

# Physical Scaling of Water Mist Protection of 260-m<sup>3</sup> Machinery Enclosure

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# Background

- **To reduce the development and certification cost for water mist fire protection systems by conducting fire tests in scaled-down facilities.**
  - Currently, full-scale testing is required for system development and listing.
  - Full-scale fire testing costs are often prohibitive for niche applications.
  
- **Goal: To confirm the feasibility of scaling approach for approval purposes by replicating the water mist fire protection results of an already FM-Approved water mist system in a 1/2-scale test facility.**

# Outline

- **Review of scaling relationships**
- **Full-Scale and 1/2-scale machinery test enclosures**
- **Full-scale and 1/2-scale test fires**
- **Full-Scale and 1/2-scale water mist sprays**
- **Test results**
- **Implementation in FM Approval Standard 5560**

# Froude-Based Physical Scaling of Spray-Plume Interaction



**In geometrically similar control volumes,  
conserve:**

**1) Froude number of gas flow**

$$Fr = \frac{\text{momentum force}}{\text{buoyancy force}} = \frac{\rho u^2}{(\rho_\infty - \rho)gL}$$

**2) Momentum transfer characteristics between water droplets and gas flow.**

**3) Droplet vaporization characteristics.**

**4) Scalar quantities in the control volumes.**

# Froude-Based Scaling Relationships

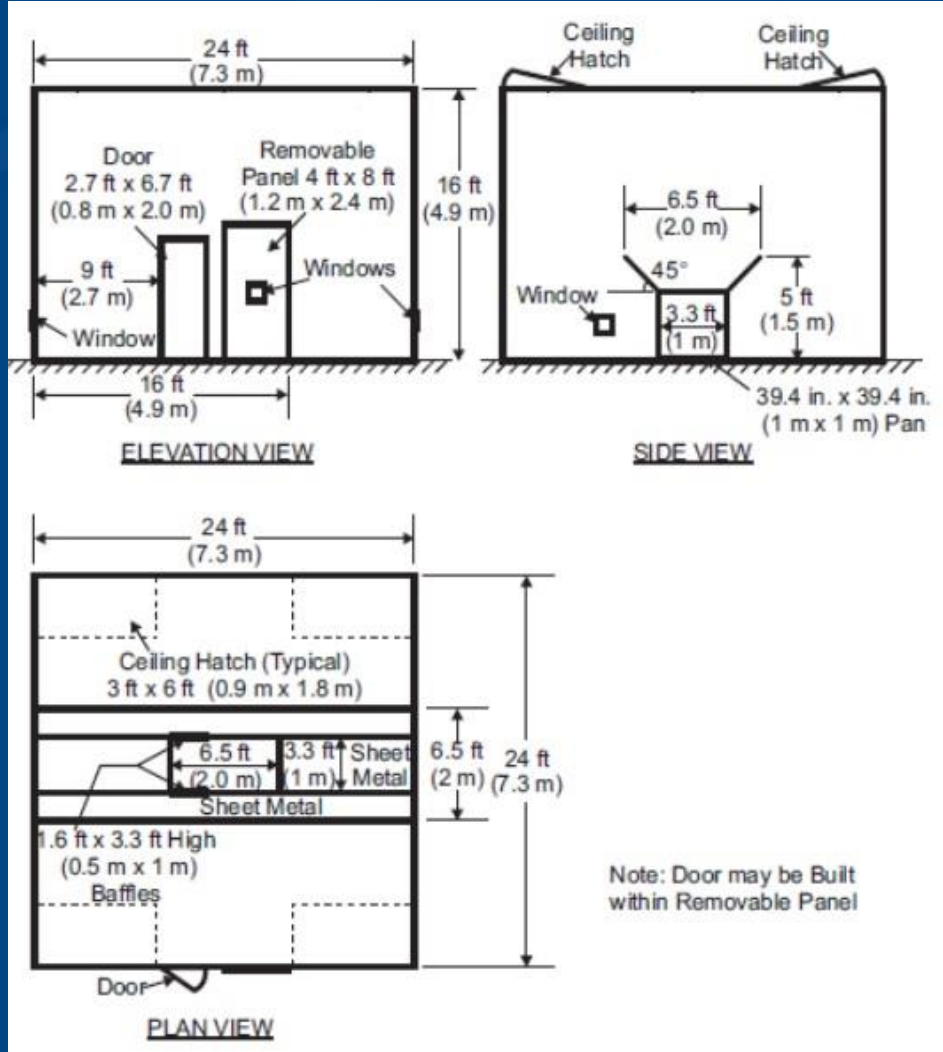
$$F = \frac{1}{2} C_D A \rho_g |\bar{u}_d - \bar{u}_g| (\bar{u}_d - \bar{u}_g), \quad C_D = \frac{k}{Re_d^x}, \quad Re_d = \frac{d |\bar{u}_d - \bar{u}_g|}{v_g}$$

Scaling Parameters	Any $Re_d$	$Re_d \leq 1^*$
Drag Coefficient, $C_D$	$\sim Re_d^{-x}$	$\sim Re_d^{-1}$
Scale Ratio $S=L_2/L_1$	$S^1$	$S^1$
Time	$S^{1/2}$	$S^{1/2}$
All Scalar Quantities	$S^0$	$S^0$
Operating Pressure	$S^1$	$S^1$
Droplet and Gas Velocities	$S^{1/2}$	$S^{1/2}$
Ventilation Rate	$S^{5/2}$	$S^{5/2}$
Fire Heat Release Rate	$S^{5/2}$	$S^{5/2}$
Total Water Mist Discharge Rate	$S^{5/2}$	$S^{5/2}$
Droplet Diameter	$S^{(2-x)/(2+2x)}$	$S^{1/4}$

