The Fire Induced Ceiling Jet Revisited

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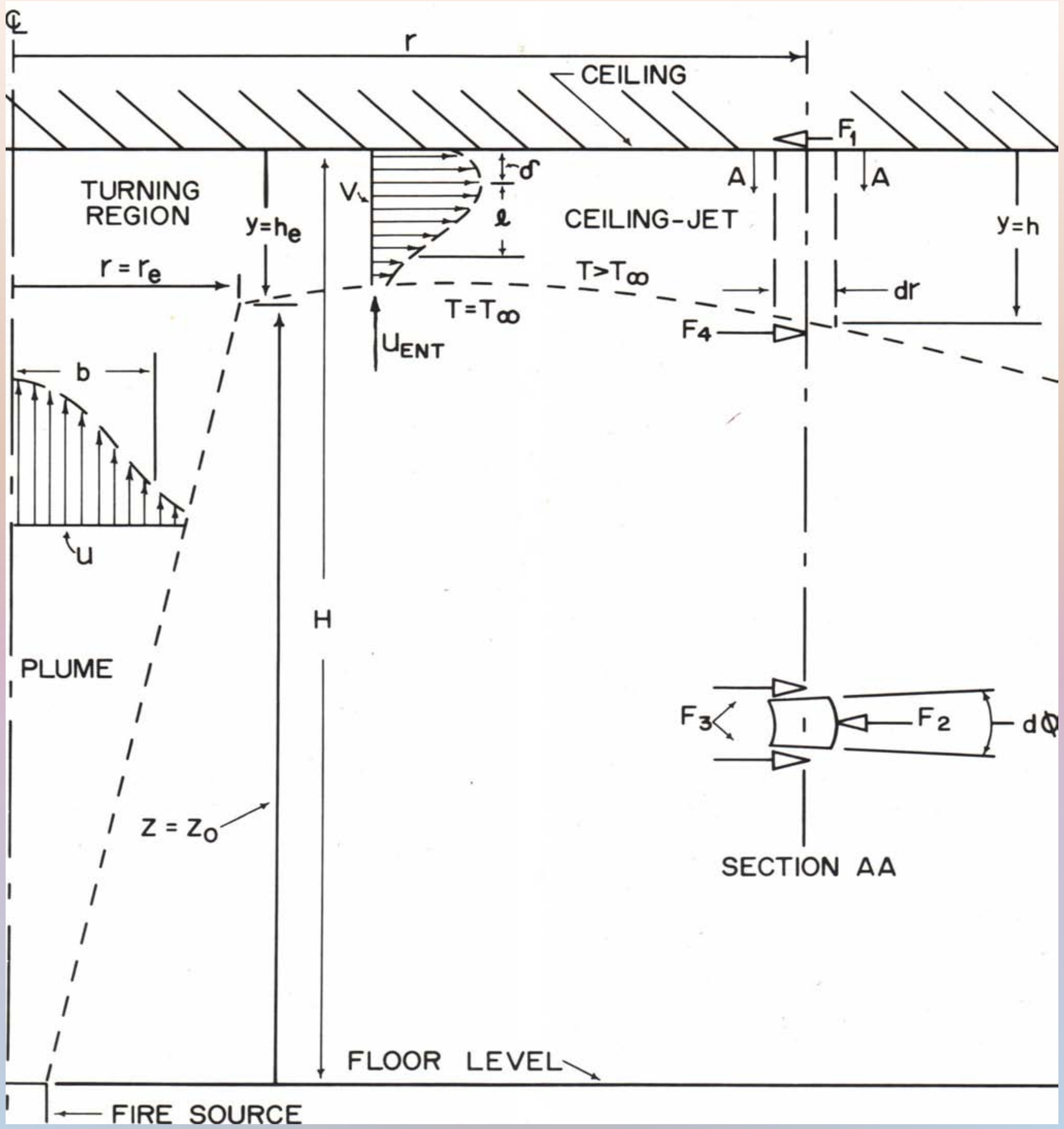
Topics to be Discussed

- Importance of Ceiling Jet for Detection/Activation
- Basis for Ceiling Jet Formulas Published in 1972
- Comparison with Regression Fit to Available Data
- Re-examination of Data from Steady-State Fire Sources Used for Original Formulas
- CFD Modeling of Spray/Fire Interactions in 1980's
- Determination of Agent Flux to Suppress a Fire

Significance of Ceiling Jet Flow

- Determines when ceiling-mounted thermal or smoke detectors will operate
- Determines when sprinkler link or bulb will trigger flow of agent from ceiling-mounted devices for fire suppression
- Determines total number of ceiling-mounted devices operating, and hence maximum agent flow rate
- Causes damage to ceiling due to ignition and flame spread or structural failure



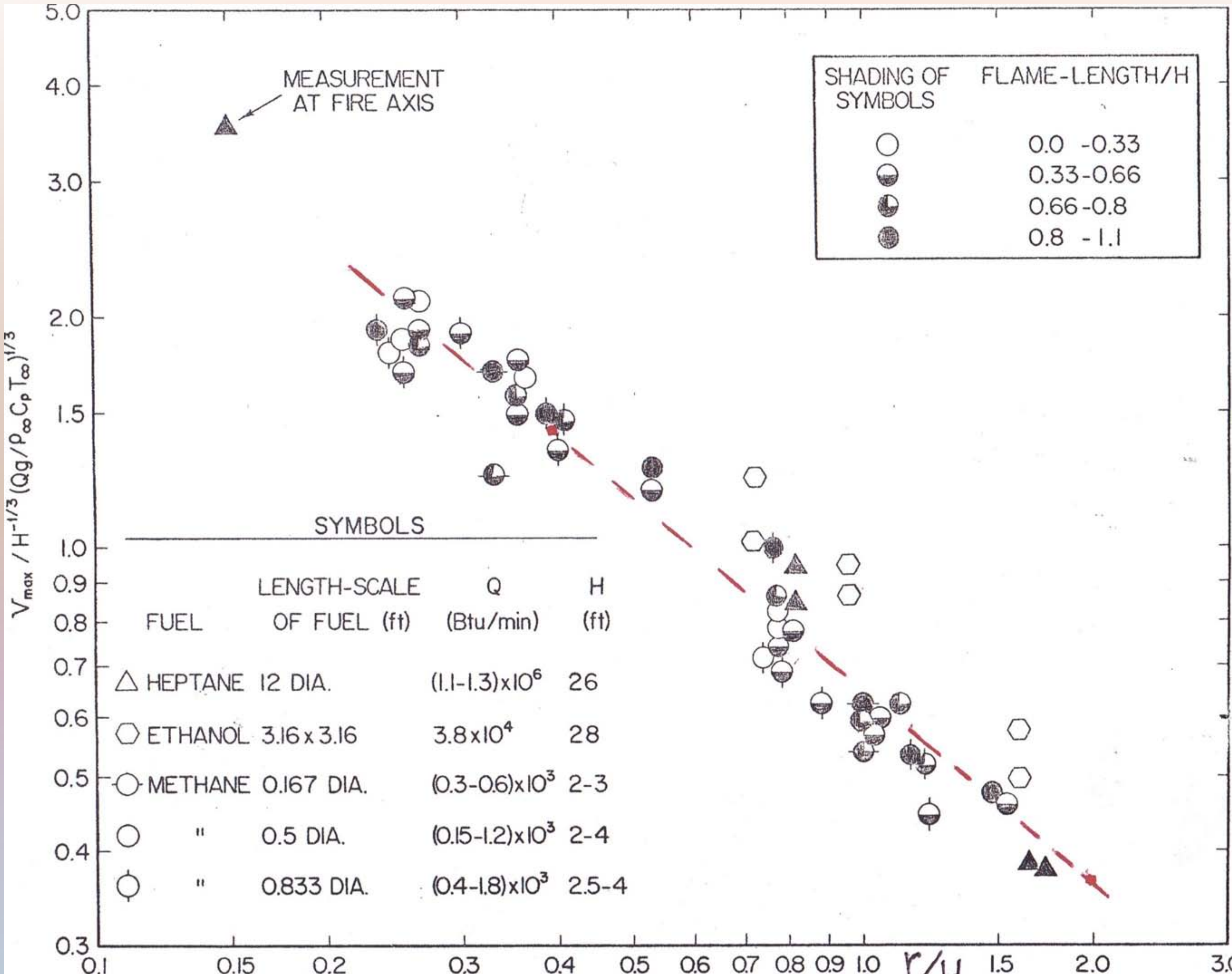
r
CEILING
F_1
TURNING REGION
$y=h_e$
V
δ
ℓ
A
A
CEILING-JET
$y=h$
$r=r_e$
$T>T_\infty$
$T=T_\infty$
dr
F_4
U_{ENT}
b
u
H
PLUME
F_3
F_2
$d\phi$
$Z=Z_0$
SECTION AA
FLOOR LEVEL
FIRE SOURCE

Ceiling Jet Formulas

- FMRC technical report on ceiling jet model, with limited data from full-scale, “distributed” in 1971
- Data on ceiling jet excess gas temperature and velocity from many full-scale fire tests obtained
- Guided by parameters from model, data correlated
- Resultant formulas presented at NFPA meeting and published in Fire Technology in 1972

