior surface area

$$A_t = 2(w_c \text{ x } l_c) + 2(h_c \text{ x } w_c) + 2(h_c \text{ x } l_c)$$
$$A_t = 2(27\text{ m x }13.8\text{ m}) + 2(15.9\text{ m x }27\text{ m}) + 2(15.9\text{ m x }13.8\text{ m}) = 2042.64\text{m}^2$$

<u>Calc</u>:

$$K_1 = \frac{2\left(0.4\sqrt{\left(0.0002\,kW/m\cdot K\right)\left(500\,kg/m^3\right)\left(0.15\,kJ/kg\cdot K\right)}\right)\left(2042.64m^2\right)}{\left(7109.208\ kg\right)\left(1\,kJ/kg\cdot K\right)} = 0.02815\ \text{s}^{-1/2}$$

<u>90 sec</u>:

$$K_2 = \frac{1706\ kW}{\left(7109.208kg\right)\left(1\,kJ/kg\cdot K\right)} = 0.23997\ \text{K/s}$$

$$T_g = \frac{2\left(0.23997\,K/s\right)}{\left(0.02815\ s^{-1/2}\right)^2}\left(\left(0.02815\ s^{-1/2}\right)\sqrt{90s} - 1 + e^{-\left(0.02815\ s^{-1/2}\right)\sqrt{90s}}\right) + 293K = 312.80\ \text{K}$$

<u>288 sec</u>:

$$K_2 = \frac{1858\ kW}{\left(7109.208kg\right)\left(1\,kJ/kg\cdot K\right)} = 0.26135\ \text{K/s}$$

$$T_g = \frac{2\left(0.26135\,K/s\right)}{\left(0.02815\ s^{-1/2}\right)^2}\left(\left(0.02815\ s^{-1/2}\right)\sqrt{288s} - 1 + e^{-\left(0.02815\ s^{-1/2}\right)\sqrt{288s}}\right) + 293K =$$

$T_g = 357.58$ K

<u>327 sec</u>:

$$K_2 = \frac{1782\ kW}{(7109.208kg)\left(1 \frac{kJ}{kg \cdot K}\right)} = 0.25066 \text{ K/s}$$

$$T_g = \frac{2\left(0.25066 \frac{K}{s}\right)}{\left(0.02815\ s^{-1/2}\right)^2}\left(\left(0.02815\ s^{-1/2}\right)\sqrt{327s} - 1 + e^{-\left(0.02815\ s^{-1/2}\right)\sqrt{327s}}\right) + 293K =$$

$T_g = 362.66$ K

<u>409.2 sec</u>:

$$K_2 = \frac{1365\ kW}{(7109.208kg)\left(1 \frac{kJ}{kg \cdot K}\right)} = 0.192 \text{ K/s}$$

$$T_g = \frac{2\left(0.192 \frac{K}{s}\right)}{\left(0.02815\ s^{-1/2}\right)^2}\left(\left(0.02815\ s^{-1/2}\right)\sqrt{409.2s} - 1 + e^{-\left(0.02815\ s^{-1/2}\right)\sqrt{409.2s}}\right) + 293K =$$

$T_g = 358.56$ K

<u>Results</u>:

Time (sec)	FDT (K)	Calculation (K)	Temp. Difference (K)
90	312.72	312.8	0.08
288	357.37	357.58	0.21
327	362.43	362.66	0.23
409.2	358.34	358.56	0.22

<u>Summary/Conclusions</u>:
Spreadsheet (02.3_Temperature_CC.xls) for Predicting Hot Gas Layer Temperature in a Fire Room With Door Closed (v. 1805.1) is valid against hand calculations.

<u>Reference</u>:
1) Beyler, C.L., "Analysis of Compartment Fires with Overhead Forced Ventilation," Fire Safety Science, Proceeding of the 3 International Symposium, International Association of Fire Safety Science (IAFSS), Cox and Langford, Editors, Elsevier Applied Science, New York, pp. 291-300, 1991.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Plume Temperature.

Process: Heskestad's Flame Height Correlation

Design Input:
$T_{\infty,air} = 20^{\circ}C = 293$ K
$\rho_{\infty,air} = 1.2$ kg/m^3
$c_p = 1$ kJ/kg-K
$g = 9.81$ m/s^2

Assumptions:
Fuel = Heptane
$A_{fuel} = 0.5$ m^2
$\dot{m}'' = 0.101$ kg/m^2-sec
$\Delta H_{c,eff} = 44{,}600$ kJ/kg
$k\beta = 1.1$ m^{-1}

Documentation for Assumptions: Fuel properties well known from Babrauskas, which is documented in SFPE Handbook of Fire Protection Engineering (Ref. 1).