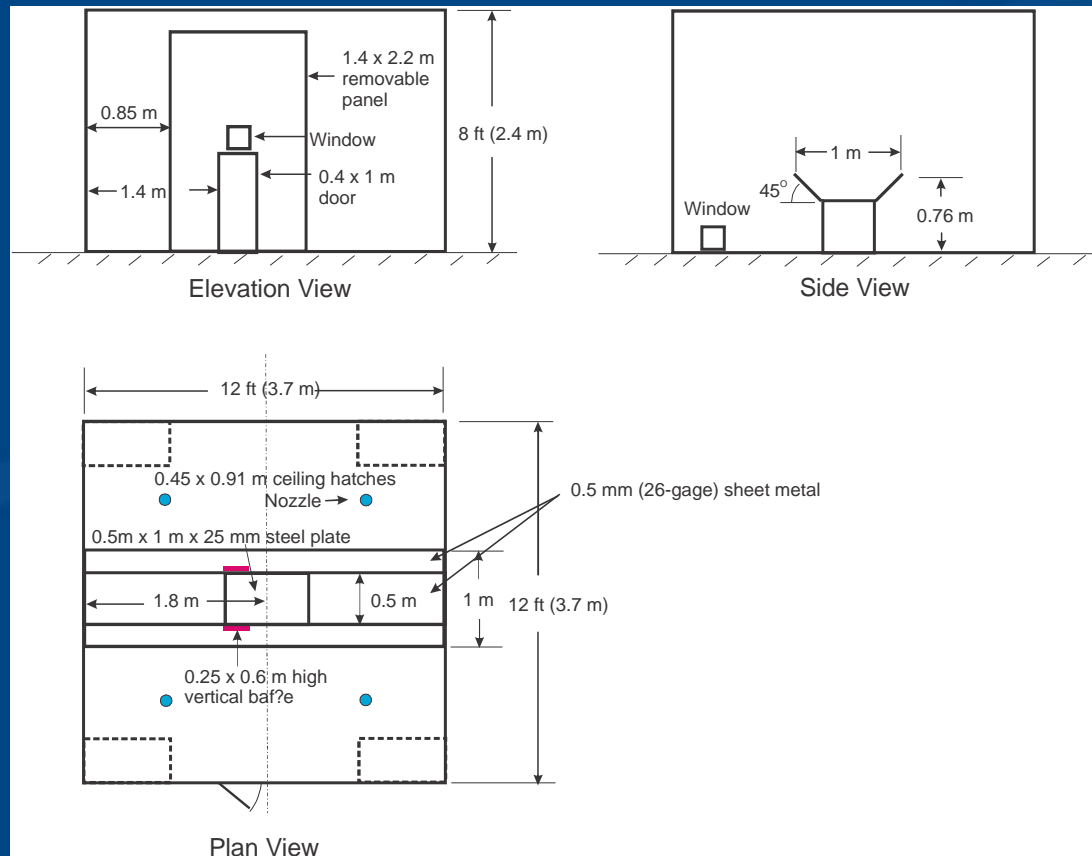
\*For droplets not larger than 100  $\mu\text{m}$ .

# 260-m<sup>3</sup> Full-Scale Machinery Enclosure Test Facility

## FM Approval Standard 5560, Water Mist Systems



# 1/2-Scale Test Facility

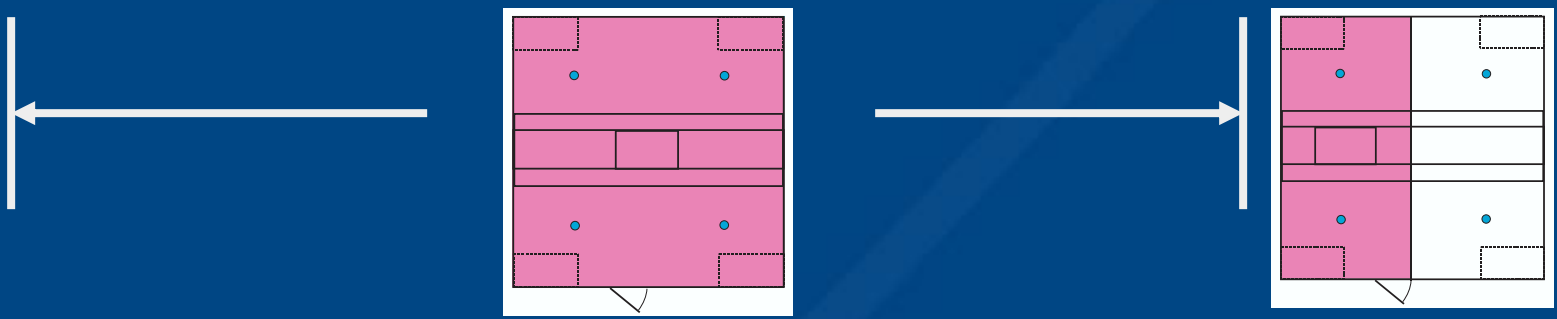


- Gypsum board thickness ( $\sim S^{3/4}$ ): 9.5 mm (13 mm full scale).
- Machinery mockup thickness ( $\sim S^1$ ): 25 mm for table (50 mm full scale), 0.5 mm for sheet metal (0.9 mm full scale) .

# 260-m<sup>3</sup> Machinery Enclosure Fire Scenarios

## FM Approval Standard 5560 – Water Mist Systems Appendix C – Heptane Fire Scenarios

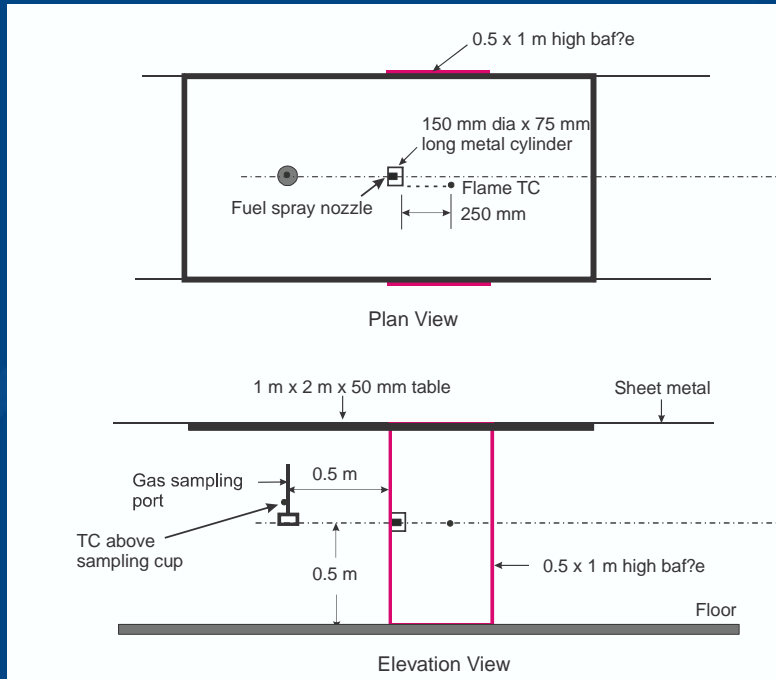
Fire Scenario ID	C4.6	C4.7	C4.8	C4.9	C4.10
Fire Scenario Name	Unshielded 1- MW Spray Fire in Full Enclosure; door Closed	Shielded 1- MW Spray Fire in Full Enclosure; Door Closed	Shielded 1- m <sup>2</sup> Pool Fire in Full Enclosure; Door Closed	Shielded 2- MW Spray Fire in Full Enclosure; Door Opened	Shielded 2- MW Spray Fire in Half Enclosure; Door Opened