Formula for Maximum Gas Velocity in Ceiling Jet Published in 1972

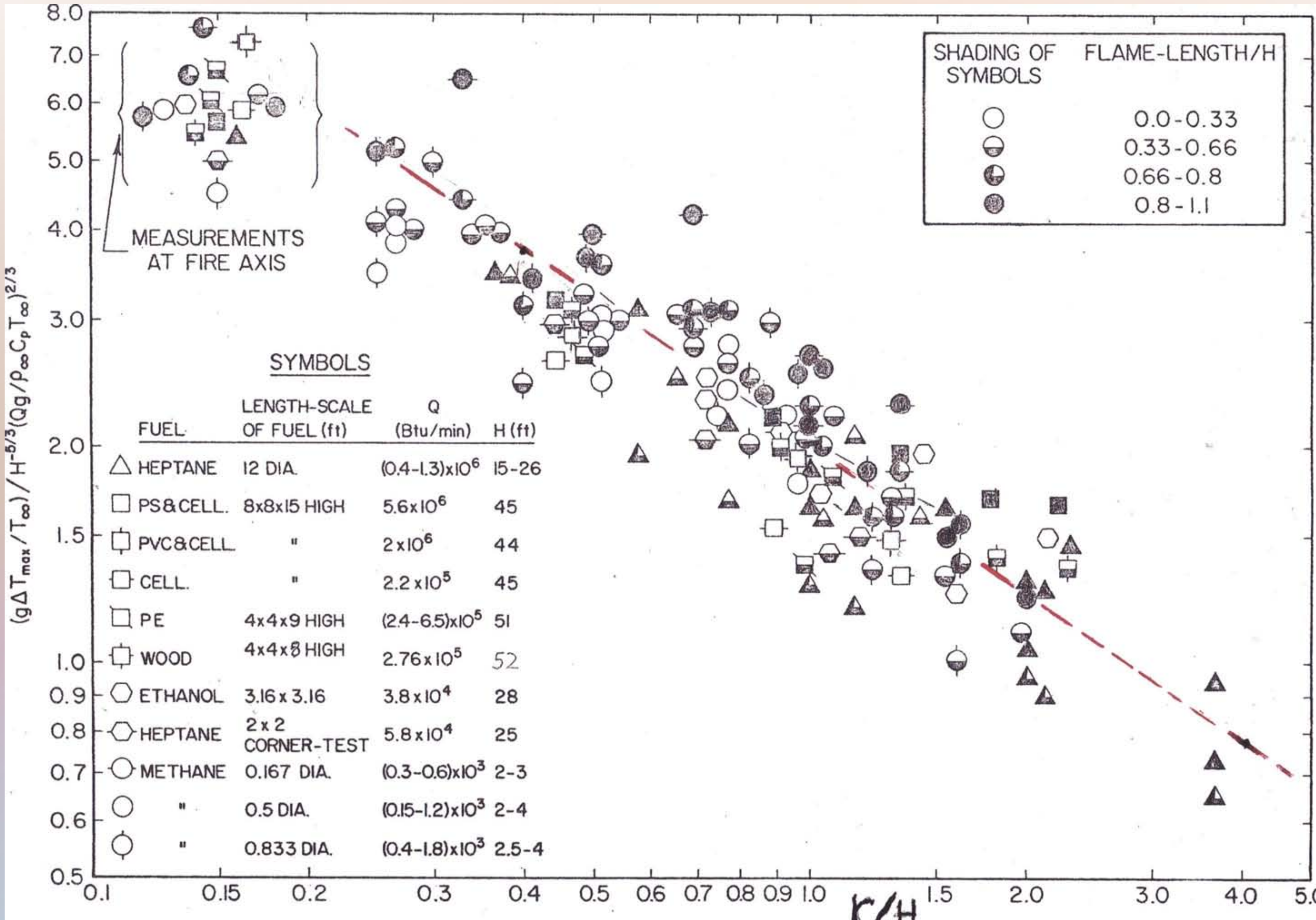
$$V_{\max} = 0.197 \frac{\left(\frac{\dot{Q}}{H}\right)^{1/3}}{\left(\frac{r}{H}\right)^{5/6}} \qquad r/H > 0.15$$



MEASUREMENT AT FIRE AXIS
SHADING OF SYMBOLS
FLAME-LENGTH/H
0.0 -0.33
0.33-0.66
0.66-0.8
0.8 - 1.1
SYMBOLS
FUEL
LENGTH-SCALE OF FUEL (ft)
Q (Btu/min)
H (ft)
HEPTANE 12 DIA. (1.1-1.3)x10^6 26
ETHANOL 3.16 x 3.16 3.8x10^4 28
METHANE 0.167 DIA. (0.3-0.6)x10^3 2-3
" 0.5 DIA. (0.15-1.2)x10^3 2-4
" 0.833 DIA. (0.4-1.8)x10^3 2.5-4
V_max / H^-1/3 (Qg/ρ∞ Cp T∞)^1/3
r/H

Formula for Maximum Excess Gas Temperature in Ceiling Jet, 1972

$$T_{\max} - T_{\infty} = 5.38 \frac{\dfrac{\dot{Q}^{2/3}}{H^{5/3}}}{\left(\dfrac{r}{H}\right)^{2/3}} \qquad r/H > 0.18$$



SHADING OF SYMBOLS
FLAME-LENGTH/H
0.0-0.33
0.33-0.66
0.66-0.8
0.8-1.1
MEASUREMENTS AT FIRE AXIS
SYMBOLS
FUEL
LENGTH-SCALE OF FUEL (ft)
Q (Btu/min)
H (ft)
HEPTANE 12 DIA. (0.4-1.3)x10^6 15-26
PS&CELL. 8x8x15 HIGH 5.6x10^6 45
PVC&CELL. " 2x10^6 44
CELL. " 2.2x10^5 45
PE 4x4x9 HIGH (2.4-6.5)x10^5 51
WOOD 4x4x8 HIGH 2.76x10^5 52
ETHANOL 3.16x3.16 3.8x10^4 28
HEPTANE 2x2 CORNER-TEST 5.8x10^4 25
METHANE 0.167 DIA. (0.3-0.6)x10^3 2-3
" 0.5 DIA. (0.15-1.2)x10^3 2-4
" 0.833 DIA. (0.4-1.8)x10^3 2.5-4
$(g\Delta T_{max}/T_\infty)/H^{-5/3}(Qg/\rho_\infty C_p T_\infty)^{2/3}$
r/H

Comparison of Original Ceiling Jet Formulas with Regression Fits to Data

- Original formulas based on qualitative curve fit to data from full-scale and scale-model tests performed in 1969-1971
- Selected data on maximum ceiling jet velocity and excess temperature from these full-scale tests are still available for analysis
- Regression fits to these data can be compared to original formulas

Original Heats of Combustion

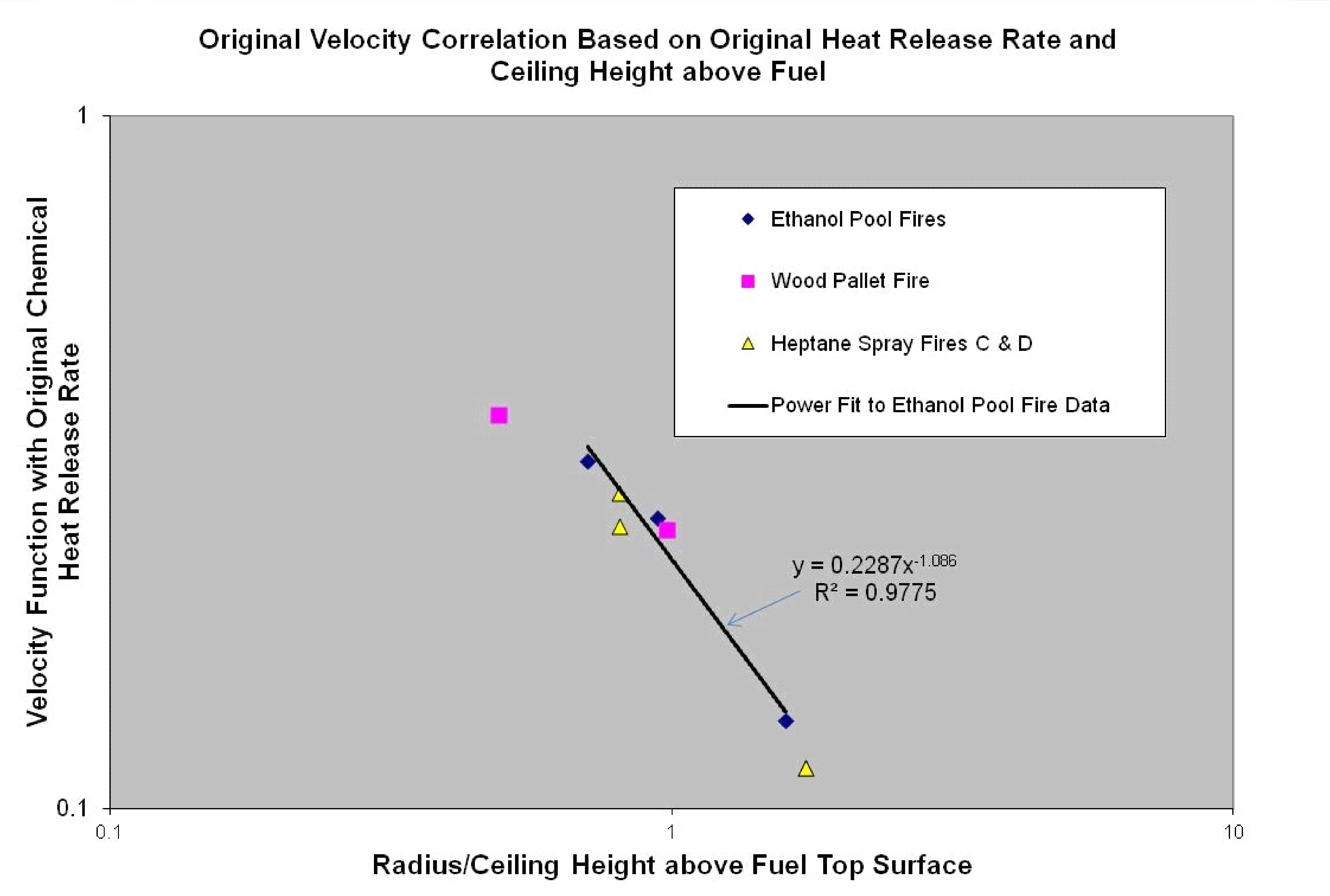
Fuel Type	***Net Heat of Complete Combustion****Error! Bookmark not defined.* ***[kJ/g]***	***Chemical Heat of Combustion Used for Original Formula [kJ/g]***
Ethanol Pool	27.70	22.38
Wood Four-way Pallet Stack	16.4	13.96
Polyethylene Bottles in Compartmented Cardboard Boxes*	28.1	24.66
Polystyrene Jars in Compartmented Cardboard Boxes**	33.7	31.63
Heptane Sprays	44.6	44.6

