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Field experiments on high expansion (HEX) foam application for controlling LNG pool fire

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ABSTRACT

Previous research suggests that high expansion foam with an expansion ratio of 500 to 1 is one of the best options for controlling liquefied natural gas (LNG) pool fire on land. However, its effectiveness heavily depends on the foam application rate, foam generator location, and the design of LNG spill containment dike. Examination of these factors is necessary to achieve the maximum benefit for applying HEX on LNG pool fires.

While theoretical study of the effects of foam on LNG fires is important, the complicated phenomena involved in LNG pool fire and foam application increase the need for LNG field experimentation. Therefore, five LNG experiments were conducted at Texas A&M University's Brayton Fire Training Field. ANGUS FIRE provided Expandol solution to form 500 to 1 high expansion foam (HEX) and its latest LNG Turbex Fixed High Expansion Foam Generators.

In this paper, data collected during five experiments are presented and analyzed. The effectiveness of high expansion foam for controlling LNG pool fires with various application rates at two different types of containment pits is discussed. LNG fire behaviors and the effects of dike wall height are also presented and discussed.

1. Introduction

Liquefied natural gas (LNG) is cryogenic. It readily receives heat from its surroundings. When LNG is spilled into a concrete containment pit, concrete acts as a warming source to the LNG. This causes the LNG to evaporate at an initially fast rate creating LNG vapors. Initially, LNG vapors are heavier than air, so when they escape, they hug the ground. It is only as the LNG vapors mix with the warmer air that they begin to rise slowly. It is near the ground where most ignition sources exist, so when the gas dilutes to its flammable range of 5–15% volume by volume in the air, vapor ignition is likely to occur. Fire burns back to the LNG pool where an intense fire is started and creates an LNG pool fire.

Expansion foam has been used as a fire extinguisher for non-liquefied hydrocarbon pool fires. Expansion foam provides an insulating effect that protects the fuel surface from the heat radiation of the fire; it also blocks free air movement crucial to prolong the fire. Water content in the foam absorbs the heat from the fire and forms steam. It provides a cooling effect and reduces the burning rate due to the heat radiation of the fire. Steam dilutes air around the fire and reduces the air necessary to sustain the fire. Based on these phenomena, expansion foam is able to extinguish non-liquefied hydrocarbon pool fire.

On the other hand, similar phenomena do not happen when expansion foam is applied to LNG, which usually leaks at its boiling point of −162 °C. The differences can only be understood by having knowledge of how expansion foam works for both LNG vapor dispersion and LNG pool fire suppression, not as an extinguishment agent. Fig. 1 illustrates expansion foam application on LNG vapor dispersion and pool fires.

Water in a limited amount in the expansion foam plays an important role as the LNG vapors' warming agent. As part of the expansion foam behavior, water content slowly degrades, releasing limited amounts of water downward, until it reaches the LNG pool surface. While draining to the LNG pool surface, the water is in contact with LNG vapors that move upward finding ways to the open air. During this contact, the LNG vapors are warmed, the vapor density is reduced, and LNG vapors become more buoyant (less dense); thus, they are dispersed more upward instead of downwind. At the same time the water is cooled down creating ice tubes along the LNG vapor pathways, which are open to the air. When drained water

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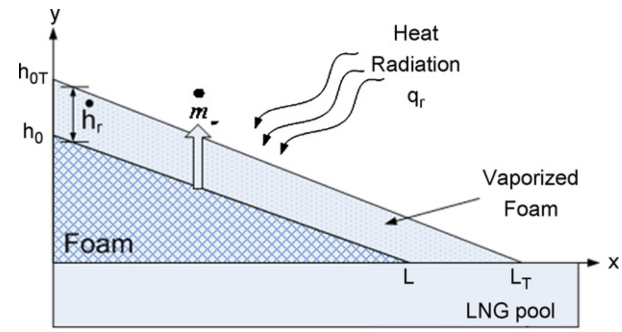
Nomenclature