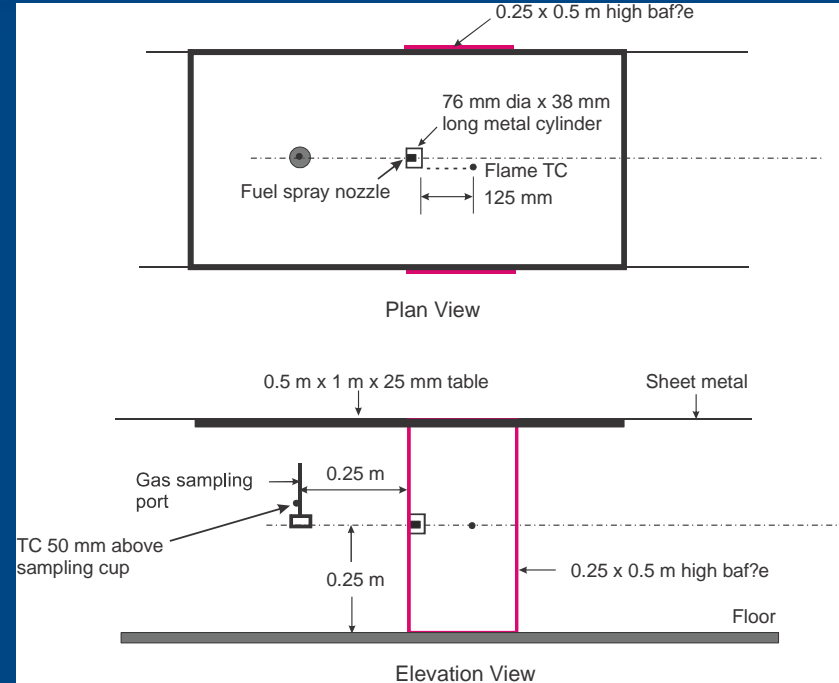


# Shielded Spray Fire Arrangement

## Full Scale



## 1/2 Scale



# Full-Scale and 1/2-Scale Heptane Spray Fires



Discharge rate  $\sim S^{5/2}$

Full scale

Fire Scenario ID	C4.6	C4.7	C4.9	C4.10
Spray Nozzle	Monarch F80, PLP, No. 24	Monarch F80, PLP, No. 24	Monarch F80, PLP, No. 50	Monarch F80, PLP, No. 50
Heptane Discharge Rate	21.8 g/s	24.1 g/s	41.3 g/s	40.9 g/s

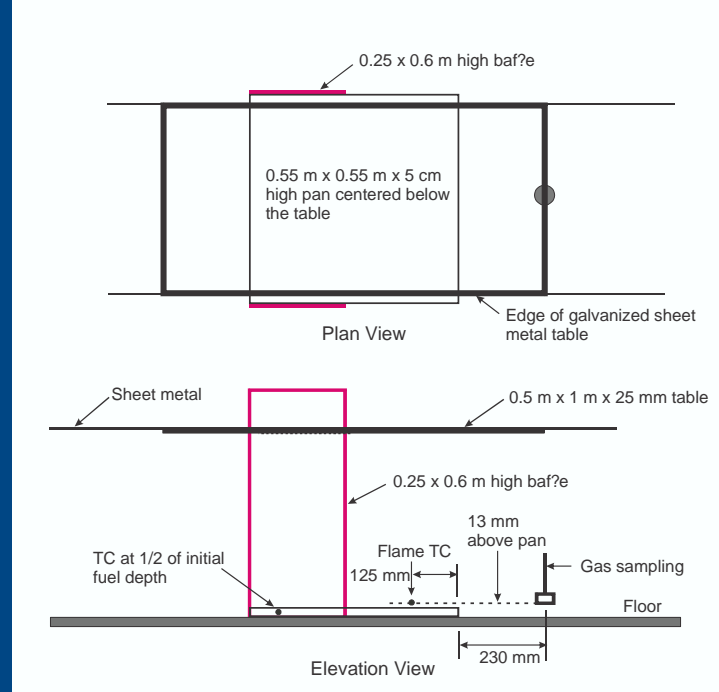
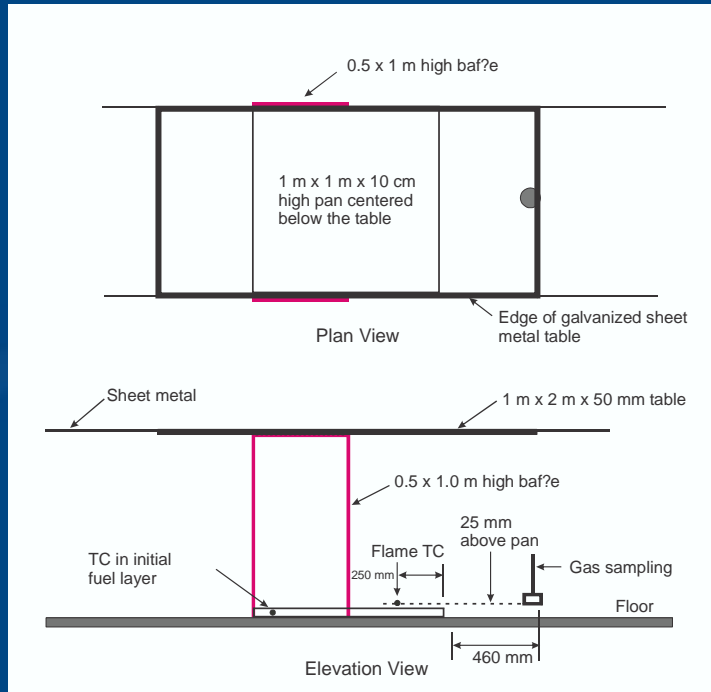
1/2-scale

Fire Scenario ID	C4.6	C4.7	C4.9	C4.10
Spray Nozzle	Monarch F80, PLP, No. 5.5	Monarch F80, PLP, No. 5.5	Monarch F80, PLP, No. 12	Monarch F80, PLP, No. 12
Heptane Discharge Rate	3.9 g/s	4.3 g/s	7.3 g/s	7.2 g/s