Original Fire Source Conditions

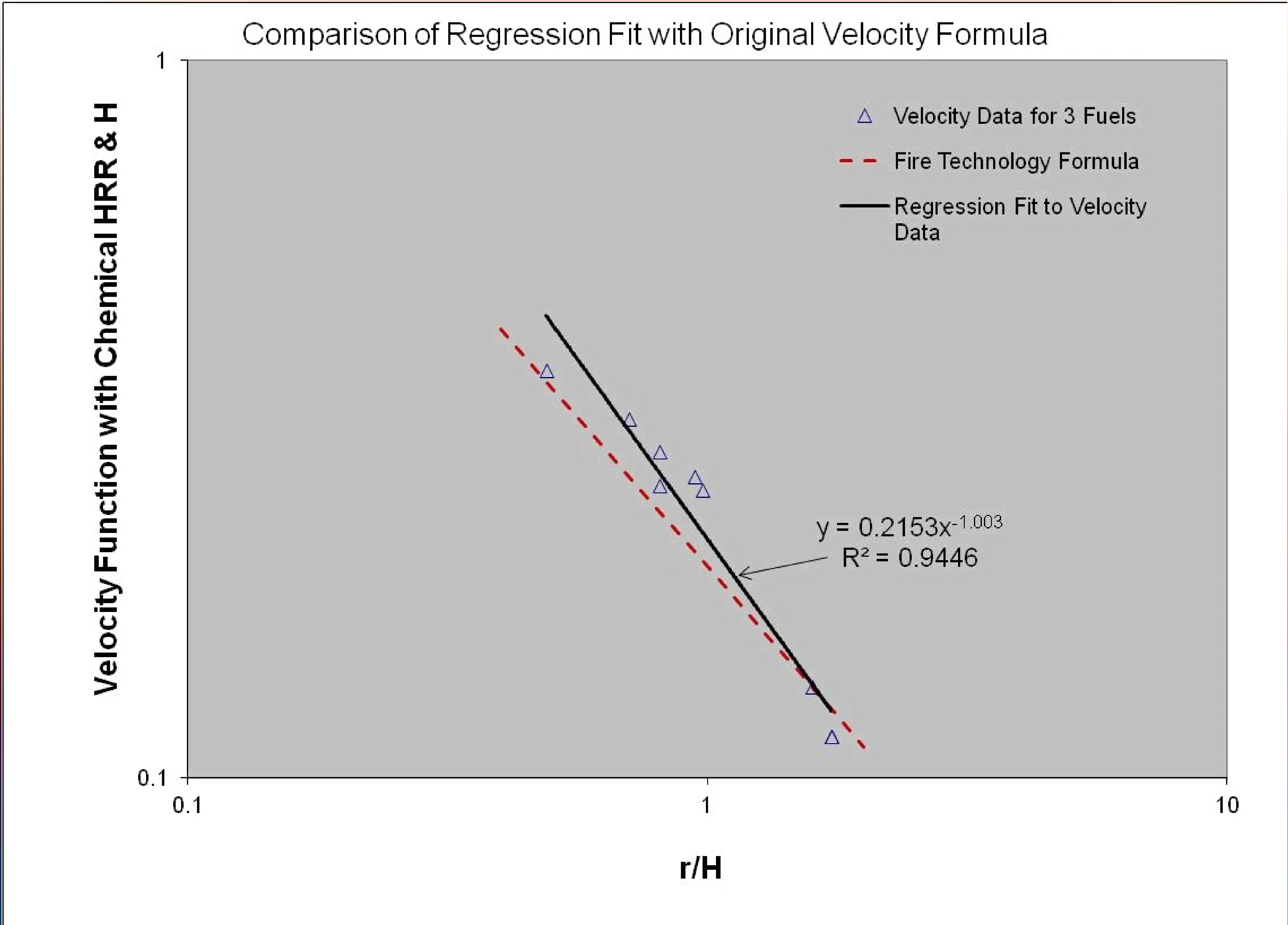
Fuel Type	***Height of Burning Fuel [m]***	***Effective Diameter of Fuel [m]***	***Ceiling Height above Top of Fuel [m]***	***Fuel Flow or Mass Loss Rate [g/s]***	***Total HRR [kW]***	***Chemical HRR [kW]***
Ethanol Pool	0.00	1.09	8.61	24.18	669.8	541.15
Wood Four-way Pallet Stack	2.44	1.38	15.54	318.0	5,215	4,439
PE Bottles in Cardboard Boxes	4.57	2.77	13.41	1,390.5	39,034	34,290
PS Jars in Cardboard Boxes	4.11	2.94	13.87	3,113	104,752	98,464
Heptane Spray A	0.00	3.66	7.92	173.6	7,744	7,744
Heptane Spray B	0.00	3.66	7.92	303.8	13,551	13,551
Heptane Spray C	0.00	3.66	7.92	434.1	19,359	19,359
Heptane Spray D	0.00	3.66	7.92	520.9	23,231	23,231
Heptane Spray E	0.00	3.66	4.572	173.6	7,744	7,744
Heptane Spray F	0.00	3.66	4.572	303.8	13,551	13,551
Heptane Spray G	0.00	3.66	4.572	434.1	19,359	19,359

Velocity Function in Ordinate

$$\frac{V_{max}(H)^{1/3}}{\dot{Q}_{chem}^{1/3}} \qquad \frac{m^{4/3}}{s \times kW^{1/3}}$$

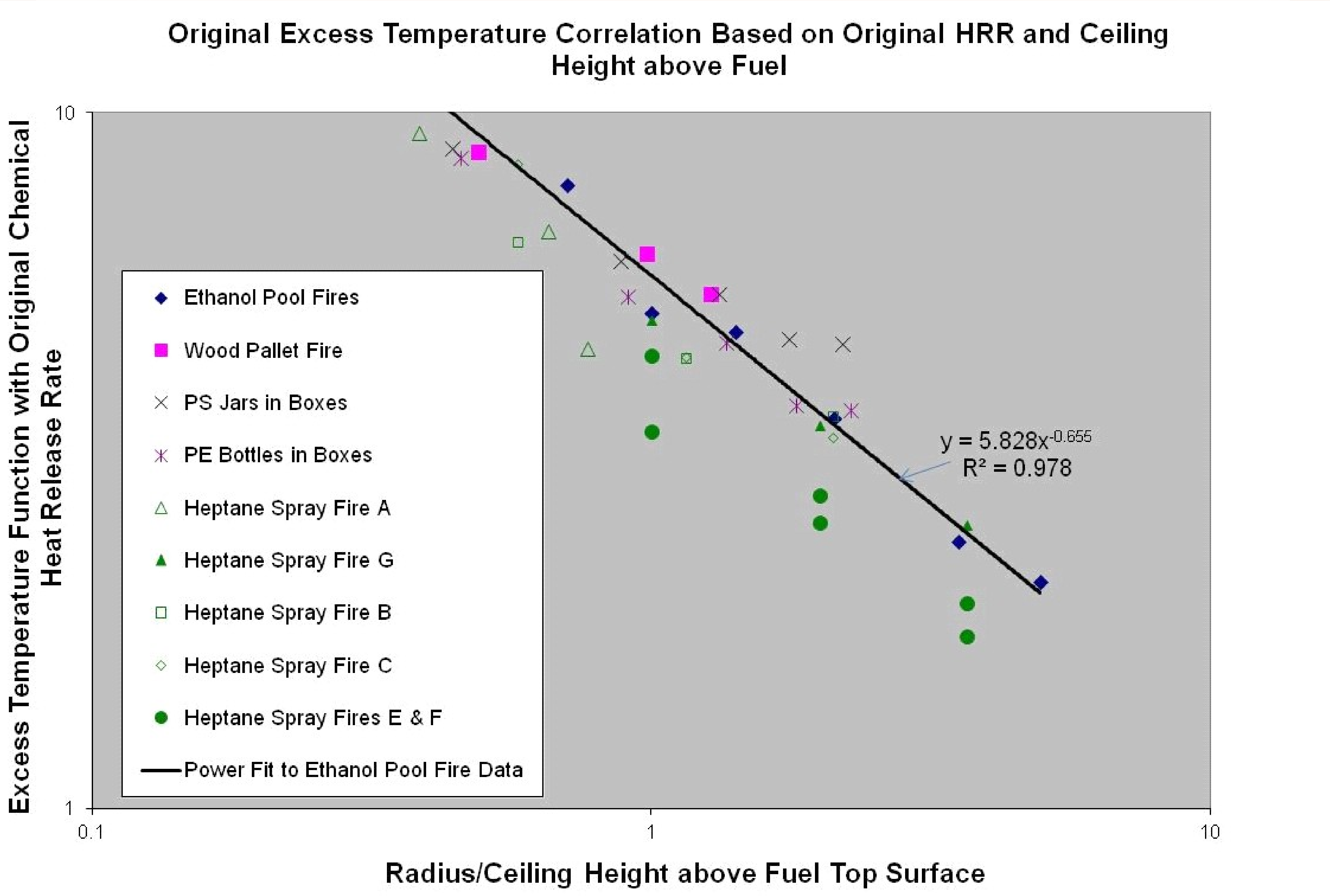


Original Velocity Correlation Based on Original Heat Release Rate and Ceiling Height above Fuel
Velocity Function with Original Chemical Heat Release Rate
Radius/Ceiling Height above Fuel Top Surface
1
0.1
0.1
1
10
Ethanol Pool Fires
Wood Pallet Fire
Heptane Spray Fires C & D
Power Fit to Ethanol Pool Fire Data
y = 0.2287x^-1.086
R² = 0.9775