h_{0T}	initial foam height (m)
h_0	foam height after drained (m)
m'_w	water evaporated (kg/(m^2 s))
L	initial foam front length (m)
L_T	foam front length after drained (m)
q_r	heat radiation (kW/m^2)
D	LNG pool fire base diameter (m)
L_f	flame length (m)
S	distance between object and the center of the fire (m)
E	surface emissivity (W/m^2)
z	z-axis direction
q''	LNG pool fire heat flux (kW/m^2)
τ	atmospheric transmissivity
θ	tilted angle (°)

reaches the LNG surface, ice or hydrate is formed in a honeycomb structure. These phenomena occur at an initially fast rate, commonly before ignition takes place. Hence, during LNG pool fires, expansion foam cannot completely insulate air movement because of the limited amount of vapors leaving the foam blanket through the ice tubes to the open air. In addition, water also participates in engaging a cooling effect by absorbing radiant heat from fire and being converted into steam. However, at the same time, expansion foam application on LNG shows unique behavior compare to the application on non-cryogenic liquid. Due to temperature difference between LNG pool surface and the sprayed expansion foam, water content in the expansion foam is considered as heat source to the LNG pool surface. This Additional heat from water increases LNG vapor generation. As fire size depends on the amount of the vapor, water introduction leads to fire size increase. Therefore, there is a need to balance the cooling effect and the fire size. Based on previous research, high expansion foam of 500:1 expansion ratio was found to be the optimum expansion foam. A lower expansion ratio means lighter foam and that means wind can easily destroy the foam layer reducing foam thickness. A higher expansion foam ratio means higher water content.

The behavior discussed above is the reason expansion foam cannot extinguish LNG pool fires. A common strategy on LNG pool fire is to use high expansion foam to control and reduce the fire's radiant heat significantly to make the fire more approachable to the fire fighter. Dry chemicals are then used to extinguish the fire if needed. One of the strategies that could be used includes extinguishing the fire while the LNG pool does what (to eliminate radiant heat) and then provide a foam blanket to control LNG vapor dispersion.



Source: Modified from [2]

Fig. 2. Foam layer exposed to heat radiation from fire.

While the effectiveness of high expansion foam application depends heavily on the thickness of the foam blanket, water drainage causes the blanket to collapse over time. Therefore, regular foam top-ups are required by pulsing the LNG Turbex generators on and off to keep the pit full and to keep fresh fluid foam at the surface in order to maximize the LNG pool fire control.

When high expansion foam is applied during an LNG pool fire, some important phenomena occur on the interface between the foam blanket and the LNG pool surface. Fig. 2 shows the initial application of high expansion foam on an LNG pool surface during a fire occurrence. In addition to its natural water drainage downward, water in the high expansion foam is heated and forms steam. This contributes to the expansion foam's collapse by reducing its thickness, and therefore, its effectiveness.

Based on previous studies, high expansion foam application on LNG pool fire can be summarized as follows [3]:

- A certain amount of high expansion foam can prevent air, as oxygen source, from reaching the fire.
- Water in the high expansion foam is heated, boiled, and converted into steam when it comes in contact with the flame. This reduces

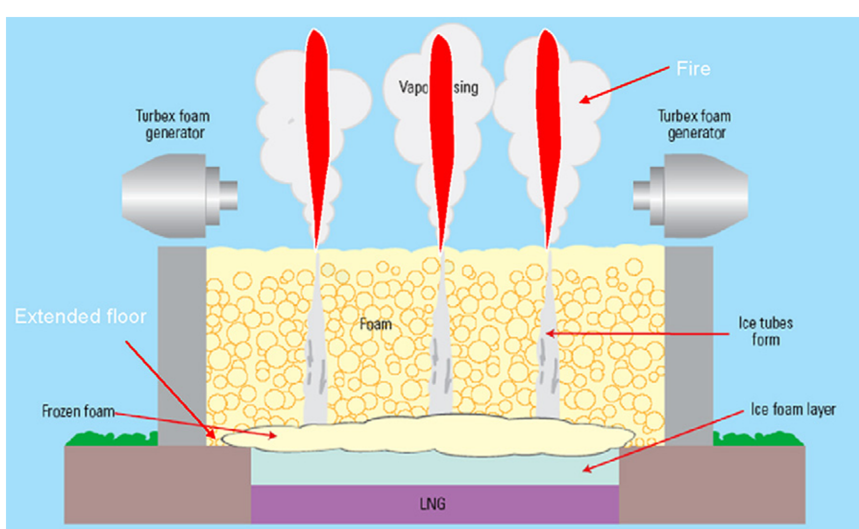


Fig. 1. HEX application on LNG liquid pool and pool fire.

