Case study

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Physical scaling of water mist protection for ignitable liquid cut-off rooms

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Abstract

Based on the Froude-modeling scaling approach, water mist protection for a $7.47 \times 7.47 \times 7.47$-m cut-off room where ignitable liquids are used was projected from the previously determined extinguishing requirement for heptane pool fires in a ½-scale enclosure and then verified with full-scale testing. The full-scale building occupancy was required to accommodate cut-off room door openings ranging from 1.86×3.73 m high up to 3.73×3.73 m. The fire challenge was a heptane spill fire cascading from the top of a 1.83-m dia. by 2.74-m high steel tank at a spill rate of 37.9 L/min. Two off-the-shelf nozzles were selected as candidates for the full-scale building to approximate the scaled-up water mist spray requirement. At a discharge pressure of 90 bar, one nozzle discharged 28 L/min, with a spray angle of 100° and a volume-median droplet dia. of 115 μm; the other discharged 24.4 L/min, with a 180° spray angle and median dia. of 96 μm. Nine nozzles were arranged at the ceiling level in a 3×3 matrix with a spacing of 1.86×1.86 m. Before the two candidate protection schemes were challenged with the spill fire, scaled-up heptane pool fires were used to ensure that the fire extinguishing propensity was consistent with that observed in the ½-scale enclosure. The pool fire tests showed that the nozzle with the smaller spray angle provided better fire extinguishing performance, which was later confirmed in the spill fire tests. The protection scheme with the smaller spray angle could extinguish the spill fire for door openings up to 3.05×3.05 m. For larger openings, two additional downward water mist sprays were required in the door opening to expedite fire extinguishment by reducing ventilation through the door opening. Water mist protection could provide adequate cooling to fuel tanks as long as such protection could extinguish the fire. Overall, the investigation demonstrated that physical scaling is a useful tool to provide an engineering estimate of water mist protection requirements.

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Introduction

Cut-off rooms used for ignitable liquid (also known as flammable or combustible liquid) operations in general can be grouped into two categories: use occupancy and storage occupancy. The former includes everything from small drum dispensing rooms to large distribution/dispensing facilities where ignitable liquids are stored in large holding tanks. Figure 1 shows an example of a large holding tank located in an ignitable liquid distribution facility. The latter refers mainly to storage facilities for ignitable liquids in portable containers arranged in different storage configurations. Because of the potentially severe fire hazard, both the use and storage occupancies are typically separated from the main building with fire walls if they are located in an enclosure connecting to the building, or simply housed in separate buildings dedicated to such operations.

Depending on their volatility, water miscibility, handling, processing and storage arrangement, ignitable liquid fires have been protected with varying degrees of effectiveness by automatic fire sprinklers, water sprays, water mist, aqueous film forming foams (AFFF), dry chemicals, carbon dioxide (CO_2) or some combinations of the above agents or protections [1,2].

Figure 1. An example of a large holding tank located in an ignitable liquid distribution facility.

AFFF is good for preventing re-ignition of surface fires but may require clean-up after discharge and may have negative environmental impact. The common concern about dry chemicals and CO_2 is re-ignition after the agent is expended. The other drawbacks of dry chemicals are their corrosion propensity and the need for clean-up after discharge. Although carbon dioxide has little environmental implications, and does not leave residues to clean up, it is usually not effective in extinguishing ventilated fires. Life safety is also a big concern when CO_2 is used, due to the asphyxiation caused by the high concentrations required for fire extinguishment. As such, the 2008 edition of NFPA 12, "Standard on Carbon Dioxide Extinguishing Systems", began to disallow new installations of total flooding carbon dioxide systems for normally occupied enclosures except for specified exceptions [3].

When sprinkler or water spray protection is used, the required water density is usually high and the water discharge duration is typically 60 min or longer [4,5]. The large volume of contaminated sprinkler water needs to be contained and processed to meet environmental regulations. Therefore, an investigation was initiated at FM Global to explore whether the use occupancy fire could be extinguished by water mist with a smaller volume of water.

The development of water mist protection in the last 20 years has expanded to buildings up to 4500 m^3 with openings up to 4 m^2. For such building conditions, these studies have shown that water mist is more effective than sprinkler and water spray protection to extinguish ignitable liquid fires. However, the use occupancy typically has access doors larger than 4 m^2, which could potentially cause large ventilation through the door opening. These access doors are usually open during operation and are required to remain open for egress after the fire protection system is activated. This article shows how the Froude-modeling-based physical scaling approach can be applied to develop water mist protection for a $7.47 \times 7.47 \times 7.47$-m use occupancy cut-off room with a door opening ranging from 1.86×3.73 m high to 3.73×3.73 m, based on a fire extinguishment requirement previously determined for a ½-scale enclosure.

Physical scaling relationships

The Froude-modeling-based scaling relationships are used in the present investigation [6]. The Froude number is defined as

$$Fr = \frac{\rho_g u_g^2}{gL(\rho_\infty - \rho_g)}, \tag{1}$$

where ρ_g and ρ_∞ are fire gas density and ambient air density, respectively, g is gravitational acceleration, L is the characteristic dimension of the enclosure and u_g is the magnitude of the gas velocity vector $\vec{u}_g$.

The principles of Froude modeling are to conserve: (1) the Froude number of gas flow at different physical scales; (2) momentum transfer characteristics between water droplets and the surrounding gas medium; (3) droplet vaporization characteristics and (4) scalar properties, such as temperature and concentrations, in the control volume.

Based on the above principles, general scaling relationships for fire suppression by water sprays have been developed as a function of droplet Reynolds number [7]. The droplet Reynolds number is defined as

$$Re_d = \frac{d\left|\vec{u}_d - \vec{u}_g\right|}{\nu_g}, \tag{2}$$

where d and $\vec{u}_d$ are the droplet diameter and droplet velocity vector, and ν_g is the gas kinematic viscosity.