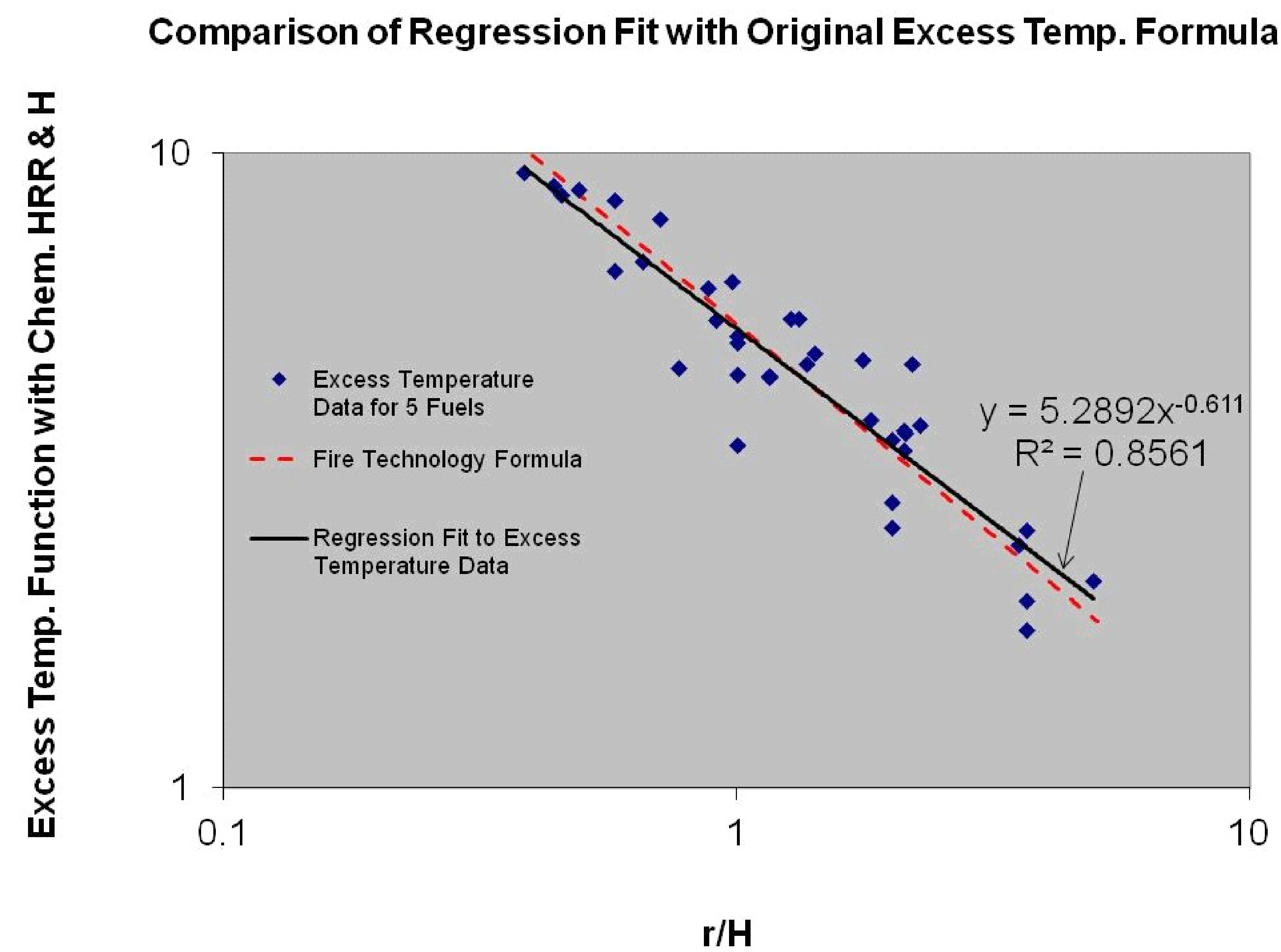

Comparison of Regression Fit with Original Velocity Formula
Velocity Data for 3 Fuels
Fire Technology Formula
Regression Fit to Velocity Data
y = 0.2153x^-1.003
R² = 0.9446
1
0.1
0.1
1
10
Velocity Function with Chemical HRR & H
r/H

Excess Temperature Function in Ordinate

$$\frac{\left(T_{max} - T_{\infty}\right)\left(H\right)^{5/3}}{\dot{Q}_{chem}^{\;2/3}} \qquad \frac{K \times m^{5/3}}{kW^{2/3}}$$



Original Excess Temperature Correlation Based on Original HRR and Ceiling Height above Fuel
Excess Temperature Function with Original Chemical Heat Release Rate
Radius/Ceiling Height above Fuel Top Surface
10
1
0.1
1
10
Ethanol Pool Fires
Wood Pallet Fire
PS Jars in Boxes
PE Bottles in Boxes
Heptane Spray Fire A
Heptane Spray Fire G
Heptane Spray Fire B
Heptane Spray Fire C
Heptane Spray Fires E & F
Power Fit to Ethanol Pool Fire Data
y = 5.828x-0.655
R² = 0.978



Comparison of Regression Fit with Original Excess Temp. Formula
Excess Temp. Function with Chem. HRR & H
10
1
0.1
1
10
r/H
Excess Temperature Data for 5 Fuels
Fire Technology Formula
Regression Fit to Excess Temperature Data
$y = 5.2892x^{-0.611}$
$R^2 = 0.8561$

•Re-examination of Data from Steady-State Fire Sources

- Only use data from ethanol pool and heptane spray fire sources, since these have well-defined HRR
- Use ceiling height above the virtual plume origin, instead of above the fuel surface or nozzle elevation
- Use convective component of heat release rate instead of the chemical (actual) heat release rate, in the velocity or excess temperature functions, since flow velocity and excess temperature are controlled by convection

Virtual Plume Origin Formula

$$z_v = 0.083\dot{Q}_{chem}^{2/5} - 1.02D_{eff}$$

Handbook Values for Heats of Combustion of Ethanol & Heptane

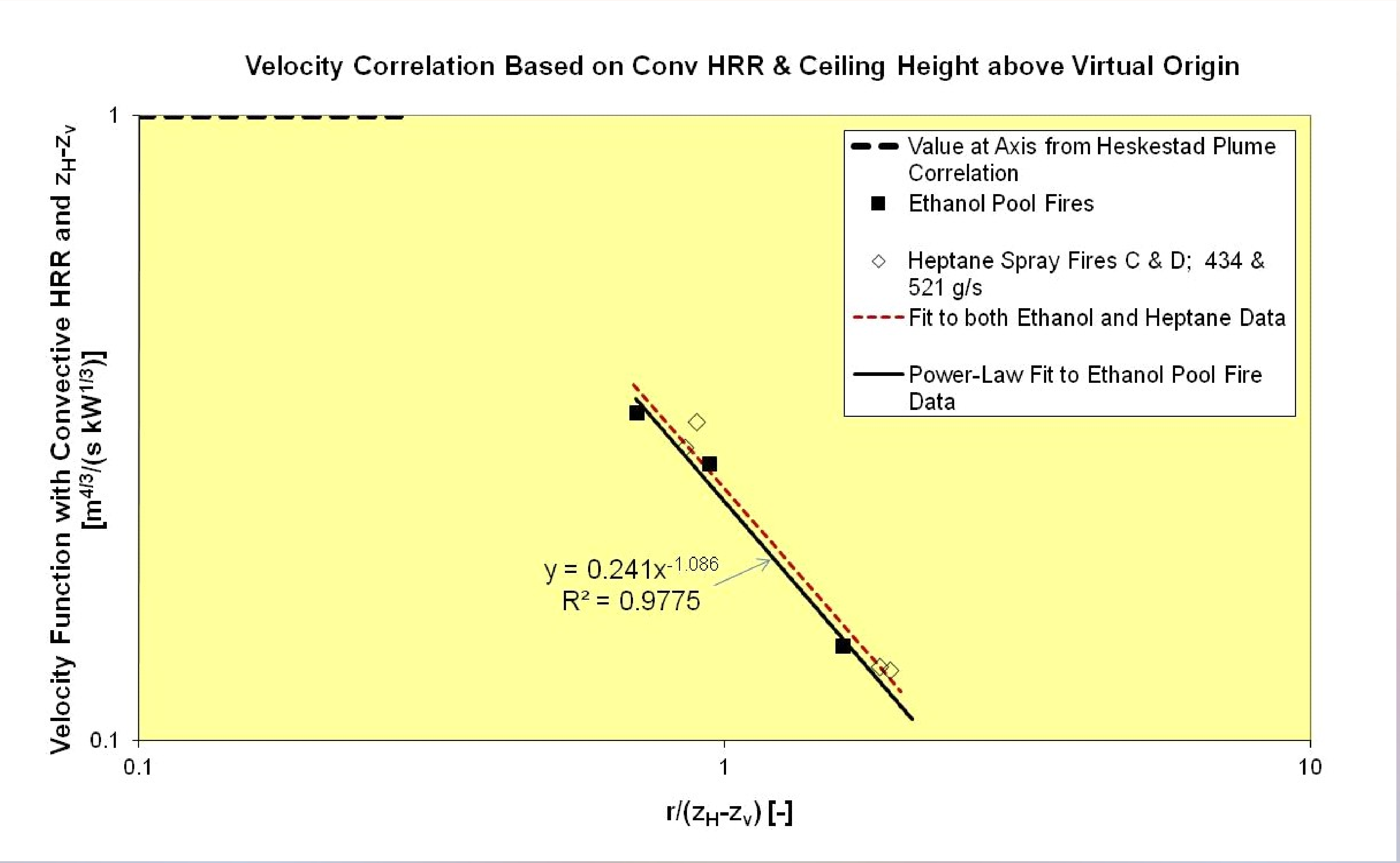
Fuel Type	*Chemical Heat of Combustion [kJ/g]*	*Convective Heat of Combustion [kJ/g]*
Ethanol Pool	25.60	19.00
Heptane Sprays	41.2	27.6

Source Conditions for Steady Fires

Fuel Type	*Effective Diameter of Fuel [m]*	*Fuel Flow or Mass Loss Rate [g/s]*	*Chemical HRR [kW]*	*Virtual Origin Height above Base of Burning Fuel, [m]*	*Ceiling Height above Virtual Origin, [m]*	*Convective HRR [kW]*
Ethanol Pool	1.09	24.18	619.0	-0.0227	8.63	459.4
Heptane Spray A	3.66	173.6	7,153	-0.8409	8.77	4,792
Heptane Spray B	3.66	303.8	12,518	-0.1159	8.04	8,386
Heptane Spray C	3.66	434.1	17,883	0.4385	7.48	11,980
Heptane Spray D	3.66	520.9	21,460	0.7539	7.17	14,376
Heptane Spray E	3.66	173.6	7,153	-0.8409	5.41	4,792
Heptane Spray F	3.66	303.8	12,518	-0.1159	4.69	8,386
Heptane Spray G	3.66	434.1	17,883	0.4385	4.13	11,980