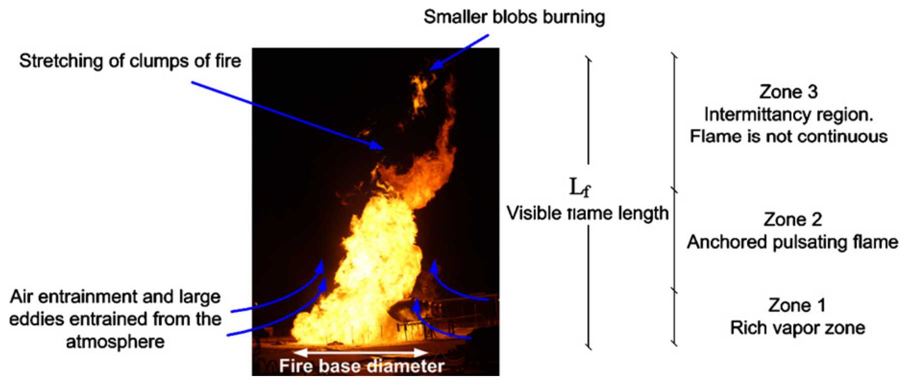


Fig. 3. Fire zones.

the amount of oxygen around the fire. At the same time, the conversion of water into steam shows that some of the heat from the fire is absorbed by the water thus reducing heat coming to the LNG pool fire. As a result, the burning rate should be reduced.
- Upon reaching its effective depth above an LNG pool surface, high expansion foam provides protection or insulation to an LNG pool fire from fire radiation.

These effects of high expansion foam in controlling an LNG pool fire have been studied for a few decades. Past studies focused on determining the expansion foam minimum application rates. However, the previous studies were conducted in earth pits while current modern facilities use concrete containment pits. In addition, previous studies did not incorporate the LNG pool fire's behavior and how it affects expansion foam effectiveness in different containment pit designs used in modern facilities.

Therefore, the objectives of the experiments were

- To investigate the effectiveness of high expansion foam with an expansion ratio of 500:1 in controlling LNG pool fires in two different types of LNG containment pit designs.