# Shielded Pool Fire Arrangement

## Full Scale

## 1/2 Scale

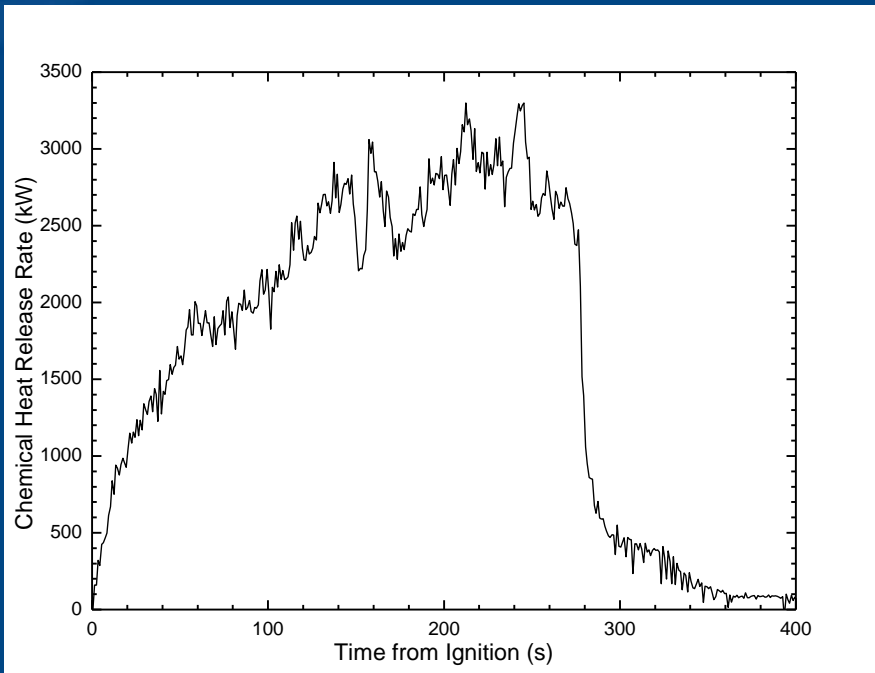


# Full-Scale and 1/2-Scale Pool Fire Heat Release Rates

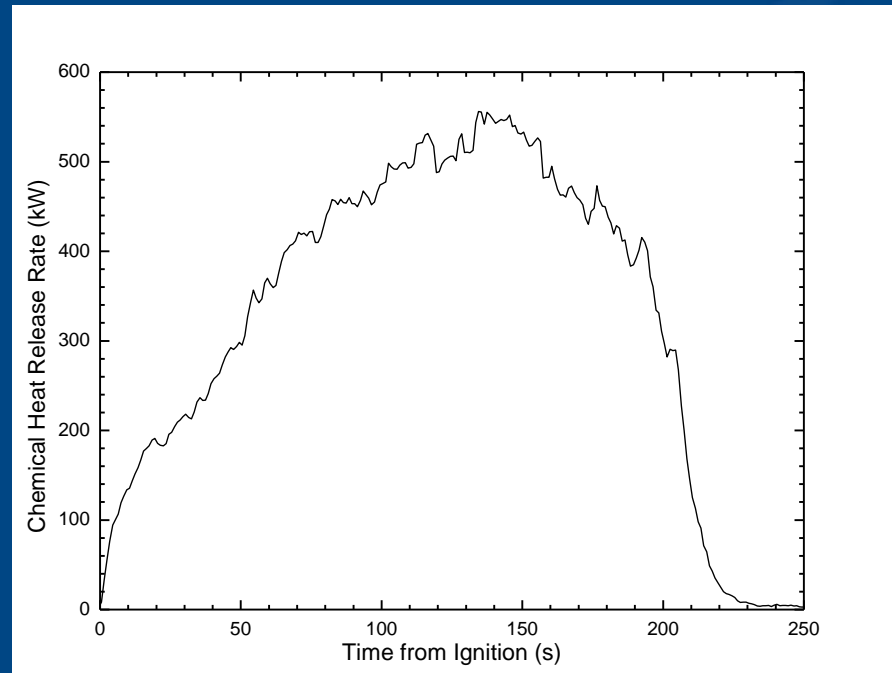
**Full scale: 1 m x 1 m x 10 cm high pan, 1.7 mm thick steel; 2 cm heptane on 5 cm deep water.**

**1/2 scale: 0.55 m x 0.55 m x 5 cm high pan, 0.9 mm thick steel; 1.5 cm heptane on 2 cm deep water.**

## Full scale

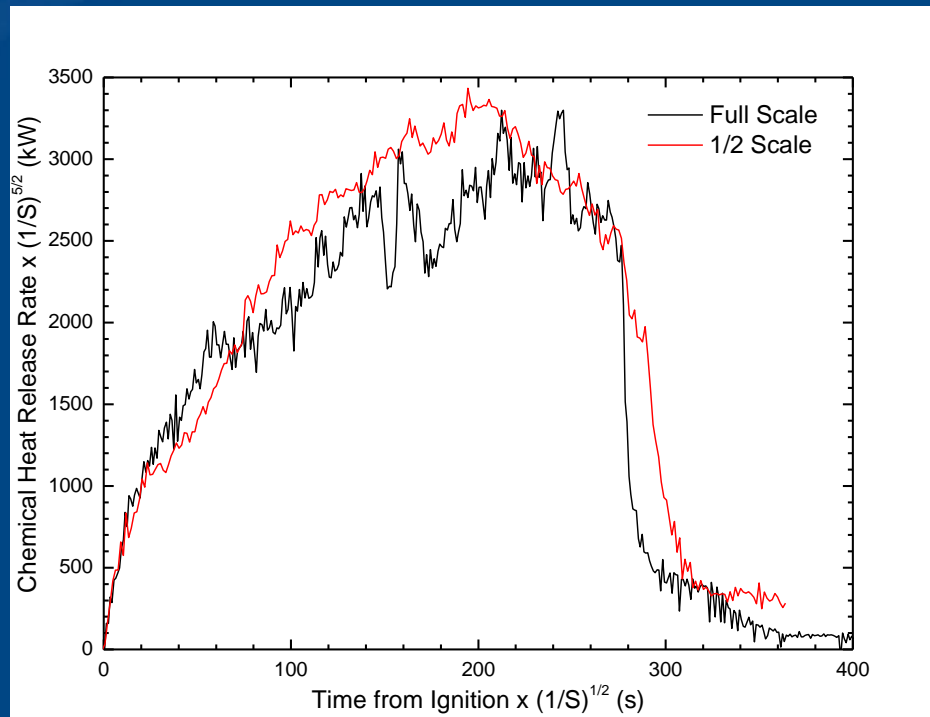


## 1/2 scale



# Comparison of Full-Scale and 1/2-Scale Pool Fire Heat-Release-Rate Histories

## Full scale



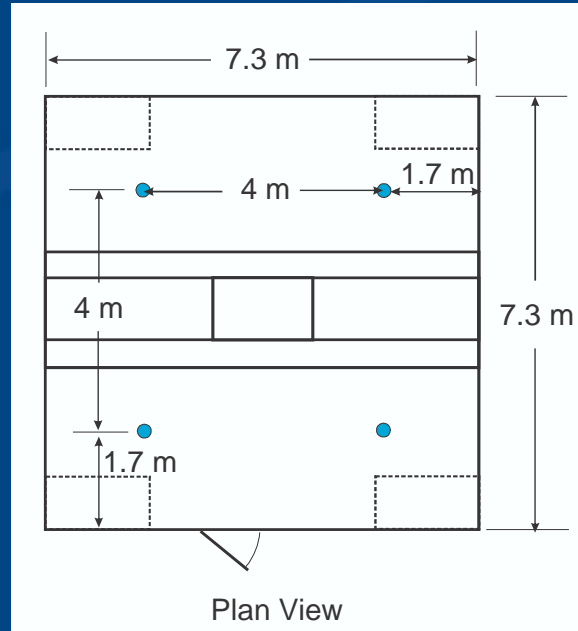
## 1/2-scale



Both heat release rate and time are plotted in the full-scale coordinates.