Modified Velocity Function in Ordinate

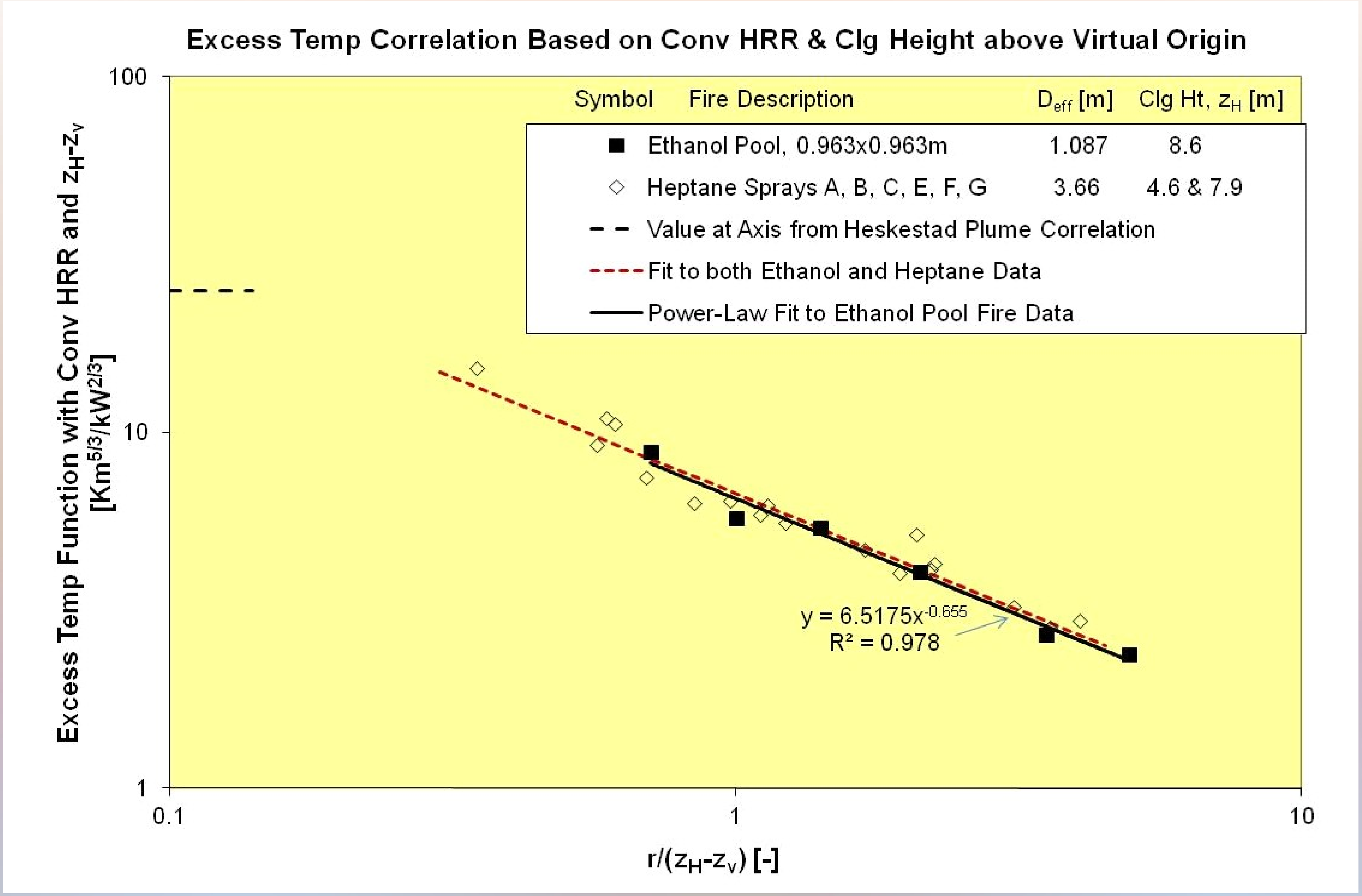
$$\frac{V_{max}\left(z_H - z_v\right)^{1/3}}{\dot{Q}_{conv}^{1/3}} \qquad \frac{m^{4/3}}{s \times kW^{1/3}}$$



Velocity Correlation Based on Conv HRR & Ceiling Height above Virtual Origin
Velocity Function with Convective HRR and z_H-z_v $[m^{4/3}/(s\ kW^{1/3})]$
1
0.1
0.1
1
10
$r/(z_H$-$z_v)$ [-]
Value at Axis from Heskestad Plume Correlation
Ethanol Pool Fires
Heptane Spray Fires C & D; 434 & 521 g/s
Fit to both Ethanol and Heptane Data
Power-Law Fit to Ethanol Pool Fire Data
$y = 0.241x^{-1.086}$
$R^2 = 0.9775$

Modified Excess Temperature Function in Ordinate

$$\frac{\left(T_{max} - T_{\infty}\right)\left(z_H - z_v\right)^{5/3}}{\dot{Q}_{conv}^{2/3}} \qquad \frac{K \times m^{5/3}}{kW^{2/3}}$$



Excess Temp Correlation Based on Conv HRR & Clg Height above Virtual Origin
Symbol
Fire Description
D_eff [m]
Clg Ht, z_H [m]
Ethanol Pool, 0.963x0.963m
1.087
8.6
Heptane Sprays A, B, C, E, F, G
3.66
4.6 & 7.9
Value at Axis from Heskestad Plume Correlation
Fit to both Ethanol and Heptane Data
Power-Law Fit to Ethanol Pool Fire Data
y = 6.5175x^-0.655
R² = 0.978
Excess Temp Function with Conv HRR and z_H-z_v [Km^5/3/kW^2/3]
r/(z_H-z_v) [-]
100
10
1
0.1
1
10

Regression Fit from Re-examination: Maximum Gas Velocity

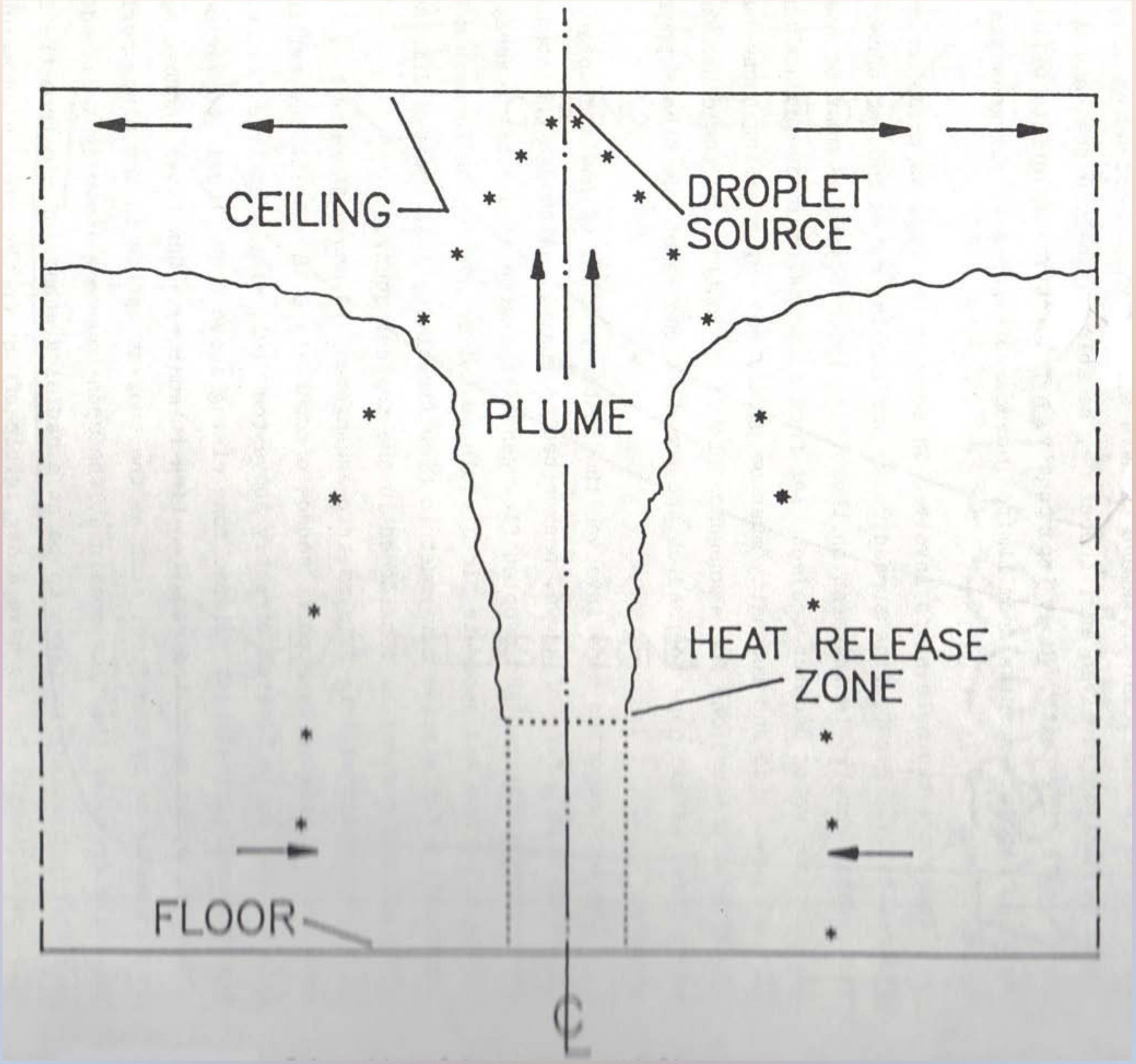
$$V_{max} = 0.2526 \frac{\dot{Q}_c^{1/3}}{\left(z_H - z_v\right)^{1/3}} \left(\frac{r}{z_H - z_v}\right)^{-1.0739} \qquad R^2 = 0.972$$

Regression Fit from Re-examination: Maximum Excess Gas Temperature

$$T_{max} - T_{\infty} = 6.721 \frac{\dot{Q}_c^{2/3}}{\left(z_H - z_v\right)^{5/3}} \left(\frac{r}{z_H - z_v} \right)^{-0.6545} \qquad R^2 = 0.958$$