While the water droplets of sprinkler sprays are more capable of retaining their momentum, water mist transfers its momentum to the gas medium quickly after discharge. As a result, water mist tends to move closely with gas currents, resulting in the condition of low droplet Reynolds numbers. Table 1 provides the general scaling relationships applicable in any droplet Reynolds number regime, and the relationships specifically for the conditions of $Re_d \leq 1$, i.e. typical for water mist applications, and $10 < Re_d \leq 500$, i.e. typically for sprinkler applications. Under $Re_d \leq 1$ conditions, the droplet drag coefficient is proportional to Re_d^{-1}, while proportional to $Re_d^{-1/2}$ for $10 < Re_d \leq 500$. Consequently, the specific scaling relationships for the conditions of $Re_d \leq 1$ and $10 < Re_d \leq 500$ can be obtained by substituting 1 and ½ for the power index x in the general expressions shown in

Table 1. Scaling relationships.

Scaling parameters	$Re_d \leq 1$	$10 < Re_d \leq 500$	Any Re_d
Drag coefficient	$\propto Re_d^{-1}$	$\propto Re_d^{-1/2}$	$\propto Re_d^{-x}$
Scale ratio	S	S	S
Time	$S^{1/2}$	$S^{1/2}$	$S^{1/2}$
Pressure	S^1	S^1	S^1
All scalar parameters except droplet number density	S^0	S^0	S^0
Drop number density	$S^{-3/4}$	$S^{-3/2}$	$S^{(3x-6)/(2+2x)}$
Velocity	$S^{1/2}$	$S^{1/2}$	$S^{1/2}$
Ventilation rate	$S^{5/2}$	$S^{5/2}$	$S^{5/2}$
Fire convective heat release rate	$S^{5/2}$	$S^{5/2}$	$S^{5/2}$
Total water discharge rate	$S^{5/2}$	$S^{5/2}$	$S^{5/2}$
Water flux	$S^{1/2}$	$S^{1/2}$	$S^{1/2}$
Total cooling rate	$S^{5/2}$	$S^{5/2}$	$S^{5/2}$
Droplet size	$S^{1/4}$	$S^{1/2}$	$S^{(2-x)/(2+2x)}$

the table. The scaling relationships for $10 < Re_d \leq 500$ reproduce those originally proposed by Heskestad for sprinkler applications [7]. As shown, all of the scaling relationships are identical for different Reynolds number regimes, except for droplet number density and droplet size.

The applicability of the above scaling relationships has been demonstrated for water mist cooling of methane and propylene fires in an open space under the condition of $Re_d \leq 1$ [6] and for the extinguishment of methane and heptane pool fires in an open space under the condition of $10 < Re_d \leq 500$ [8,9]. Furthermore, [10] and [11] show that the suppression and extinguishment of propane fires and heptane pool fires in enclosures can also be scaled for water mist applications.

Full-scale fire scenario

The objective was to develop water mist protection for a targeted $7.47 \times 7.47 \times 7.47$-m use occupancy cut-off room. The volatility of the liquids to be handled in the cut-off room was up to that of heptane, i.e., with flashpoints not lower than the typical heptane flashpoint of –4°C. The cut-off room had a large garage door on the front wall and large storage steel tanks located along the back wall. Each tank measured 1.83 m dia. by 2.74 m high and was raised 0.91 m above the floor by steel footings. The tanks were surrounded by a steel grating platform, which was 3.05 m above the floor and had uniformly distributed openings comprising about 70% of the platform area. To contain the liquid spill, each tank was positioned in a 3.1×3.1-m dike. The fire scenario was a cascading heptane fire originating from the top of one of the tanks at a spill rate of 37.9 L/min. It was estimated that the spill fire could produce a heat release rate up to 8 MW.

The protection goal was to (1) extinguish the spill fire for door openings ranging from 1.86×3.73 m high to 3.73×3.73 m high and (2) provide adequate cooling of the steel tanks to maintain their structure integrity.

Fire extinguishment experiments conducted in a ½-scale enclosure

In a previous study on the scaling of suppression and extinguishment of pool fires by water mist in enclosures, experiments were conducted with heptane fires in a $3.66 \times 3.66 \times 3.66$-m, steel-framed enclosure [11]. This enclosure, to be referred to henceforth as the ½-scale enclosure, had a scale ratio of 0.49 relative to the full-scale building. With the ½-scale enclosure, the experiments were conducted with an opening centered on the front wall for two opening dimensions: 0.91×1.83 m high and 1.83×1.83 m. The lower end of the opening was extended to the enclosure floor. These two openings corresponded to the full-scale door openings of 1.86×3.73 m high and 3.73×3.73 m.

The water mist sprays in the ½-scale enclosure were provided with nine nozzles arranged in a 3×3 matrix beneath the ceiling with a spacing of 0.91 m, corresponding to the full-scale nozzle spacing of 1.86 m. At a discharge pressure of 43.7 bar, each nozzle discharged 2.86 L/min, with a volume-median droplet diameter of 88 μm and a spray angle of about 60°.

Two heptane pool fires were used in the ½-scale experiments, producing free-burn heat release rates of 380 and 860 kW, which corresponded to the fire heat release rates of 2.3 and 5.1 MW, respectively, in the full-scale building.

Some of the ½-scale experiments were conducted by locating the pool fire close to the back wall, similar to the fuel tank positioning in the full-scale building. The liquid pool was centered in a semi-open metal shield to obstruct direct impingement of water mist sprays on the fire. The shield consisted of a horizontal top cover welded to two opposite vertical plates. The shield's top cover and each of its two side plates measured 1.22 × 1.22 m and 1.22 × 1.83 m high, respectively. To evaluate the impact of air flow pattern from the door opening to the fire on extinguishment, two shield orientations were evaluated in the experiments. The first orientation aligned the two shield openings to the door opening; the second orientation rotated the shield by 90° so that the shield's vertical plates were aligned to the door opening to block the direct air flow to the fire.