Calculation: Heskestad's Flame Height Correlation

The HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire is given by the following equation:

$$\dot{Q} = \dot{m}''\Delta H_{c,eff} A_f \left(1 - e^{-k\beta\beta}\right) \qquad (1)$$

Where:
$\dot{Q}$ = heat release rate of the fire (kW)
$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
$\Delta H_{c,eff}$ = effective heat of combustion (kJ/kg)
A_f = horizontal burning area of the fuel (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of burning area (m)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Where:
D = diameter of the fire (m)

A_f = fuel spill area or curb area (m^2)

$$H_f = 0.235\dot{Q}^{2/5} - 1.02D \qquad (2)$$

Where:
H_f = flame height (m)
$\dot{Q}$ = heat release rate of the fire (kW)
D = diameter of the fire (m)

The above correlation can also be used to determine the length of the flame extension along the ceiling and to estimate radiative heat transfer to objects in the enclosure.

Calc:

$$\dot{Q} = \left(0.101\,\mathrm{kg}/\mathrm{m^2 \cdot s}\right)\left(44{,}600\,\mathrm{kJ}/\mathrm{kg}\right)\left(0.5\mathrm{m}^2\right)\left(1 - e^{-(1.1\mathrm{m}^{-1})(0.798\mathrm{m})}\right) = 1316.02\ \mathrm{kW}$$

$$D = \sqrt{\frac{4\left(0.5\ \mathrm{m}^2\right)}{\pi}} = 0.798\ \mathrm{m}$$

$$H_f = 0.235\left(1316.02\ \mathrm{kW}\right)^{2/5} - 1.02\left(0.798\ \mathrm{m}\right) = 3.34\mathrm{m}$$

Results:

Fuel	Flame Height FDT (m)	Flame Height Calculation (m)	Height Difference (m)
Heptane	3.34	3.34	0.00

Summary/Conclusions:
Spreadsheet (03_HRR_Flame_Height_Burning_Duration_Calculations.xls) for Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height (Flame Height Only) (v. 1805.0) is valid against hand calculations.

Reference:
1) Babrauskas, V., "Burning Rates," Section 3, Chapter 3-1, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2002.

2) Heskestad, G., "Fire Plumes," Section 2, Chapter 2-2, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Point Source Radiation Model

Process: Point Source Radiation Model

Design Input:
$T_{\infty,air} = 23.9^{\circ}C = 296.9K$
$\rho_{\infty,air} = 1.19\ kg/m^3$
$c_p = 1\ kJ/kg\text{-}K$
$g = 9.81\ m/s^2$
$\chi_r = 0.44$
$A_f = 0.79\ m^2$
$D = 1m$

Heat Release Rate: 1190 kW

Distance from fire to target (m): varied for multiple calculations

Calculation: Point Source Radiation Model

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi R^2} \qquad (1)$$

Where:
$\dot{q}''$ = radiant heat flux (kW/m$^{2)}$
$\dot{Q}$ = heat release rate of the fire (kW)
R = radial distance from the center of the flame to the edge of the target (m)
χ_r = fraction of total energy radiated

Distance from Center of the Fire to Edge of the Target Calculation

$$R = L + \frac{D}{2}$$

Where:
R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire distance (m)