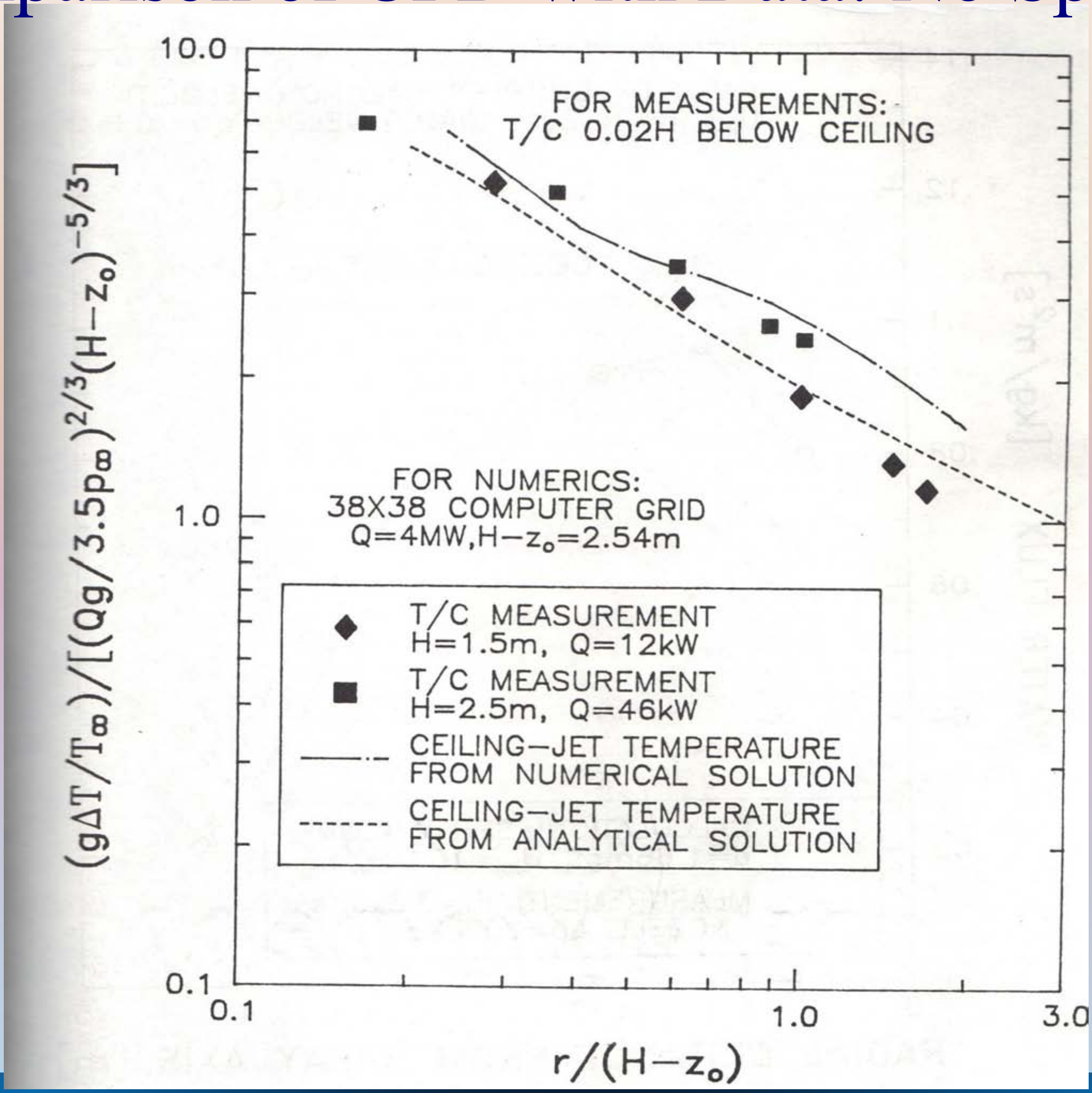
CFD Modeling of Spray-Fire Interactions, 1980-1985

- Predict suppression effectiveness once spray device is activated by the ceiling jet flow
- Simplified axisymmetric geometry: spray above fire
- Iterative Eulerian gas solution using TEACH CFD
- Iterative Lagrangian droplet tracking after several gas flow iterations
- Full mass, momentum and energy transfer between gas and droplet phases