These experiments showed that both pool fires, when located near the back wall, could be extinguished with both shield orientations for the smaller opening of 0.91 × 1.83-m high. For the larger opening of 1.83 × 1.83 m, only the 380-kW fire was tested in [12]. The tests with the larger opening showed that the 380-kW fire could not be extinguished when the shield openings were facing the enclosure opening but could be extinguished when the shield's vertical plates were facing the enclosure opening. This indicated that the fire could be extinguished with the larger opening if the ambient air flow to the fire could be somehow blocked or reduced.

It is well known that larger fires in an enclosure are easier to extinguish due to the fact that larger fires eventually lead to lower oxygen concentrations, due to the higher rates of fire gas production, oxygen depletion and water mist vaporization. Therefore, based on the ½-scale results, it was expected that the scaled-up water mist protection should extinguish the relatively larger heptane spill fire in the full-scale building for the 1.86 × 3.73-m high door opening. On the other hand, for the door opening of 3.73 × 3.73 m, the ventilation at the door opening might need to be interrupted in order to extinguish the spill fire.

Full-scale water mist sprays

Based on the scaling relationships for $Re_d \leq 1$, the full-scale water mist protection can be projected from the ½-scale protection described above, as presented in Table 2.

A survey of the market-available water mist nozzles was subsequently conducted to select nozzles which would provide the volume-median droplet diameter as close to 105 μm as possible at a discharge pressure of 90-bar. The survey led to two candidates: designated as Nozzle A and Nozzle B. Based on the technical data

Table 2. Projected full-scale water mist protection.

Ceiling nozzle layout	Nozzle spacing (m)	Discharge pressure (bar)	Spray angle (°)	Volume-median droplet diameter (μm)	Water mist discharge rate per nozzle (liter/min)
3 × 3	1.86	89.2	60	105	17

Table 3. The spray properties of Nozzles A and B operating at 90 bar.

Nozzle ID	Spray angle (°)	Volume-median droplet size (μm)	Water mist discharge rate per nozzle (liter/min)
A	180	96	24.2
B	100	115	28.2

provided by the manufacturers, the spray properties of these two selected nozzles operating at 90 bar are presented in Table 3.

Comparing the spray properties of Nozzles A and B to the projected requirements shown in Table 2, it is apparent that the greatest discrepancies are the spray angle and the water mist discharge rate. The higher-than-projected water mist discharge rates, afforded by both nozzles at a discharge pressure of 90 bar, provide some degree of protection conservativeness. However, the larger spray angles tend to reduce the downward spray thrust force, and thus the fire plume penetration capability of the water mist sprays. The consequence is that the mixing of gases and water mist tends to be less uniform in the enclosure, especially in the region near the floor, leading to a less favorable fire extinguishing result. The downward thrust force of the discharged spray, as affected by the spray angle, velocity and discharge rate, can be estimated by assuming that the angular distribution of the spray is uniform in the vicinity of the nozzle. With the above assumption, the downward spray thrust force from each nozzle can be expressed with the following equation:

$$\dot{M} = \frac{1}{2}\rho_{\mathrm{w}} v_{\mathrm{d}} \dot{V} \frac{\sin^2 \phi}{1 - \cos \phi}, \tag{3}$$

where ρ_{w}, v_{d}, $\dot{V}$ and ϕ are water density, discharge velocity, volumetric discharge rate and spray half angle.

Assuming that the discharge velocities are comparable among different nozzles, the factors that influence the spray downward thrust force are the spray discharge rate and the spray angle. Based on the pertinent values shown in Tables 2 and 3, the downward spray thrust force from Nozzles A and B is about 0.77 and 1.46 times that of the ideally projected water mist spray. Therefore, it is expected that the

Nozzle A spray, with relatively lower thrust force, has the lower fire plume penetration capability as compared to the ideally projected water mist spray and as compared to the Nozzle B spray, resulting in poorer mixing of water mist and fire gases in the enclosure. Therefore, Nozzle A is expected to not perform as well in terms of fire extinguishment as compared to Nozzle B and any nozzle which provides the ideally projected spray properties.

The full-scale test building and instrumentation

The full-scale building was constructed with 0.4-mm thick galvanized corrugated steel panels on steel frames. A door opening was centered on the north wall with the opening's lower end extending to the floor as in the ½-scale enclosure. The dimensions of the door opening could be varied from 1.86×3.73 m high to 3.73×3.73 m.

The vertical temperature distribution inside the building was measured using a thermocouple tree located near the back corner on the west side of the building. The tree consisted of nine inconel-sheathed, 26-gage, K-type thermocouples, positioned at 0.61, 1.52, 2.44, 3.05, 3.66, 4.27, 4.88, 5.49 and 6.10 m below the ceiling. The thermocouple beads were 0.20 m from the two adjacent walls (i.e. south and west walls). To prevent direct water mist spray impingement on the thermocouple beads, a vertical steel sheet 0.20-m wide was installed 0.10 m in front of the tree, extending from 0.30 m below the ceiling to 0.30 m above the floor.

Water mist protection in the full-scale building

As in the ½-scale enclosure, nine open nozzles of either Nozzle A or Nozzle B were deployed beneath the ceiling in the 3×3 matrix with equal spacing between adjacent nozzles and between nozzles and adjacent walls. As a result, the nozzle-to-nozzle and nozzle-to-wall spacing was 1.86 m.

The water supply to the nozzles was provided by several small high-pressure pumps connected in a parallel manner. A 25-μm filter was used to remove particulates from the in-take water. The total water flow rate to the nine nozzles was measured with an ultrasonic flow meter, and two pressure transducers were used to monitor the nozzle-operating pressure.

Pool fire tests in the full-scale building

Before the protection provided by the two candidate nozzles was tested with the heptane spill fire, several heptane pool fire tests were conducted to evaluate fire extinguishing capability with the 1.86×3.73-m high door opening. The purpose of the pool fire tests was to see if similar fire extinguishment results could be achieved as in the ½-scale enclosure. As described above, in the ½-scale enclosure, a heptane pool fire as small as 380 kW located near the back wall could be extinguished when the opening was 0.91×1.83-m high.