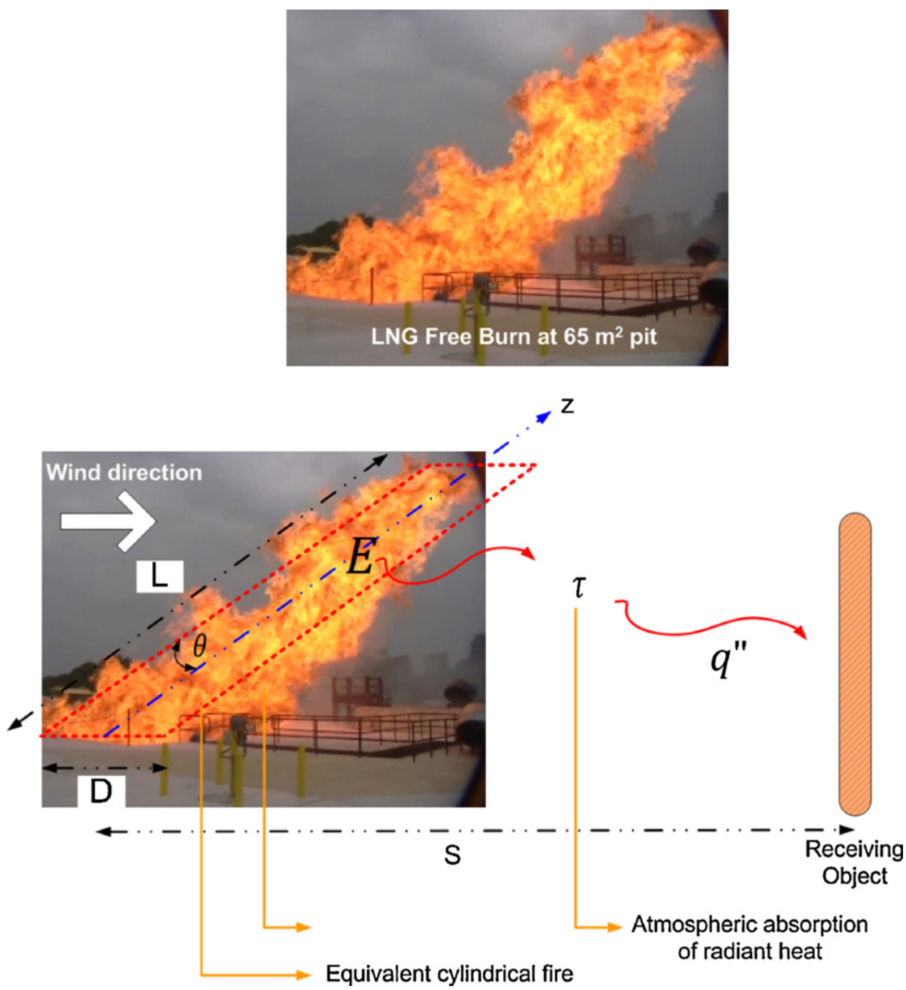


Fig. 4. Fire characteristics.

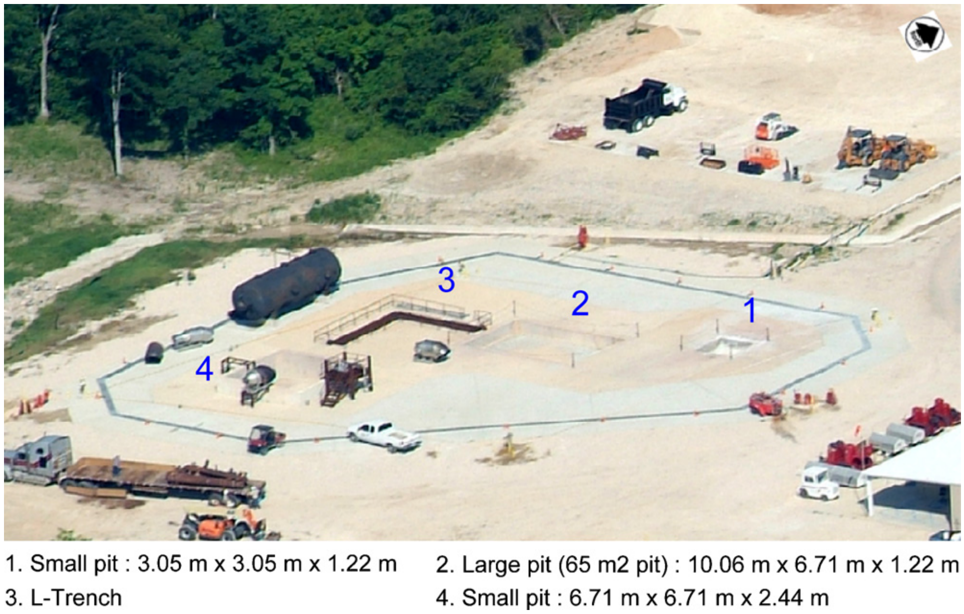


Fig. 5. LNG props at TEEX's Brayton fire training field.

- To validate the effectiveness of the recommended high expansion foam application rate (10 L/(min m^2)) and to compare it with lower foam application rates (3.5 L/(min m^2) and 7 L/(min m^2)) in a concrete containment pit. This tests the feasibility of having a more economic HEX application rate. This experiment is designed to obtain the minimum application rate. NFPA 11 is used as the guideline for the practical application rate determination.

This paper focuses on the analysis of these experiments. Angus Fire provided its latest LNG Turbex Fixed High Expansion Foam Generators and instrumentation to measure the Expandol High Expansion foam application rate released by the foam generator and the heat radiation flux.