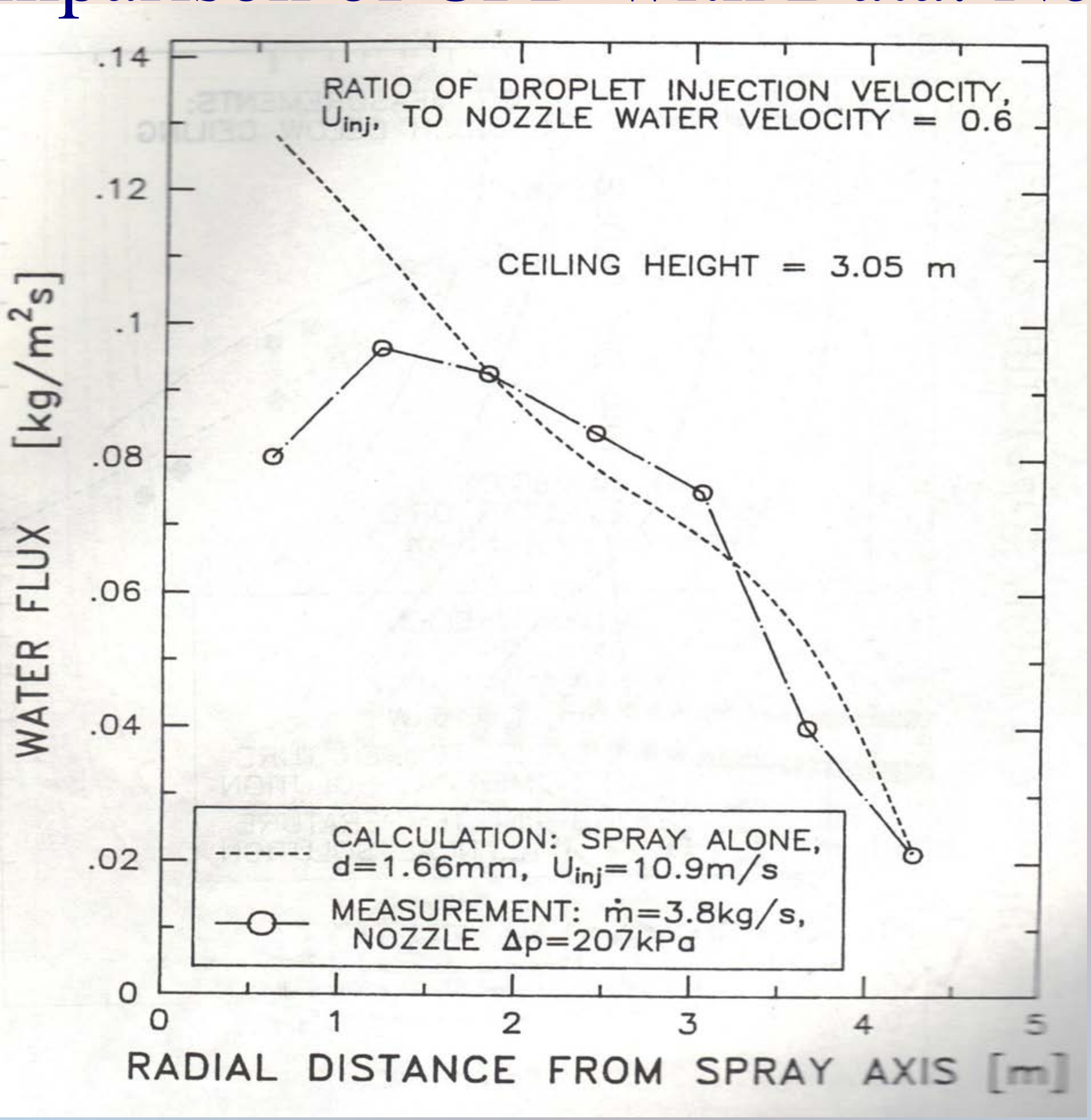


CEILING
DROPLET SOURCE
PLUME
HEAT RELEASE ZONE
FLOOR
℄

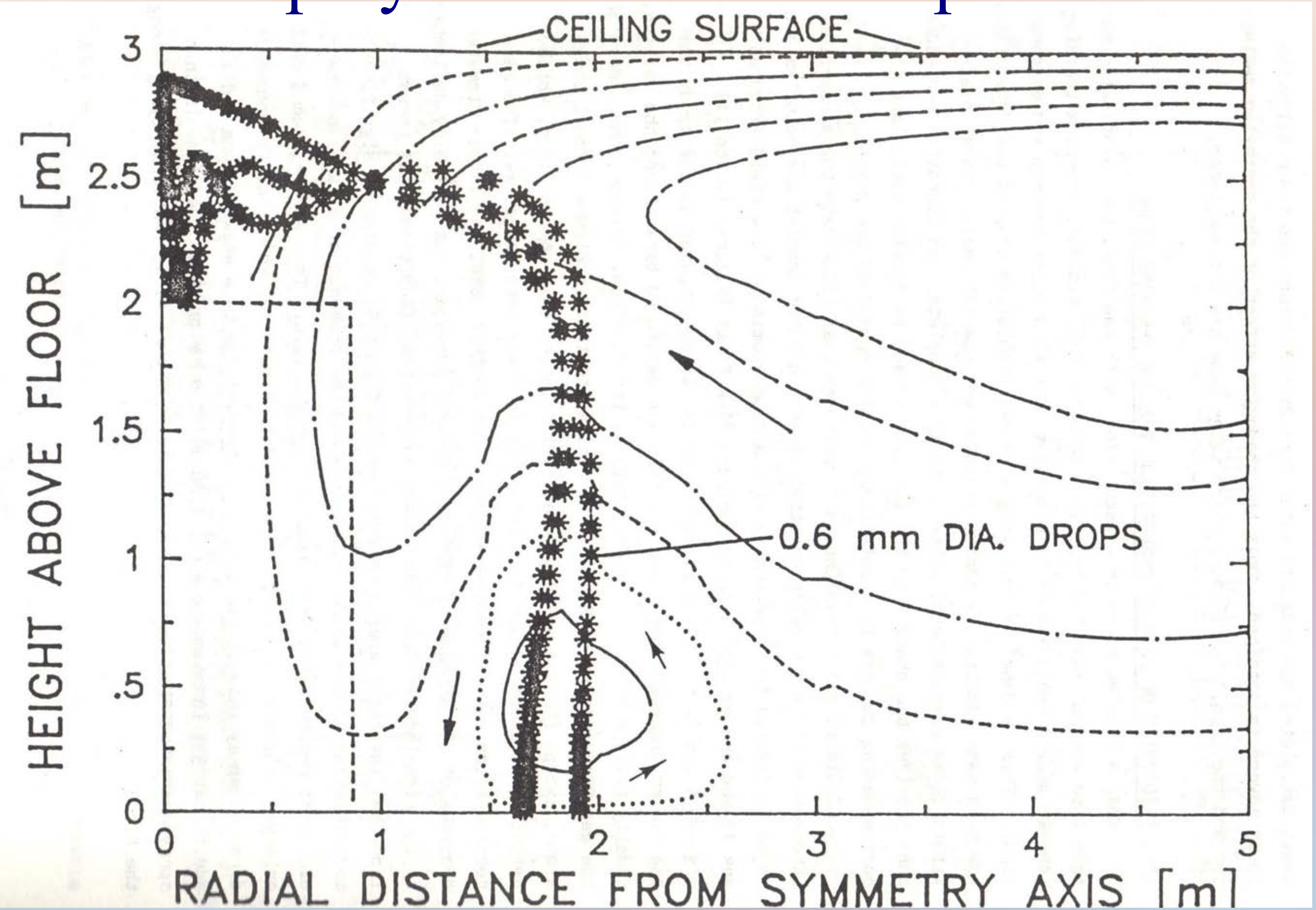
Comparison of CFD with Data: No Spray



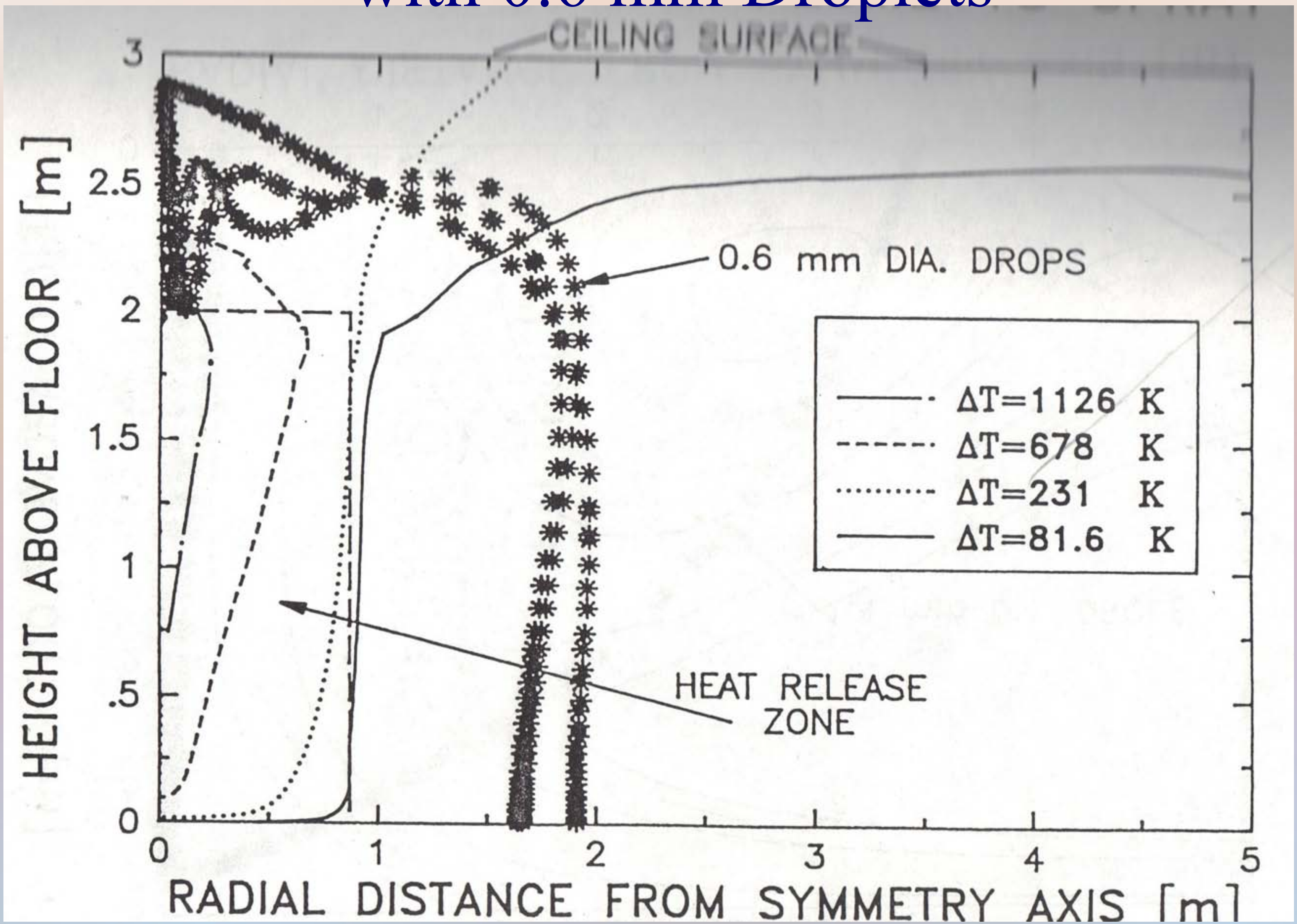
Comparison of CFD with Data: No Fire



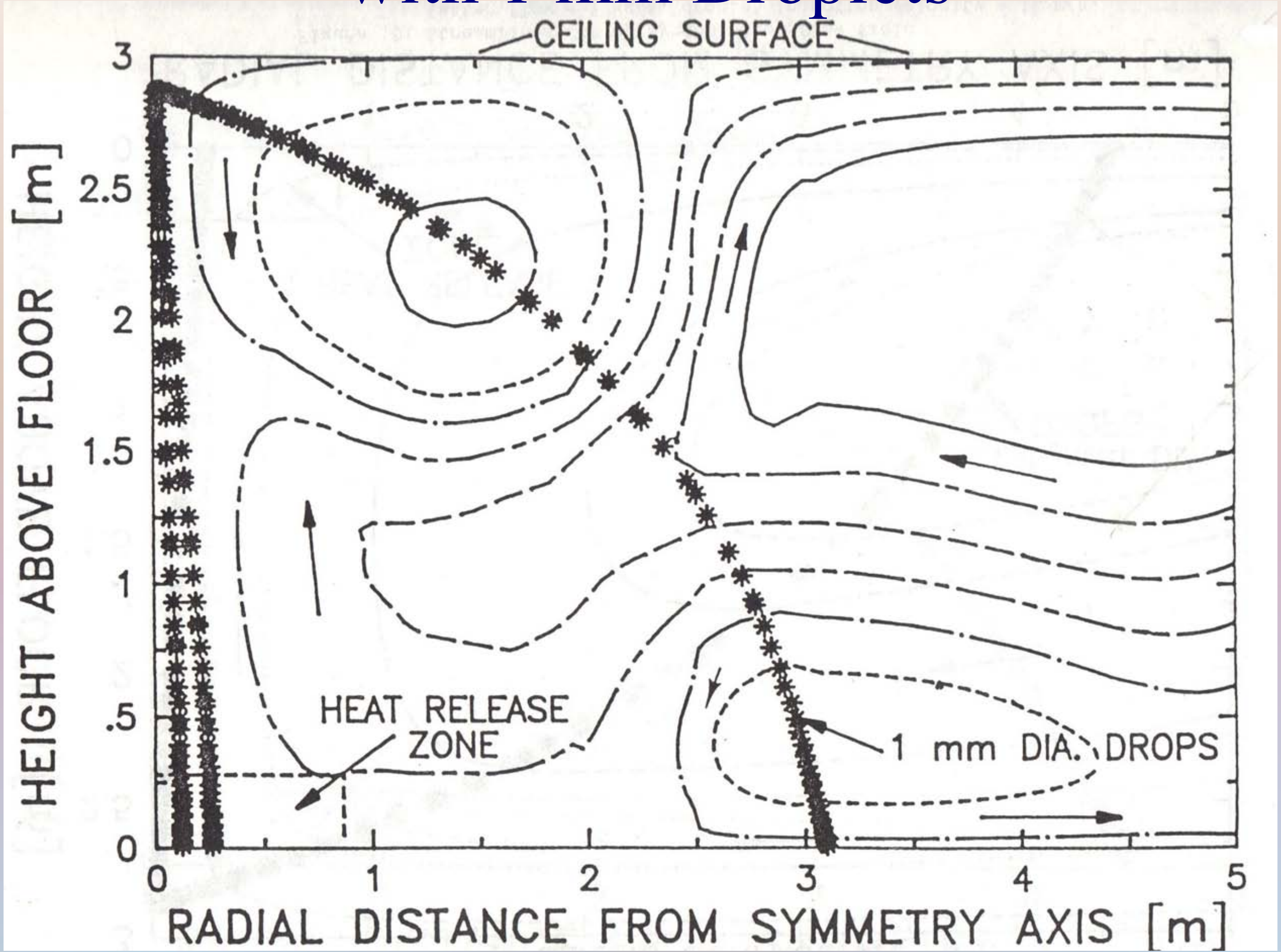
Streamlines for Strong (3.8 MW) Plume vs. Spray with 0.6 mm Droplets



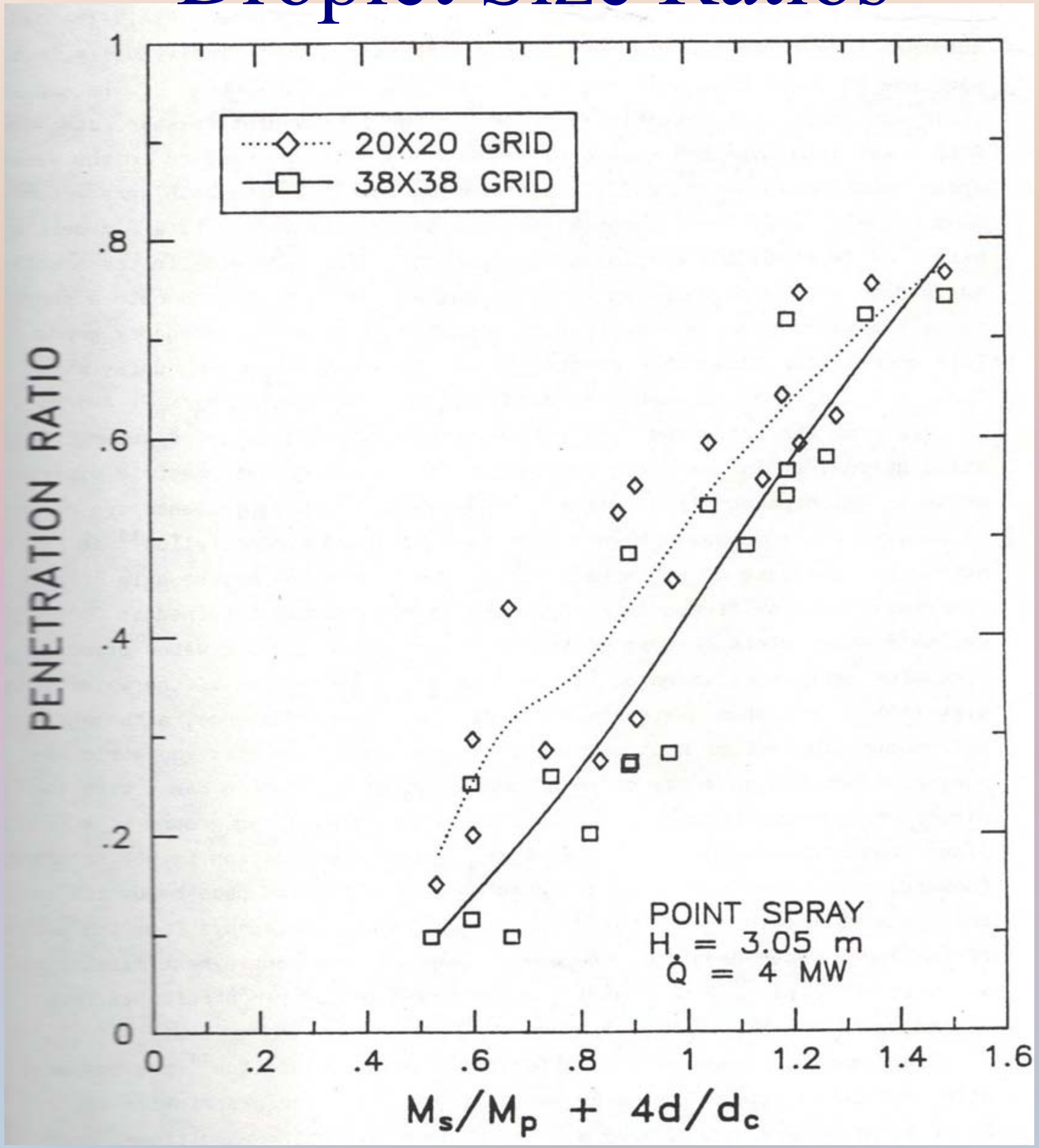
Isotherms for Strong (3.8 MW) Plume vs. Spray with 0.6 mm Droplets