Two heptane pool fires with diameters of 1.24 and 1.42 m were tested separately in the full-scale building, which produced heat release rates of about 2800 and 4100 kW. Based on the scaling law of $S^{5/2}$, these two fire intensities corresponded to 470 kW and 690 kW for the ½-scale enclosure. Both were comparatively greater than the 380-kW fire which was extinguished in the ½-scale enclosure. For the same enclosure size and door opening size, the gas temperature inside the enclosure is expected to increase with the fire size, enhancing the water vapor generation rate. As mentioned earlier, with the higher generation rate of water vapor and fire products, the oxygen concentration inside the enclosure is expected to decrease at a higher rate and eventually reach a lower concentration. Therefore, the two full-scale pool fires should be extinguished relatively more quickly (i.e., by comparing the extinguishing time in the full-scale building divided by $S^{1/2}$ to the extinguishing time in the ½-scale enclosure) in the full-scale building if the water mist protection is not worse than the projected requirement. Each of the heptane pools was contained in a 152-mm high pan made of 3.2-mm thick steel. Before each test, the pan was first filled with a layer of water 51-mm high and then topped with heptane 38 and 51 mm deep. The pre-burn time was about 70 s before water mist discharge in these full-scale pool fire tests.

To replicate the water mist spray obstruction condition in the ½-scale enclosure, the heptane pool was partially shielded from direct water mist sprays using a metal shield which was geometrically similar to that used in the ½-scale enclosure. The scaled-up dimensions of the shield's top cover measured 2.49×2.49 m, and the two opposite vertical plates each measured 2.49×3.73 m high. To examine the effect of shield orientation on fire extinguishment as performed in the ½-scale enclosure, the tests were conducted with shield openings aligned to the door opening and rotated 90° so that the two opposite plates of the shield were aligned to the door opening.

Table 4 below presents the pool fire test results in the full-scale building with the 1.86×3.73-m high door opening. As shown in the Table, Nozzle B extinguished pool fires for both shield orientations, as expected from the ½-scale results. For Nozzle A, although both pool fires were extinguished when the shield plates faced the door opening, the fires were not extinguished when the shield openings faced

Table 4. The pool fire test results in the full-scale building with the 1.86×3.73-m high door opening.

	Nozzle A		Nozzle B	
Fire size (kW)	Shield openings facing the door opening	Shield plates facing the door opening	Shield openings facing the door opening	Shield plates facing the door opening
2800	Not extinguished	Extinguished	Extinguished	Extinguished
4100	Not extinguished	Extinguished	Extinguished	Extinguished

the door opening. The above pool fire results confirmed that Nozzle A was the poorer performer between the two candidate nozzles.

Although Nozzle A discharged about 1.4 times that of the projected rate, its fire extinguishing performance was still not favorable. As discussed above, Nozzle A's downward spray thrust force was only 0.77 times the projection from the ½-scale spray. The result demonstrated that, besides a sufficient water mist discharge rate and an adequate droplet size, effective water mist protection also requires a sufficient spray thrust force to break down the thermal stratification to promote uniform mixing inside the building. Figure 2 shows the vertical distribution of thermocouple temperatures when either Nozzle A or Nozzle B was tested with the 4100-kW fire. As shown, the stratification was indeed more pronounced when the test was conducted with Nozzle A.

Use occupancy fire scenario full-scale mockups

Each fuel tank of 1.83 m in diameter by 2.74 m high was made of 4.0-mm thick steel. Four evenly spaced, 102 × 102 × 6.4-mm steel-angle footings were welded to each tank in order to raise the tank 0.91 m above the floor. The inside of the tank was left empty to simulate the worst thermal condition of the tank. The heptane spill from the top of the tank was provided with a schedule-40, 25-mm vertical pipe passing vertically through the center of the tank. The heptane outlet above the tank was augmented by connecting a schedule-40, 51-mm pipe to the 25-mm pipe to provide a gentle heptane release at the outlet. All the heptane supply lines exposed to the thermal environment in the enclosure were insulated. Figure 3 shows a schematic of the tank mockup. An identical 2nd tank was placed 0.91 m from the spill tank to evaluate whether the water mist protection could provide sufficient cooling of storage tanks adjacent to the tank on fire. Tests were also conducted with the 2nd tank as the spill tank, and the 1st tank as the exposure tank. The liquid spill containment on the floor was simulated with a 3.05 × 3.05-m steel pan of 102-mm height placed under the spill tank as shown in Figure 4.

A grated steel platform of about 70% opening, spanning from the enclosure's one-side wall to the opposite side wall, and extending from the back wall midway towards the front wall, was installed 3.05 m above the floor. The platform was made of rectangular steel members of 6.4 mm wide by 25 mm high. The openings between the rectangular steel members were about 24 × 83 mm. Figure 5 shows a plan view of the layout of the ceiling nozzles, two tank mockups and platform in the enclosure.

At each of the elevations of 0.15 m above and 0.15 m below the spill tank, two inconel-sheathed, 20-gage thermocouples were positioned to detect fire extinguishment: one at the tank centerline and the other 0.61 m from the centerline. To determine whether the water mist protection could provide sufficient cooling of the tanks, inconel-sheathed 20-gage K-type thermocouples were installed at mid-height in the footings of the tanks: two for the tank near the building corner and