<u>Distance from fire to radiant heat flux gauge</u>: 4.88 m

$$D = \sqrt{\frac{4\left(0.79\ m^2\right)}{\pi}} = 1m$$

$$R = 4.88\ m + \frac{1\ m}{2} = 5.38\ m$$

$$q'' = \frac{(0.44)(1190\ kW)}{4\pi(5.38\ m)^2} = 1.44\,{}^{kW}\!/_{m^2}$$

<u>Distance from fire to radiant heat flux gauge</u>: 4.24 m

$$D = \sqrt{\frac{4\left(0.79\ m^2\right)}{\pi}} = 1\ m$$

$$R = 4.24\ m + \frac{1\ m}{2} = 4.74\ m$$

$$q'' = \frac{(0.44)(1190\ kW)}{4\pi(4.74\ m)^2} = 1.85\,{}^{kW}\!/_{m^2}$$

<u>Distance from fire to radiant heat flux gauge</u>: 3.80 m

$$D = \sqrt{\frac{4\left(0.79\ m^2\right)}{\pi}} = 1\ m$$

$$R = 3.80\ m + \frac{1\ m}{2} = 4.30\ m$$

$$q'' = \frac{(0.44)(1190\ kW)}{4\pi(4.30\ m)^2} = 2.25\,{}^{kW}\!/_{m^2}$$

<u>Distance from fire to radiant heat flux gauge</u>: 1.81 m

$$D = \sqrt{\frac{4\left(0.79\ m^2\right)}{\pi}} = 1\ m$$

$$R = 1.81\ m + \frac{1\ m}{2} = 2.31\ m$$

$$\dot{q}'' = \frac{(0.44)(1190\ kW)}{4\pi(2.31\ m)^2} = 7.80\, {}^{kW}\!/_{m^2}$$

Results:

Distance	Heat Flux FDT (kW/m^2)	Heat Flux Calculation (kW/m^2)	Heat Flux Difference
4.88	1.44	1.44	0.00
4.24	1.85	1.85	0.00
3.8	2.25	2.25	0.00
1.81	7.80	7.80	0.00

Summary/Conclusions:
Spreadsheet (05.1_Heat_Flux_Calculations_Wind_Free.xls) for Estimating Radiant Heat Flux From Fire to a Target Fuel at Ground Level Under Wind-Free Condition (Point Source Radiation) (v.1805.0) is valid against hand calculations.

Reference:

1) Drysdale, D.D., *An Introduction to Fire Dynamics*, Chapter 4, "Diffusion Flames and Fire Plumes," 2nd Edition, John Wiley and Sons, New York, pp. 109-158, 1998.

2) Babrauskas, V., "Burning Rates," Section 3, Chapter 3-1, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Solid Flame Radiation Model

Process: Solid Flame Radiation Model (Above Ground)

Design Input:

$T_{\infty,air} = 23.9^{\circ}C = 296.9K$

$\rho_{\infty,air} = 1.19$ kg/m^3

$c_p = 1$ kJ/kg-K

$g = 9.81$ m/s^2

D = 1m

Heat Release Rate: 1400 kW

Distance and height of target to fire:

Distance (m)	Height (m)
1.5	2.3

Calculation: Solid Flame Radiation Model

$$\dot{q}'' = EF_{1\rightarrow 2} \qquad (1)$$

Where:

$\dot{q}''$ = incident radiative heat flux (kW/m^2)

E = average emissive power at flame surface (kW/m^2)

$F_{1\rightarrow 2}$ = configuration factor

$$E = 58\left(10^{-0.00823D}\right) \qquad (2)$$

Where:

E = flame emissive power (kW/m^2)

D = diameter of pool fire (m)

The Heskestad correlation is widely used to determine the flame height of pool fires

$$H_f = 0.235\dot{Q}^{2/5} - 1.02D \qquad (3)$$

Where:

H_f = flame height (m)

$\dot{Q}$ = heat release rate of the fire (kW)

D = diameter of the fire (m)

Distance from center of the fire to edge of the target calculation

$$L = R + \frac{D}{2}$$

Where:
L = distance from center of the pool fire to edge of the target (m)
R = distance between pool fire and target (m)
D = pool fire distance (m)

The following expressions are used to estimate the configuration factor (or view factor) under wind-free conditions for targets above ground level: (4)

$$F_{1\rightarrow 2,V_1} = \left(\begin{array}{l} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_1}{\sqrt{S^2-1}}\right) - \frac{h_1}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_1 h_1}{\pi S\sqrt{A_1^{\,2}-1}}\tan^{-1}\sqrt{\frac{(A_1+1)(S-1)}{(A_1-1)(S+1)}} \end{array} \right)$$

Where:

$$S = \frac{2L}{D}$$

$$h_1 = \frac{2H_{f_1}}{D}$$

$$A_1 = \frac{h_1^2 + S^2 + 1}{2S}$$

$$F_{1\rightarrow 2,V_2} = \left(\begin{array}{l} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_2}{\sqrt{S^2-1}}\right) - \frac{h_2}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_2 h_2}{\pi S\sqrt{A_2^{\,2}-1}}\tan^{-1}\sqrt{\frac{(A_2+1)(S-1)}{(A_2-1)(S+1)}} \end{array} \right)$$