# Full-Scale Water Mist Protection

- **Four ceiling nozzles: 4 x 4 m spacing**



- **Nozzle elevation: 0.25 m below ceiling**
- **Each nozzle consists of 6 identical orifices**
- **Total K-factor: 0.72 lpm/bar<sup>1/2</sup>**
- **Operating pressure: 100 bar**
- **Median droplet diameter: 79  $\mu\text{m}$**



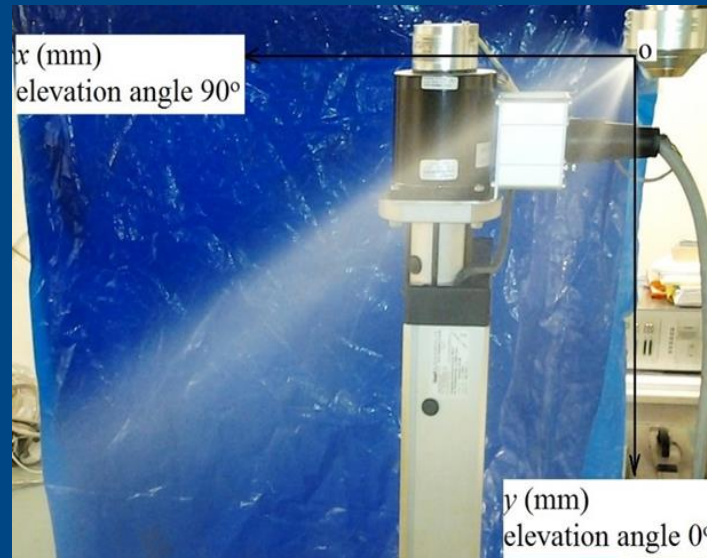
# 1/2-Scale Nozzle

**Use a 1/2-scale nozzle with orifices geometrically similar to those of the full-scale nozzle.**

- Does not need additional R&D to develop
- Automatically meets the scaling requirement for discharge rate  $\sim S^{5/2}$
- $d \sim S^{1/3} \rightarrow$  only 6% less than the ideal  $d_{v50}$ .

# Orifice Spray Measurements

- Orifice K-factor: 0.12 lpm/bar<sup>1/2</sup>, full scale  
0.03 lpm/bar<sup>1/2</sup>, 1/2-scale (~S<sup>2</sup>)
- Operating pressure for measurements: 96 bar full scale  
48 bar 1/2-scale (~S)
- Distance from orifice: 914 mm full scale  
457 mm 1/2-scale (~S)