2. LNG pool fire characteristics

One of the LNG hazards is LNG pool fire. The fire burns on the top of the LNG pool, as shown in Fig. 3 and continues to exist until the fuel from the LNG pool below is fully consumed. McCaffrey separates pool fire into three different zones, as explained by Raj [4]. The first zone, a vapor rich zone, is where the LNG vapor is at maximum concentration from the boiling liquid LNG pool. Unburned LNG vapor in the first zone, due to the above upper flammability limit (UFL), will move upward and create the second zone, where the flame is anchored to the flame base and where flame pulsating occurs. The pulsating is also caused by the entrained air and large eddies from the atmosphere. The third zone, the intermittency zone, is where the rest of unburned LNG vapor moves. Depending on the amount of oxygen available, the pulsating will occur and can be seen as peeled-off fragments of fuel burning in irregular clumps [4].

LNG pool fires can be represented as a circular cylindrical shape with fire diameter equal to the base diameter, as suggested in solid flame model [5]. There are two effects of wind on LNG pool fires, flame tilt and flame drag. Fig. 4 illustrates the LNG pool fire at 65 m^2 concrete pit tilted by the wind speed of 2.2 m/s. The length of the

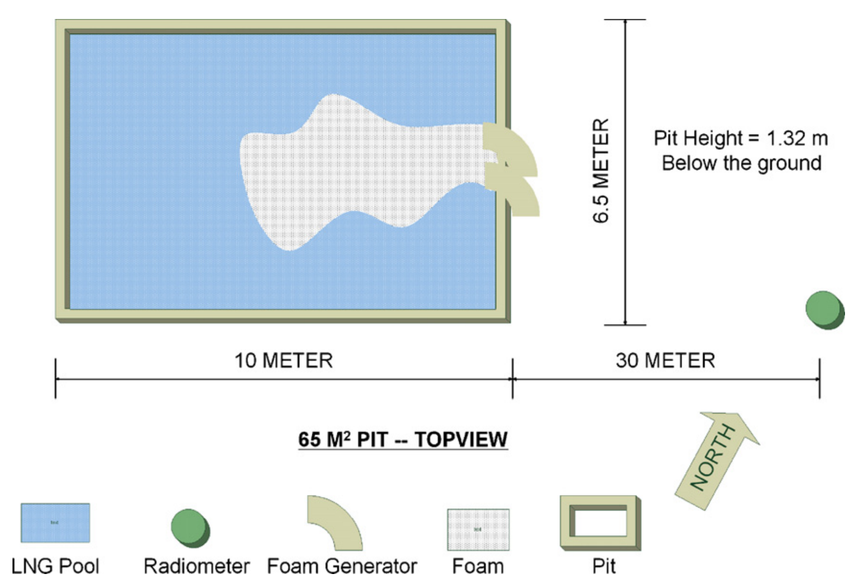


Fig. 6. Experiment layout for the 65-m^2 pit.

flame is the length of the fire measured from the fire base to the last visible top part.

3. Experimental setup

An LNG emergency response training facility was constructed at Texas A&M University System (TAMUS) Emergency Services Training Institute (ESTI), as shown in Fig. 5. The facility is located at Texas Engineering Extension Services (TEEX) Brayton Fire School where emergency response training and research is conducted. One of the focuses of the research is to study the effectiveness of HEX application to suppress LNG vapor and LNG pool fire heat radiation. Fire fighters at BFTF helped and provided supervision to ensure the safety of the experiment.

Two LNG containment concrete pits (dikes) were used to simulate industrial LNG spills. The large pit is called the "65 m^2" pit, as shown in Fig. 5 (number 2) and in Fig. 6, while the smaller pit is the "45 m^2 pit" or "marine pit," as shown in Fig. 5 (number 4) and in Fig. 7. The main differences between the two types are the surface area and wall height. The 65-m^2 pit has a 4 ft deep (1.2 m) underground wall while the 45 m^2 pit has an 8 ft deep (2.4 m) with 4 ft of the wall height above ground as illustrated in Fig. 8.