Where:

$$S = \frac{2L}{D}$$

$$h_2 = \frac{2H_{f_2}}{D}$$

$$A_2 = \frac{h_2^2 + S^2 + 1}{2S}$$

And:

L = the distance between the center of the cylinder (flame) to the target (m)
H_f = the height of the cylinder (flame) (m)
D = the cylinder (flame) diameter (m)

The total configuration factor or (view factor) at a point is given by the sum of two configuration factor as follows:

$$F_{1\to 2,V(\text{no-wind})} = F_{1\to 2,V1} + F_{1\to 2,V2}$$

<u>Calc:</u>

$$H_f = 0.235(1400\,kW)^{\frac{2}{5}} - 1.02(1\,\text{m}) = 3.24\text{ m}$$

$$L = 1.50m + \frac{1m}{2} = 2\,m$$

$$E = 58\left(10^{-0.00823(1\text{m})}\right) = 56.91\,{}^{kW}\!/_{m^2}$$

Vertical distance of target from ground (H_{f1}) = 2.3m

$$S = \frac{2(2\,\text{m})}{1\text{m}} = 4$$

$$h_1 = \frac{2(2.3\text{m})}{1\text{m}} = 4.6$$

$$A_1 = \frac{(4.6)^2 + (4)^2 + 1}{2(4)} = 4.77$$

$$F_{1\to 2,V_1} = \left(\begin{array}{l} \frac{1}{\pi(4)}.\tan^{-1}\left(\frac{4.6}{\sqrt{(4)^2 - 1}}\right) - \frac{4.6}{\pi(4)}\tan^{-1}\sqrt{\frac{(4-1)}{(4+1)}} + \\ \frac{(4.77)(4.6)}{\pi(4)\sqrt{(4.77)^2 - 1}}\tan^{-1}\sqrt{\frac{(4.77+1)(4-1)}{(4.77-1)(4+1)}} \end{array} \right) = 0.114$$

$H_{f2} = H_f - H_{f1}$ = 3.24m – 2.30m = 0.94m

$$S = \frac{2(2\,\text{m})}{1\text{m}} = 4$$

$$h_2 = \frac{2(0.94\text{m})}{1\text{m}} = 1.88$$

$$A_2 = \frac{(1.88)^2 + (4)^2 + 1}{2(4)} = 2.57$$

$$F_{1\rightarrow 2, V_2} = \left(\begin{array}{l} \frac{1}{\pi(4)} .\tan^{-1}\left(\frac{1.88}{\sqrt{(4)^2 - 1}} \right) - \frac{1.88}{\pi(4)} \tan^{-1} \sqrt{\frac{(4-1)}{(4+1)}} + \\ \frac{(2.57)(1.88)}{\pi(4)\sqrt{(2.57)^2 - 1}} \tan^{-1} \sqrt{\frac{(2.57+1)(4-1)}{(2.57-1)(4+1)}} \end{array} \right) = 0.077$$

$$F_{1\rightarrow 2, V(no-wind)} = 0.114 + 0.077 = 0.191$$

$$\dot{q}'' = \left(56.91\, kW/m^2\right)(0.191) = 10.87\, kW/m^2$$

Results:

Distance	Height	Heat Flux FDT (kW/m^2)	Heat Flux Calculation (kW/m^2)	Heat Flux Difference
1.50	2.30	10.93	10.87	0.05

Summary/Conclusions:
Spreadsheet (05.1_Heat_Flux_Calculations_Wind_Free.xls) for Estimating Radiant Heat Flux From Fire to a Target Fuel at Ground Level Under Wind-Free Condition (Solid Flame 2 Models) (v.1805.0) is valid against hand calculations.

Reference:
1) Beyler, C.L., "Fire Hazard Calculations for Large Open Hydrogen Fires," Section 3, Chapter 1, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2002.

2) Shokri, M., and C.L. Beyler, "Radiation from Large Pool Fires," *SFPE Journal of Fire Protection Engineering*, Volume 1, No. 4, pp.141–150, 1989.

3) Heskestad, G., "Fire Plumes," Section 2, Chapter 2-2, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

4) Beyler, C.L., "Fire Hazard Calculations for Large Open Hydrogen Fires," Section 3, Chapter 1, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2002.