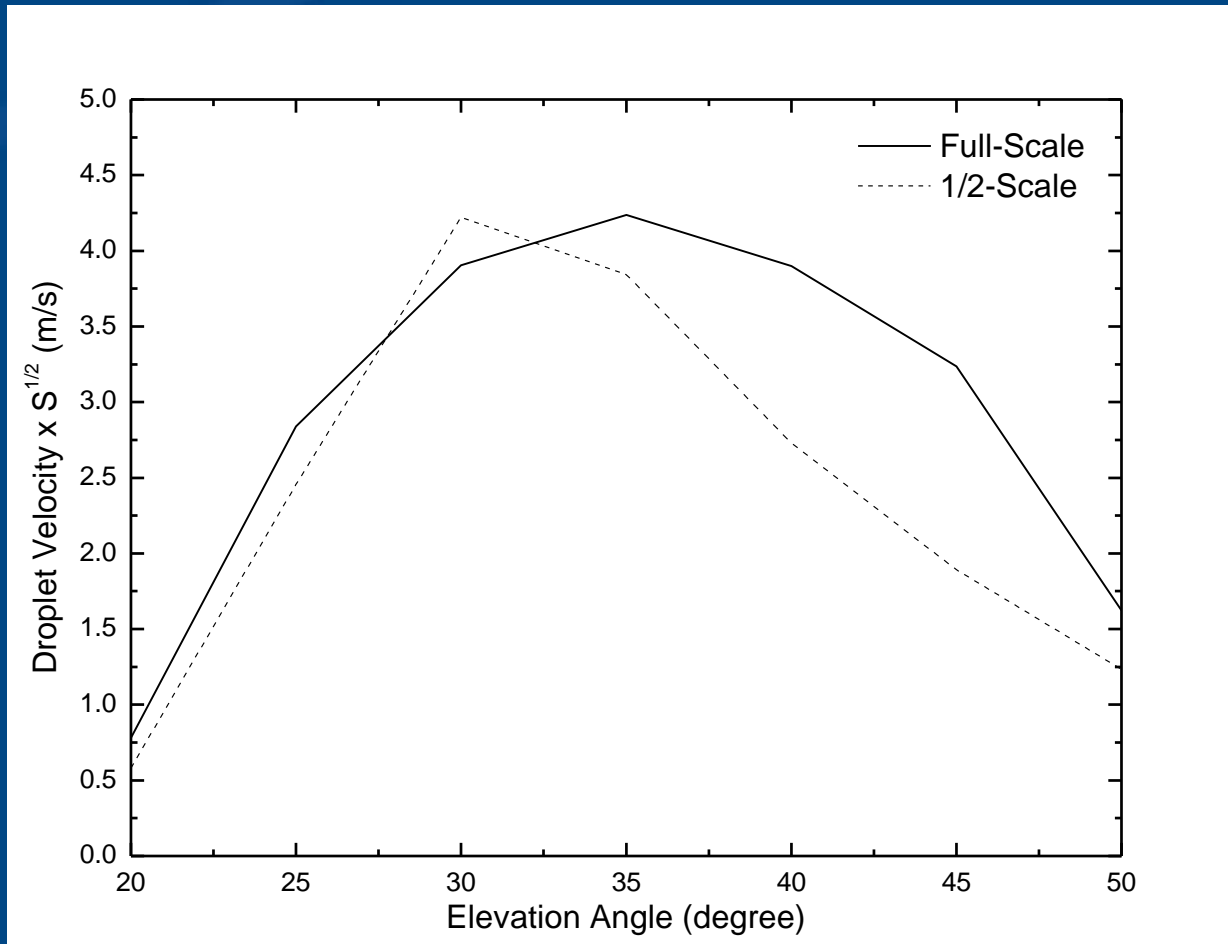




# Full-Scale and 1/2-Scale Volume-flux-weighted Droplet Velocity Distributions



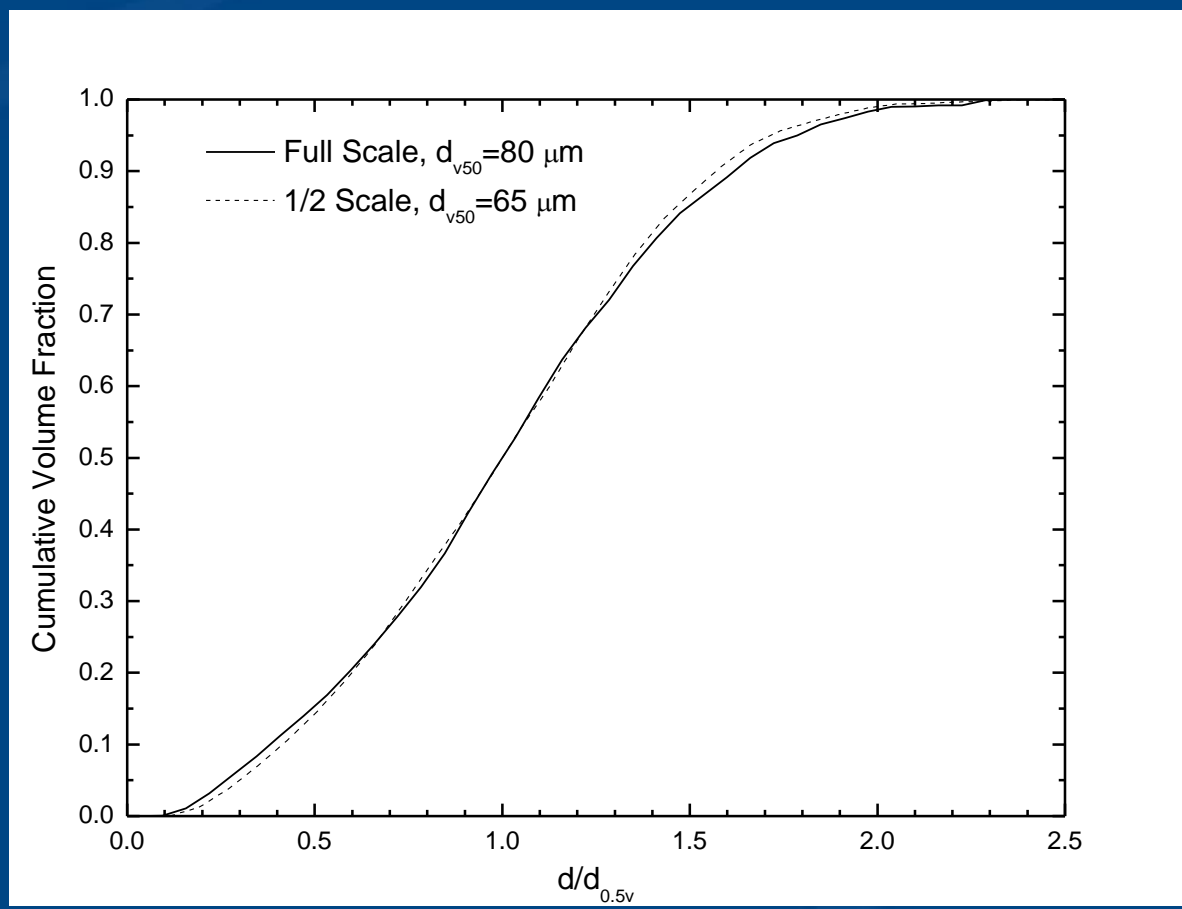
**Full scale: 96 bar, 914 mm from orifice**  
**1/2-scale: 48 bar, 457 mm from orifice**



# Full-Scale and 1/2-Scale Gross Droplet Size Distribution

Full-scale: 96 bar,  $d_{0.5V} = 80 \mu\text{m}$

1/2 scale: 48 bar,  $d_{0.5V} = 65 \mu\text{m}$  (vs.  $67 \mu\text{m}$  for the ideal size)



# Complete Full-Scale and 1/2-Scale Sprays

**Full Scale at 100 bar**

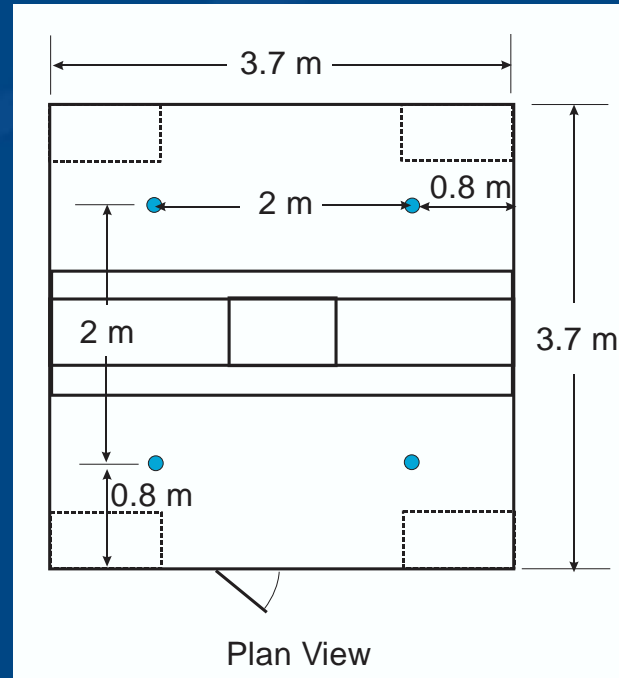


**1/2-Scale at 50 bar**



# 1/2-Scale Water Mist Protection

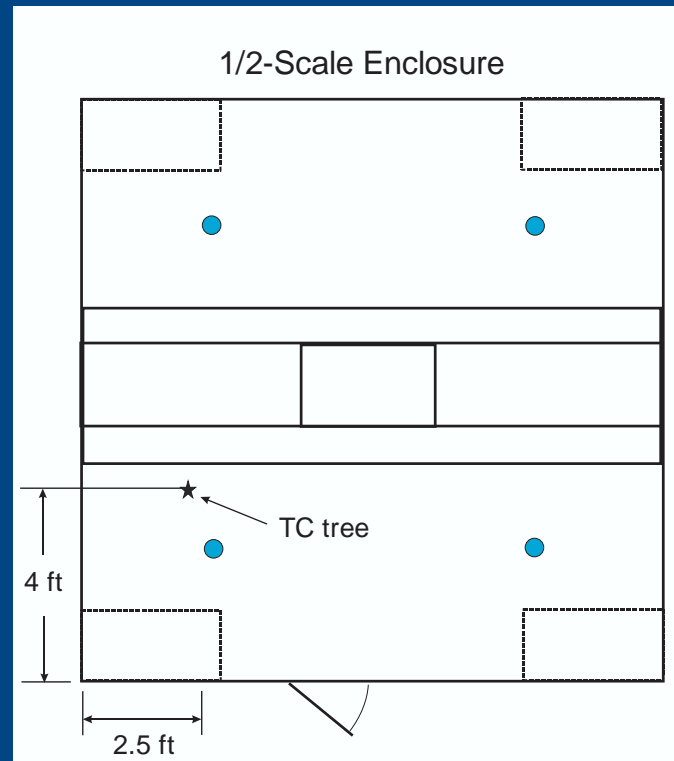
- **Four ceiling nozzles: 2 x 2 m spacing (4 x 4 m full-scale)**



- **Nozzle elevation: 0.13 m below ceiling (0.25 m full-scale)**
- **Each nozzle consists of 6 identical orifices**
- **Total K-factor: 0.18 lpm/bar<sup>1/2</sup> (0.72 lpm/bar<sup>1/2</sup>)**
- **Operating pressure: 50 bar (100 bar full-scale)**