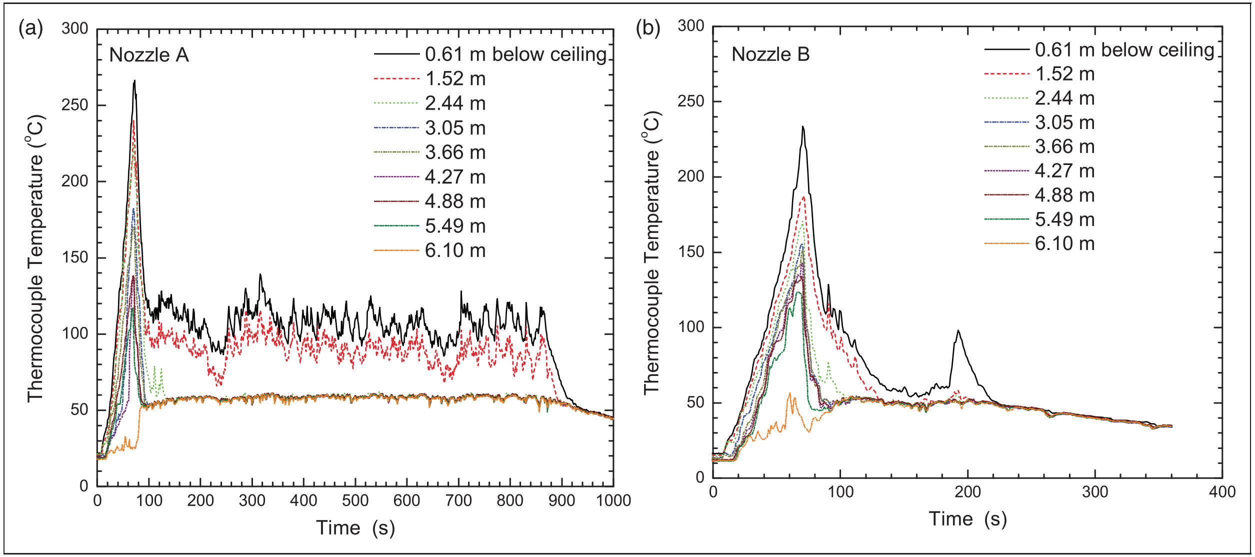

Figure 2. Vertical distributions of thermocouple temperatures inside the enclosure near the right back corner when the 4100-KW pool fire was tested in the full-scale building.

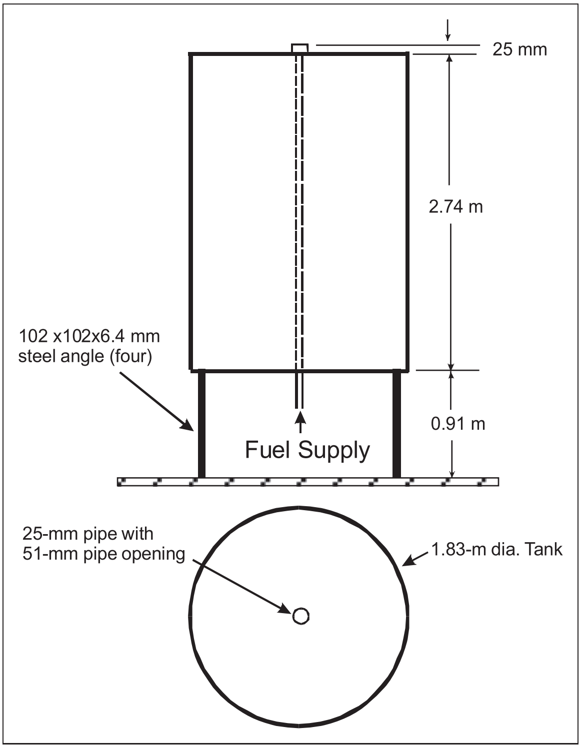

Figure 3. A schematic of the ignitable liquid storage tank mockup.

Figure 4. A photographic view of the tank mockup arrangement in the enclosure.

four for the tank nearer to the floor center. The thermocouple beads were embedded in the footings at a depth of about 3 mm from the footing surface. The inside surface temperatures of the tanks were measured along the tank wall areas at the shortest distance between these two tanks. In each tank, the inside

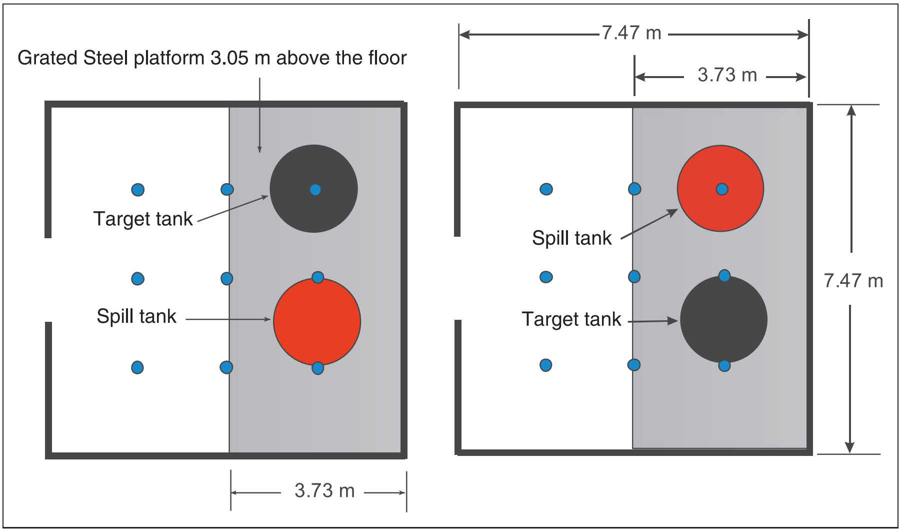

Figure 5. The layout of ceiling nozzles, storage tanks and grated steel platform in the full-scale building.

surface temperatures were measured at one-third (0.91 m), one-half (1.37 m) and two-third (1.83 m) tank heights from the top of the tank.

Each full-scale use occupancy test was started by initiating the heptane spill at the top center of one of the two tanks. As soon as the heptane spill reached about one-third tank height from the top of the tank, the heptane was ignited with a propane torch. The cascading fire on the tank wall and the pool fire below the tank were then allowed to burn freely for 60 s before water mist discharge. A test was terminated after the fire was extinguished or deemed not extinguishable.