Five experiments were conducted during October 2005 and April 2006. The summary of the experiment parameters is provided in Table 1.

Four scenarios were performed on the 65-m^2 pit in 2005 and 2006 with application rates of 3.5, 7, and 10 L/(min m^2). Consequently, in both years experiments with 10 L/(min m^2) were tested to ensure consistency of results. The experimental layout is shown in Fig. 6.

Based on data from the 65-m^2 pit, a further experiment was conducted on the 45-m^2 pit to determine whether pit design had an influence on control, so this was also conducted using foam application rate of 10 L/(min m^2). The experiment was performed on 20th April 2006.

4. Results and discussions

Table 2 summarizes the experimental results. There was only one experiment conducted in the 45-m^2 pit while there were four experiments performed in the 65-m^2 pit. In addition, there were two experiments performed in the 65-m^2 pit with the same application rate, 10 L/(min m^2). These experiments were conducted to confirm that an application rate of 10 L/(min m^2) is the most practical application. While recognizing the maximum heat flux reduction achieved by HEX application is important, in the discussion, the fire control time is defined as the time required by the HEX to reduce 90% of the heat flux, as specified by NFPA 11 [6]. In addition, it is essential to understand that in current technology, an LNG pool fire's extinction can only be achieved by the application of Dry Chemical Powder above the HEX blanket. Thus, as expected, the HEX did not extinguish any fire during the experiment. Generally, as stated by Zuber [7] and White [1], HEX and dry chemicals can be used together to fight an LNG pool fire. However, it should be noted that extinguishing LNG pool fires might not be the solution when pool fires occur. It depends on the situation. This experiment was not designed to suggest whether the application of high expansion foam should be accompanied by dry chemicals or not.

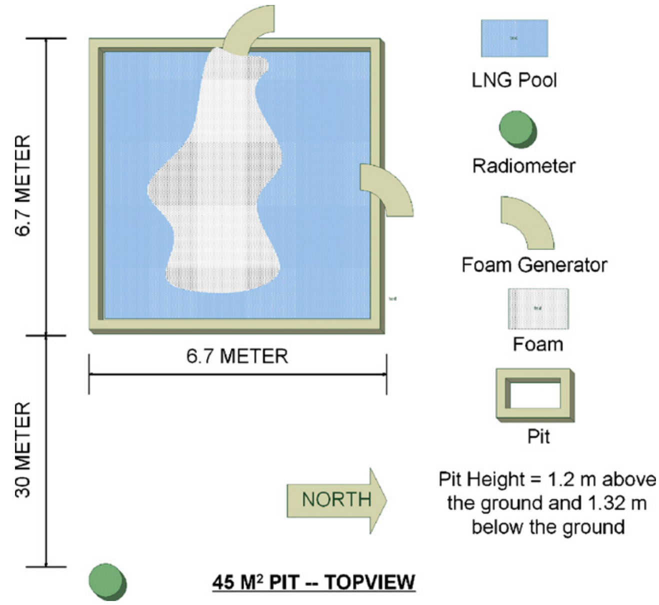


Fig. 7. Experiment layout for the 45-m^2 pit.

Table 1
Experiment condition.

Test ID	1	2	3	4A	4B
Pit size (m)	45	65	65	65	65
HEX application rate (L/(min m^2))	10	3.5	7	10	10
Radiometer location for pit edge (m)	30	30	30	30	27
Initial LNG pool depth (m)	0.13	NA	0.10	0.15	0.15
Average wind speed (m/s)	3.7	NA	1.2	2.2	3.7
Air temperature (°C)	15.8	NA	26.7	24.5	28.7
Relative humidity (%)	83	NA	74.8	81.3	71

Table 2
Foam application experiment on LNG pool fire in 2005 and 2006.