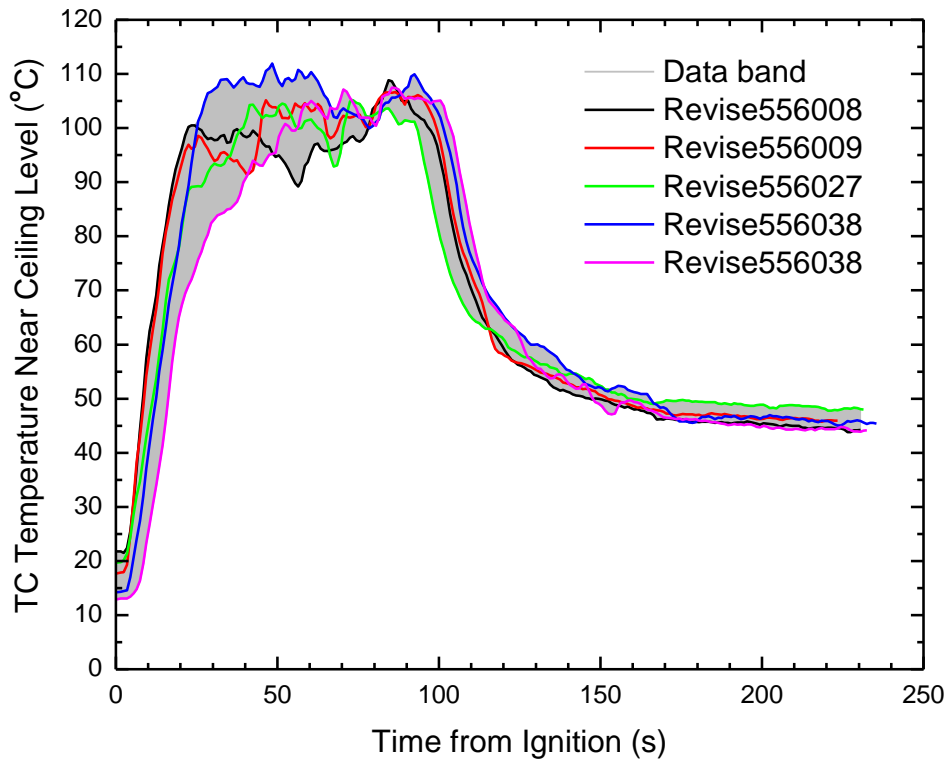
# Key Measurements

- Oxygen concentration
- Flame temperature
- Gas temperature at 1/3 and 2/3 of ceiling height, and near ceiling level



# Fire Tests

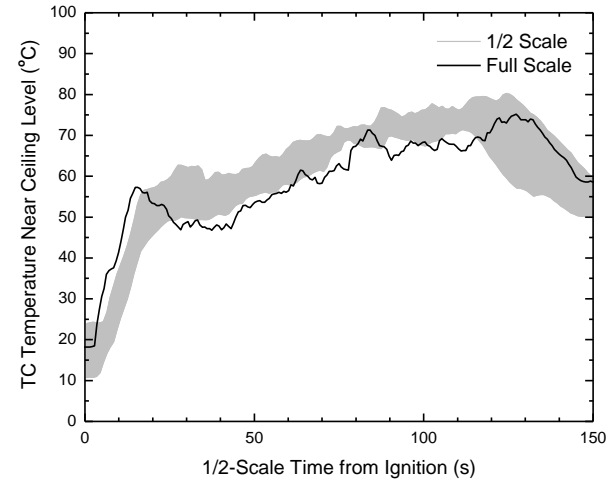
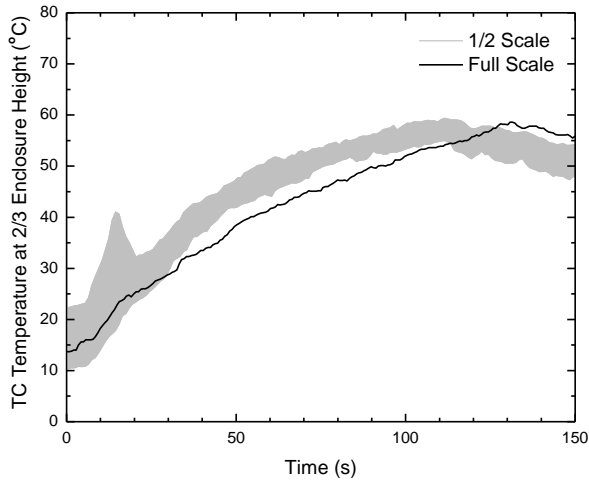
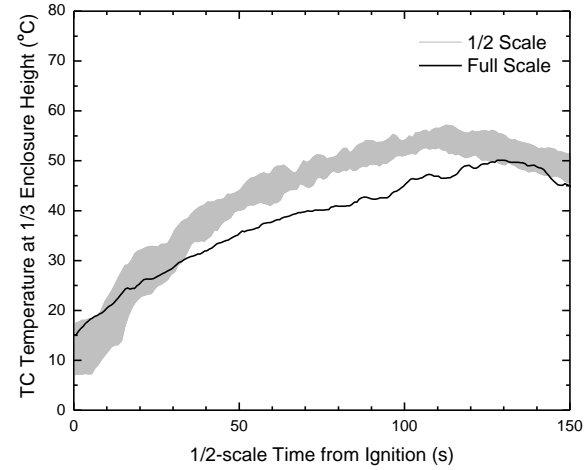
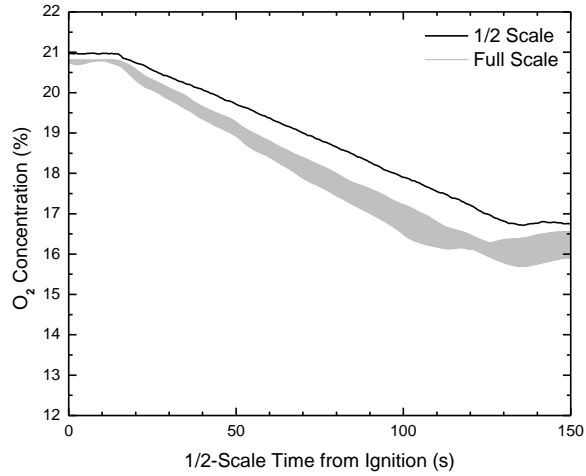
- Full scale: one test per fire scenario
- 1/2 scale: five tests for Scenarios C4.6 – C4.9, six tests for Scenario C4.10



# Scenario C4.7 – Shielded 1-MW Spray Fire

Conditions	Full Scale	Half Scale
Full or Half Enclosure	Full enclosure	Full enclosure
Spray Fire Orientation	Horizontal	Horizontal
Fuel Nozzle	Monarch F80, PLP, No. 24	Monarch F80, PLP, No. 5.5
Nozzle Location (~S)	Centered 0.5 m below the mockup table	Centered 0.25 m below the mockup table
Heptane Discharge Rate (~S <sup>2.5</sup> )	24.1 g/s (990 kW)	4.3 g/s (180 kW)
Access Door Opening (~S)	0.4 x 2 m door opening; closed	0.2 x 1 m door opening; closed
Preburn Time (~S <sup>1/2</sup> )	15 s	11 s
Heptane Spray Duration after Extinguishment (~S <sup>1/2</sup> )	15 s	11 s

# Scenario C4.7 – Shielded 1-MW Spray Fire





# Scenario C4.7 – Shielded 1-MW Spray Fire

Fire extinguishment time after ignition  
 observed in full-scale test: 181 s  
 → 128 s in the equivalent 1/2-scale time scale