Full-scale test results for the use occupancy where ignitable liquids are used

Fire extinguishment

The use occupancy tests were conducted by progressively increasing the door opening from 1.86 × 3.73 m high to 3.73 × 3.73 m, for the two fire locations as shown in Figure 5. As discussed above, the ½-scale tests conducted with the 1.83 × 1.83 m opening (i.e. corresponding to the 3.73 × 3.73-m opening for the full-scale building) indicated that, in order to extinguish the fire in the full-scale building for the larger door openings in the above range, the ventilation through the door opening might need to be restricted. Indeed, for door openings larger than 3.05 × 3.05 m, the tests showed that neither Nozzle A nor Nozzle B could extinguish the fire without the interruption of door ventilation. To restrict the ventilation through door openings of 3.05 × 3.05 m and larger, two B nozzles were installed symmetrically above the door opening. These two door nozzles were oriented downward, with the nozzle tips positioned 0.15 m above the door and 0.20 m behind the front wall. The distance between these two nozzles was half the door opening width, i.e. 1.52 m for the 3.05-m wide opening and 1.86 m for the 3.73-m wide opening. It was observed that the two door nozzles discharging at a pressure of 90 bar provided a steady spray curtain in the door opening for the tested spill fire. When the door nozzles were deployed, the less-effective Nozzle A was used as the ceiling nozzle. The rationale was that if the fire could be extinguished with Nozzle A as the ceiling nozzle, the fire should also be extinguished with Nozzle B.

Table 5 presents the fire extinguishment results obtained from the spill fire scenario. For door openings ranging from 1.86 × 3.73 m high to 3.05 × 3.05 m and with no door nozzle deployment, Nozzle A could extinguish the fire located near the floor center but could not extinguish the fire near the building corner. On the other hand, Nozzle B could extinguish the fire at both the fire locations for door openings up to 3.05 × 3.05 m. Again, the above results reaffirmed that Nozzle B was indeed a better performer as compared to Nozzle A. When the door nozzles were deployed above the door openings of 3.05 × 3.05 m and 3.73 × 3.73 m, the tests were conducted only with the fire located near the building corner, considering the fact that this fire location was more challenging when Nozzle A was used as the ceiling nozzle. The tests showed that the fire could be extinguished within 15 s after the

Table 5. Full-scale use occupancy test results.

		Nozzle configuration		
Door opening (m × m high)	Fire location	Nine A nozzles at ceiling level only	Nine B nozzles at ceiling level only	Nine A nozzles at ceiling level plus two B nozzles above door opening
1.86 × 3.73	Near floor center	Yes	Yes	–
	Near building corner	No	Yes	–
2.44 × 3.05	Near floor center	Yes	Yes	–
	Near building corner	No	–	–
3.05 × 2.74	Near floor center	–	–	–
	Near building corner	No	–	–
3.05 × 3.05	Near floor center	Yes	Yes	–
	Near building corner	No	Yes	Yes
3.73 × 3.73	Near floor center	–	–	–
	Near building corner	–	–	Yes

start of water mist discharge for the 3.05×3.05-m opening, and within 90 s for the 3.73×3.73-m opening. Based on the above test results, the protection for a $7.47 \times 7.47 \times 7.47$-m use occupancy cut-off room is summarized as follows: (1) when Nozzle B is used as the ceiling nozzle, the building can be protected for door openings ranging from 1.86×3.73 m high to 3.05×3.05 m without the need of the door nozzle deployment; (2) For door openings larger than 3.05×3.05 m and up to 3.73×3.73 m, the door nozzles are required, while either Nozzle A or Nozzle B can be used as the ceiling nozzle.

Fuel tank temperature

As mentioned above, one of the protection objectives is to provide sufficient cooling of the fuel tanks so that the fire damage is limited locally. The structural integrity of the fuel tank under fire exposure can be determined by its temperature based on the fact that steel strength weakens as temperature increases. The 2007 ASME Boiler & Pressure Vessel Code sets 538°C as the maximum temperature limit for pressure vessels constructed with ferrous materials [12].

The tests conducted in this investigation showed that adequate cooling of fuel tanks was provided by the water mist protection as long as the fire was extinguished. For instance, Figure 6 shows the footing temperatures (top two plots) and inside tank surface temperatures (bottom two plots) of the spill tank (plots on the left) and target tank (plots on the right) when the fire was located near the building corner, Nozzle B was used as the ceiling nozzle, and the door opening was 3.05×3.05 m. Figure 7 shows similar temperature measurements under the same conditions except that the fire was located near the floor center. As shown, both the footing and inside tank surface temperatures were well below the limit of 538°C for both fire locations.

Figure 8 shows the footing and inside tank temperatures measured when both ceiling nozzles and door nozzles were deployed, with the following test conditions: (1) Nozzle A was used as the ceiling nozzle; (2) Nozzle B was deployed as the door nozzle; (3) the fire was near the building corner and (4) the door opening was 3.73×3.73 m. As shown, the measured temperatures also were all well below the 538°C limit for both the spill and target tanks.

Summary and conclusions

Based on the results obtained in this investigation, a $7.47 \times 7.47 \times 7.47$-m use occupancy cut-off room can be adequately protected with nine B nozzles installed at the ceiling level operating at a discharge pressure of 90 bar, for a door opening up to 3.05×3.05 m, without the need of door nozzles to reduce the ventilation through the door opening. The ceiling nozzles are arranged in a 3×3 matrix, with a spacing of 1.86×1.86 m. For larger door openings up to 3.73×3.73 m, the cut-off room can be protected with Nozzle A or Nozzle B as the ceiling nozzle, and two B nozzles symmetrically positioned above the door opening, all operating at 90 bar. The two