Streamlines for Weak (0.5 MW) Plume vs. Spray with 1 mm Droplets



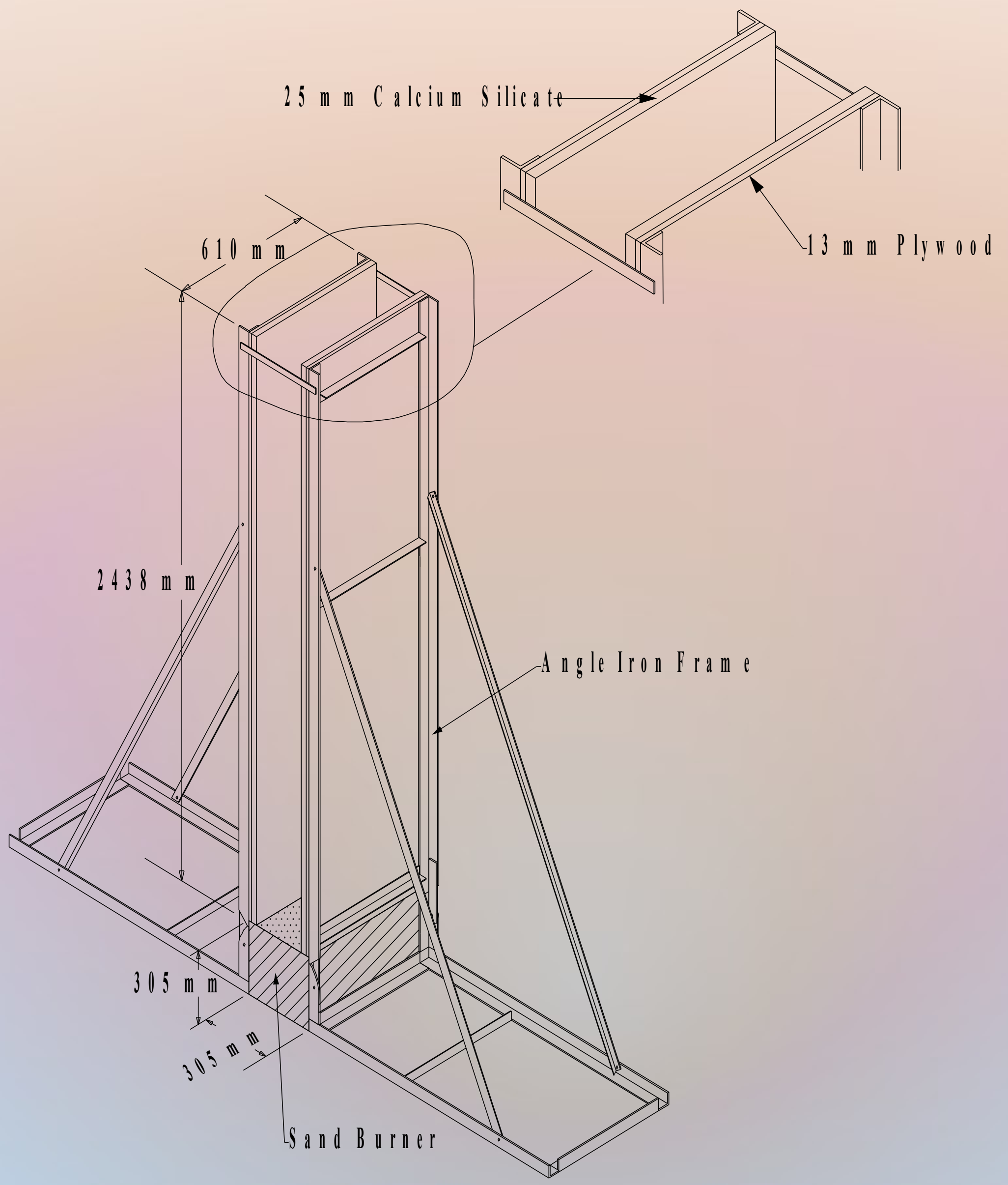
Correlation of CFD Results Using Momentum & Droplet Size Ratios



Determination of Minimum Agent Flux Required to Suppress a Fire

- Measurement of Flame Heat Flux within a Burning Fuel Array Can be Used to Infer Agent Flux Needed from a Single Fire Test
- Most Dangerous Fuel Arrays Involve Vertical Flues
- Rugged Measurement Instrument Developed to Obtain Flame Heat Flux within a Combustible Flue
- Parallel Vertical Panel Apparatus Represents Essential Element of Such Flue Arrays
- Fire exposure is propane sand burner, 30-100 KW

Parallel Vertical Surface Fire Test

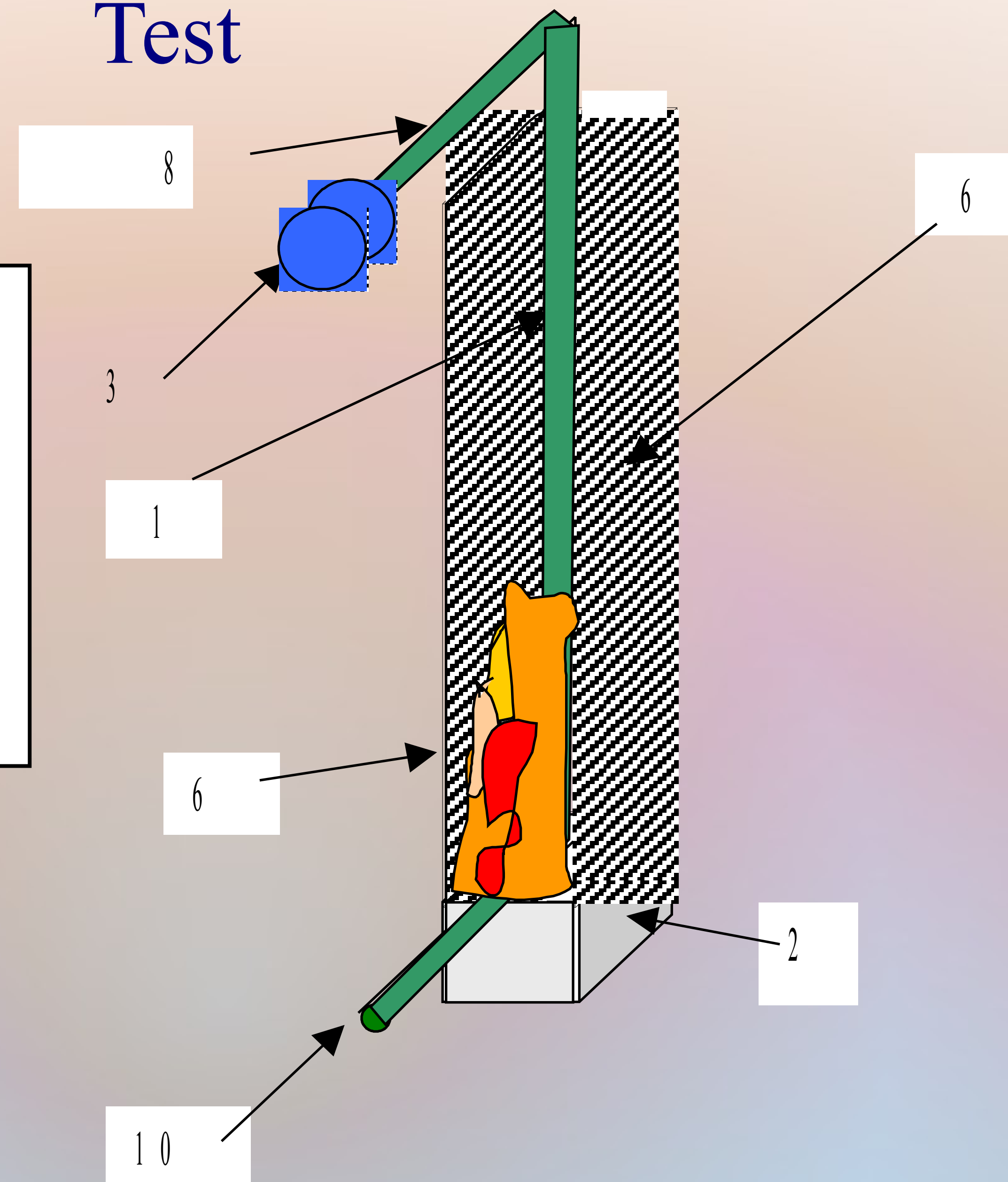


Heat Flux Measurement Pipe

- Water-cooled, rugged pipe is 22 mm diameter to minimize flow disturbance
- Water flow rate of about 8 l/min to obtain maximum Temp differences and prevent boiling at 100 kW/m^2
- Fully turbulent flow in a spiral pipe annulus insures efficient heat transfer to water-immersed T/C's
- At the design water flow rate, the system response time is about 7 s

Measurement of Flame Heat Flux during Fire Test

1 – Heat Flux Pipe
2 – Gas Burner
3 – Flow Meter and T/C Outlet
6 – Parallel Panels
8 – Cold Water In
10 – Water Out



Summary

- Since early 1970's, has been possible to predict when spray suppression devices in the ceiling jet will be activated
- Since early 1980's, has been possible to predict how much of agent flow from spray suppression devices will reach burning fuel locations
- Since early 2000's, has been possible to predict, from a single fire test, the minimum agent flux required for fire suppression