Purpose: Demonstrate compliance of FDT's spreadsheet to that of hand calculations for Plume Temperature

Process: Heskestad's Plume Temperature Correlation

Design Input:
$T_{\infty,air} = 20^{\circ}C = 293$ K
$\rho_{\infty,air} = 1.2$ kg/m^3
$c_p = 1$ kJ/kg-K
$g = 9.81$ m/s^2
$A_{fuel} = 0.5$ m^2
$\chi_c = 0.65$
$z = 7$ m

Heat Release Rate: varied for multiple calculations

Calculation: Heskestad's Plume Temperature Correlation

$$T_{p(centerline)} - T_a = \frac{9.1\left(\frac{T_a}{g c_p^2 \rho_a^2}\right)^{1/3} \dot{Q}_c^{2/3}}{(z - z_o)^{5/3}} \qquad (1)$$

Where:
$T_{p(centerline)}$ = plume centerline temperature (K)
T_a = ambient air temperature (K)
$\dot{Q}_c$ = convective HRR (kW)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-k)
ρ_a = ambient air density (kg/m^3)
z = elevation above the fire source (m)
z_o = hypothetical virtual origin of the fire (m)

The virtual origin z_o, depends on the diameter of the fire source and the total energy released, as follows:

$$\frac{z_o}{D} = -1.02 + 0.083\frac{\dot{Q}^{2/5}}{D} \qquad (1)$$

Where:
z_o = virtual origin (m)
D = diameter of fire source (m)

$\dot{Q}$ = total HRR (kW)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Where:
D = diameter of the fire (m)
A_f = fuel spill area or curb area (m^2)

<u>HRR</u>: 1251 kW

$$D = \sqrt{\frac{4(0.5\ m^2)}{\pi}} = 0.7978\ m$$

$$z_o = -1.02(0.7978\ m) + 0.083(1251\ kW)^{2/5} = 0.6264\ m$$

$$\dot{Q}_c = \dot{Q}\chi_c = (1251\ kW)(0.65) = 813.15\ kW$$

$$T_{p(centerline)} = \left[\frac{9.1\left(\dfrac{293\ K}{\left(9.81\ m/s^2\right)\left(1\ kJ/kg\cdot K\right)^2\left(1.2\ kg/m^3\right)^2}\right)^{1/3}(813.15\ kW)^{2/3}}{(7\ m - 0.6264\ m)^{5/3}}\right] + 293\ K = 392.42\ K$$

<u>HRR</u>: 1706 kW

$$D = \sqrt{\frac{4(0.5\ m^2)}{\pi}} = 0.7978\ m$$

$$z_o = -1.02(0.7978\ m) + 0.083(1706\ kW)^{2/5} = 0.8151\ m$$

$$\dot{Q}_c = \dot{Q}\chi_c = (1706\ kW)(0.65) = 1108.9\ kW$$

$$T_{p(centerline)} = \left[\frac{9.1\left(\dfrac{293\ K}{\left(9.81\ m/s^2\right)\left(1\ kJ/kg\cdot K\right)^2\left(1.2\ kg/m^3\right)^2}\right)^{1/3}\left(1207.7\ kW\right)^{2/3}}{\left(7\ m - 0.8716\ m\right)^{5/3}} \right] + 293\ K = 431.16\ K$$

HRR: 1858 kW

$$D = \sqrt{\frac{4\left(0.5\ m^2\right)}{\pi}} = 0.7978\ m$$

$$z_o = -1.02\left(0.7978\ m\right) + 0.083\left(1858\ kW\right)^{2/5} = 0.8716\ m$$

$$\dot{Q}_c = \dot{Q}\,\chi_c = (1858\ kW)(0.65) = 1207.7\ kW$$

$$T_{p(centerline)} = \left[\frac{9.1\left(\dfrac{293\ K}{\left(9.81\ m/s^2\right)\left(1\ kJ/kg\cdot K\right)^2\left(1.2\ kg/m^3\right)^2}\right)^{1/3}\left(1207.7\ kW\right)^{2/3}}{\left(7\ m - 0.8716\ m\right)^{5/3}} \right] + 293\ K = 431.16\ K$$

Results:

HRR (kW)	FDT (K)	Calculation (K)	Temp. Difference (K)
1251	392.11	392.42	0.31
1706	421.19	421.54	0.35
1858	430.79	431.16	0.37

Summary/Conclusions:
Spreadsheet (09_Plume_Temperature_Calculations.xls) for Estimating Centerline Temperature of a Buoyant Fire Plume (v. 1805.0) is valid against hand calculations.

Reference:
1) Heskestad, G., “Fire Plumes,” Section 2, Chapter 2, *SFPE Handbook of Fire Protection Engineering*, 2 Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.