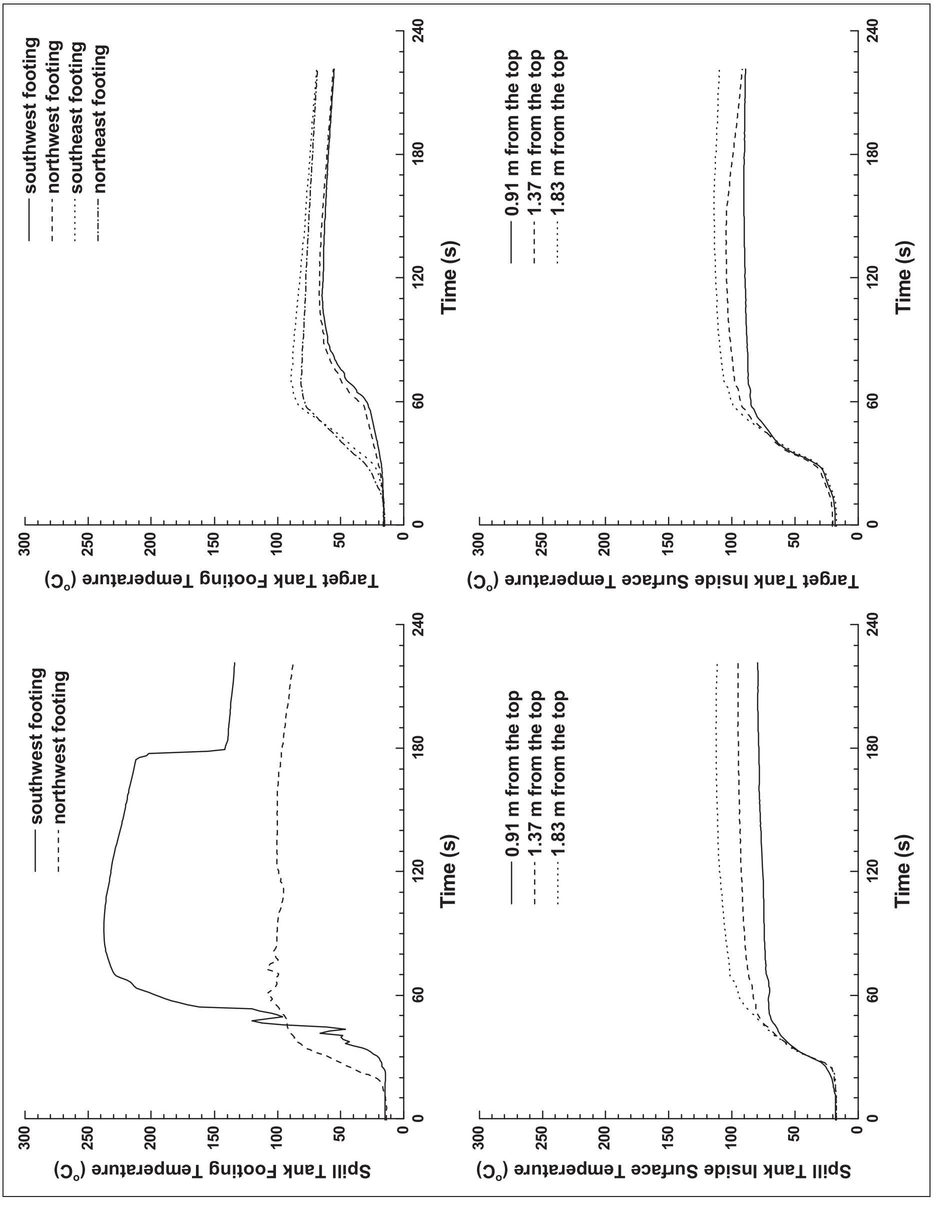

Figure 6. Spill tank and target tank temperatures measured with the following test conditions: (1) Nozzle B as the ceiling nozzle, (2) near-corner fire location and (3) 3.05 × 3.05-m door opening.

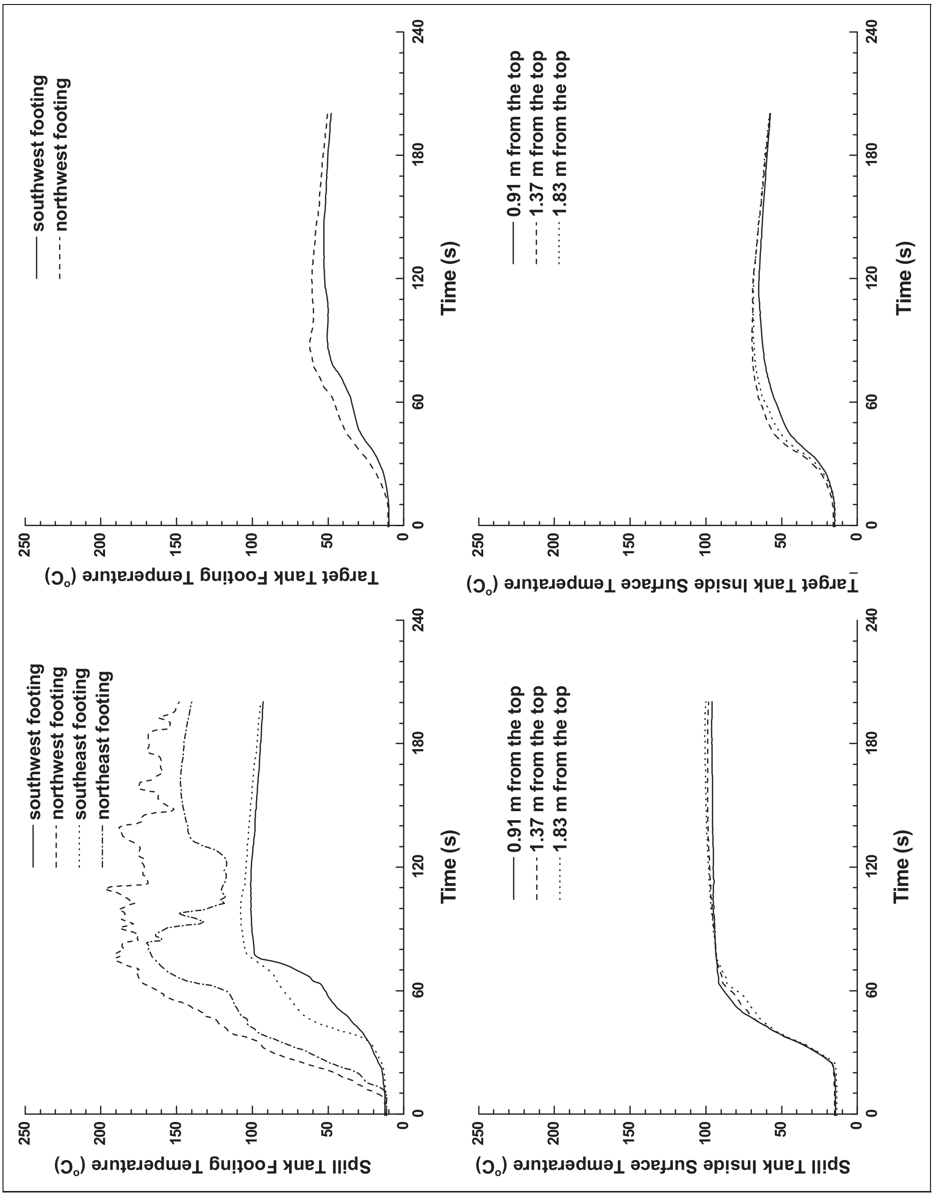

Figure 7. Spill tank and target tank temperatures measured with the following test conditions: (1) Nozzle B as the ceiling nozzle, (2) near-floor-center fire location and (3) 3.05 × 3.05-m door opening.