## 1/2-Scale Tests

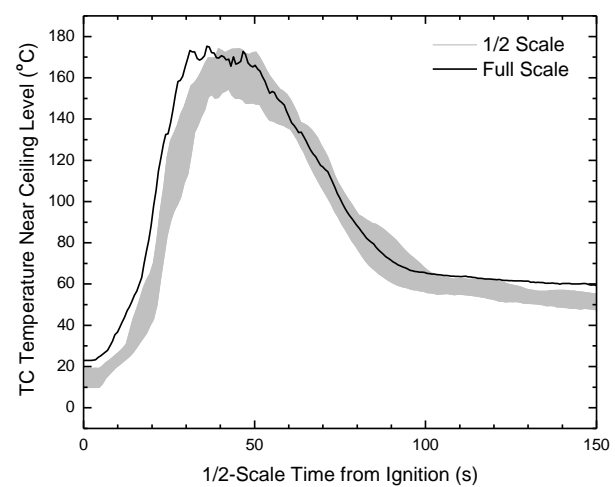
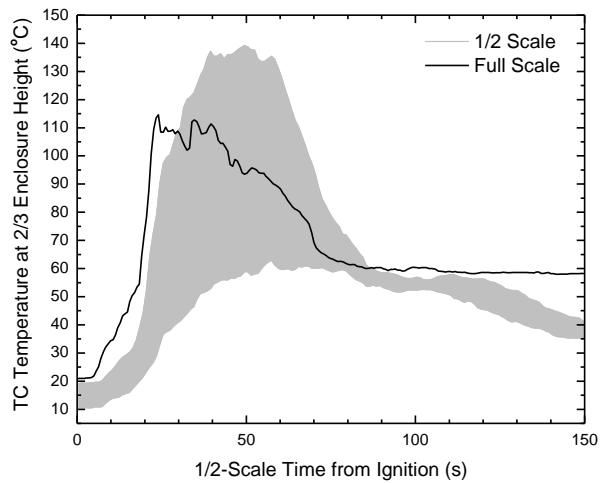
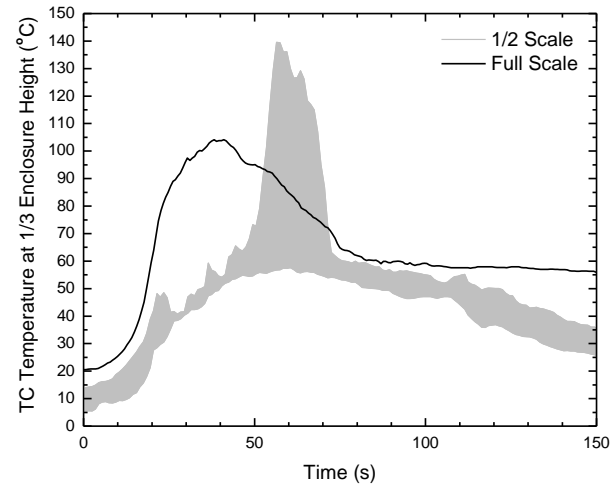
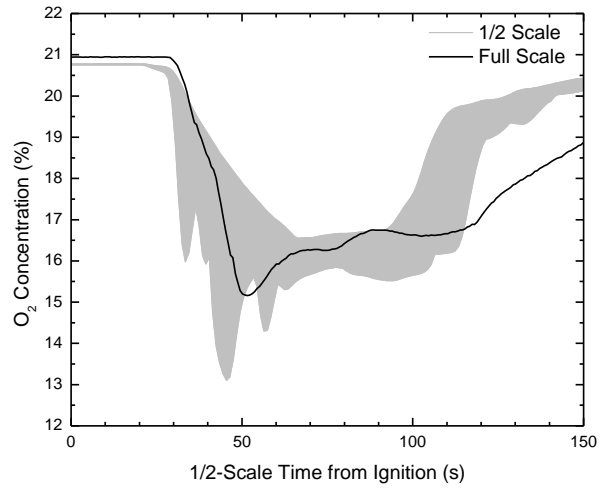
Test ID	Visual Observation	O <sub>2</sub> Concentration	Flame Temperature
Revise556006	125 s	134 s	122 s
Revise556028	114 s	110 s	118 s
Revise556035	152 s	118 s	129 s
Revise556036	130 s	134 s	142 s
Revise556037	126 s	131 s	138 s
mean	129±18* s	125±14* s	130±13* s

\*95% confidence interval with statistical t-distribution.

# Scenario C4.8 – Shielded 1-m<sup>2</sup> Pool Fire

Conditions	Full Scale	Half Scale
Full or Half Enclosure	Full enclosure	Full enclosure
Steel Pan Dimension	1 m x 1 m x 10 cm (3000 kW max.)	0.55 m x 0.55 m x 5 cm (550 kW max.)
Pool Composition	2 cm heptane on 5 cm water	1.5 cm on 2 cm water
Pool Location	Centered below the mockup table and on the floor	Centered below the mockup table and on the floor
Access Door Opening (~S)	0.4 x 2 m door opening; closed	0.2 x 1 m door opening; closed
Preburn Time (~S <sup>1/2</sup> )	30 s	21 s

# Scenario C4.8 – Shielded 1-m<sup>2</sup> Pool Fire



# Scenario C4.8 – Shielded 1-m<sup>2</sup> Pool Fire

Fire extinguishment time after ignition  
 observed in full-scale test: 106 s  
 → 75 s in the equivalent 1/2-scale time scale

## 1/2-Scale Tests

Test ID	Visual Observation	O <sub>2</sub> Concentration	Flame Temperature
Revise556045	84 s	88 s	79 s
Revise556046	80 s	77 s	86 s
Revise556049	67 s	63 s	63 s
Revise556053	84 s	87 s	90 s
Revise556055	85 s	82 s	88 s
Mean*	80±10* s	79±13* s	81±14* s

\*95% confidence interval with statistical t-distribution.

# Summary of Fire Extinguishment Times

Fire Scenario	½ Scale			Full Scale
	Visual Observation <sup>#</sup>	Oxygen Concentration <sup>#</sup>	Flame Temperature <sup>#</sup>	
C4.6	111±3 s	112±5 s	108±6 s	88 s (124 s)*
C4.7	129±17 s	125±13 s	130±13 s	128 s (181 s)*
C4.8	80±9 s	79±13 s	81±14 s	75 s (106 s)*
C4.9	98±6 s	113±7 s	100±5 s	98 s (138 s)*
C4.10	58±4 s	56±4 s	58±5 s	66 s (94 s)*

\*Observed times after ignition in the full-scale tests.

#Expected 95% confidence interval with t-distribution.

# Implementation into FM Approvals 5560

- The physical scaling approach is being implemented in the FM Approval Standard 5560 as an alternative for the evaluation of water mist protection of machinery enclosures, and other similar occupancies.
- Approval process:
  - Manufacturer applies for system approval with parameters for full-scale protection.
  - Manufacturer submits full-scale nozzle and geometrically similar 1/2-scale nozzle samples to FM Approvals.
  - FM Approvals conducts dimension measurements to ensure that all the 1/2-scale nozzle samples to be used for fire tests are geometrically similar to the full-scale nozzle with a designated precision requirement.
  - FM Approvals conducts tests for all the fire scenarios with the verified 1/2-scale nozzles in the 1/2-scale test enclosure to demonstrate that the fire can be extinguished for all the fire scenarios.
  - Approval is granted for full-scale protection by scaling up the 1/2-scale test results according to the scaling relationships. The required system water supply and discharge duration are assessed based on the highest water mist discharge rate and the longest fire extinguishment time determined in the 1/2-scale tests.

# Acknowledgment

- **Ultra Fog AB**
- **Jonathan Carpenter, FM Approvals**

Questions?