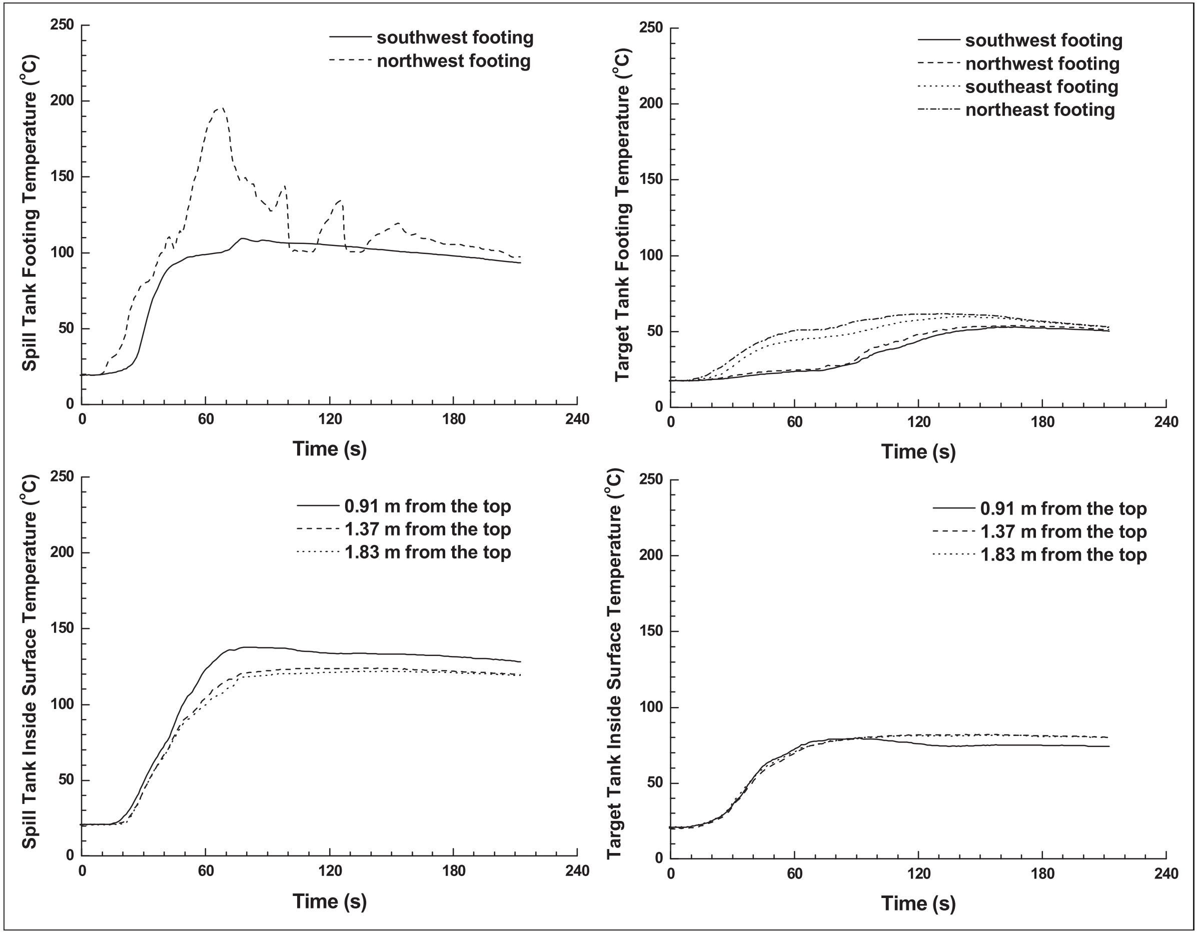

Figure 8. Spill tank and target tank temperatures measured with the following test conditions: (1) Nozzle A used as the ceiling nozzle, (2) Nozzle B as the door nozzle, (3) near-corner fire location and (4) 3.73 × 3.73-m door opening.

door nozzles, oriented vertically downward, are spaced at half the door opening width.

The average water mist density provided by the nine ceiling nozzles is about 4.5 mm/min when Nozzle B is used as the ceiling nozzle, well below the required water density of 12 mm/min for sprinkler protection. When the water mist discharge from the two door nozzles is included, the average density increases to 5.5 mm/min, still much less than the sprinkler application density of 24 mm/min to suppress a heptane spill fire [13].

The two nozzles used in this investigation were selected simply because they were readily available. Either nozzle can be substituted with other nozzles that can provide spray properties comparable to those shown in Table 2.

The downward spray thrust force varies with the discharge rate, discharge velocity and spray angle. For a spray angle much larger than the designated angle, a higher discharge rate is required to obtain comparable downward thrust force and to compensate for the water mist lost to the enclosure walls. For total flooding applications, the key water mist spray properties are the droplet size, total discharge rate, spray thrust force, and spray angle.

The present investigation demonstrated that the physical scaling approach is a useful tool to provide an engineering estimate of the water mist protection requirement. However, since the validation study to date for the scaling relationships has been performed only up to a scale ratio of 9 to 1 [14], it is recommended that the scaling application should not exceed this scale ratio until further validation work shows otherwise.

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