Test ID	1	2	3	4A	4B
Pit area (m^2)	45	65	65	65	65
Radiometer distance (× pool diameter)	4.0	3.3	3.3	3.3	3.0
Radiometer distance (m)	30	30	30	30	27
Maximum heat flux (kW/m) (95% confidence level)	3.88 ± 0.14	7.01 ± 0.70	3.78 ± 1.11	6.85 ± 0.55	4.07 ± 0.92
HEX solution application rate (L/(min m^2))	10	3.5	7	10	10
Maximum heat radiation reduction (%)	91	94	95	97	93
Time to reach 90% heat radiation reduction (min)	3.5	2.45	1.7	1	0.85
Time to reach maximum heat reduction (min)	3.6	4.5	2	1.2	1.5
Equivalent pool diameter (m)	7.57	9.10	9.10	9.10	9.10

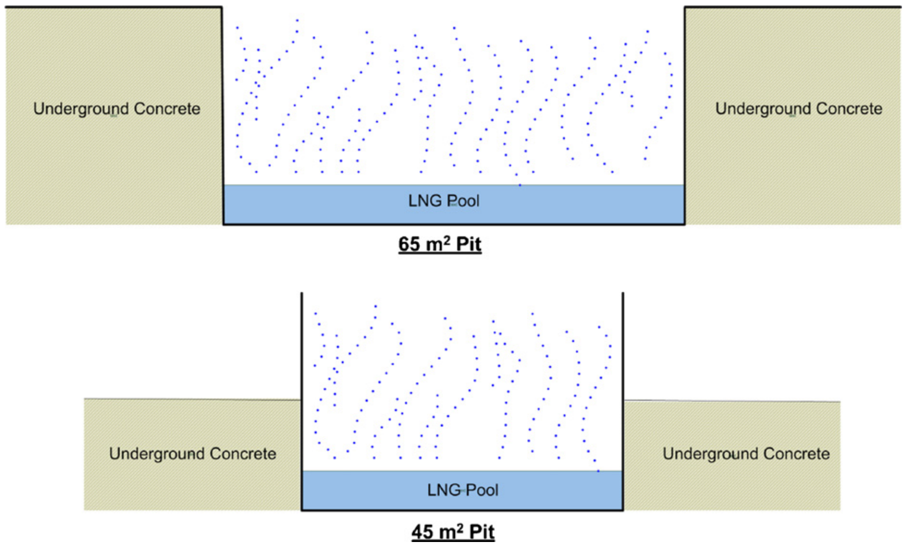


Fig. 8. Side view of the pit.

The following section discusses the results and observation on:

- LNG spill containment pit design effect on fire.
- HEX application rate of 10 L/(min m^2) on the 45-m^2 pit (Test 1).
- HEX application rate of 3.5 L/(min m^2) on the 65-m^2 pit (Test 2).
- HEX application rate of 7 L/(min m^2) on the 65-m^2 pit (Test 3).
- HEX application rate of 10 L/(min m^2) on the 65-m^2 pit (Test 4A and 4B).

4.1. HEX application rate

The summary of fire control time at the tested application rates is shown in Fig. 9. There are two observations that can be made and will be discussed in the following section:

- The experiment clearly demonstrates that higher application rates reduce the fire control time.
- The two different types of containment pit applied in the experiment give different results. HEX application rate of 10 L/(min m^2) operated on the 45-m^2 pit presents a smaller fire control time compared to the HEX application rate of 3.5 L/(min m^2) utilized at the larger 65 m^2 pit.

4.1.1. HEX application rate of 3.5 L/(min m^2) in the 65 m^2 pit (Test 2)

This experiment was conducted on 6 October 2005. Fire control time was 177 s and maximum heat reduction at 94% was achieved after 270 s. As shown in Fig. 9, this low application rate had greater pool fire control time compared to foam application rates of 7 and 10 L/(min m^2). With a lower application rate, it takes significantly more time for the foam to cover the LNG pool. In this case, it took 5 min to nearly fill the pit. The application rate was not high enough to overcome the foam breakdown by the fire, which was considered unacceptable for operational use, as there was insufficient foam application to deal with ideal conditions. All of the pool fire surfaces were not covered to the required depth in an adequate time frame to ensure reduced heat radiation could be achieved.

Another observation is that HEX re-topping is important to maintain HEX coverage. HEX breaks down due to the heat, as illustrated in Fig. 2. On the other hand, HEX works effectively when the effective depth is reached and maintained. Fig. 10, shows that foam

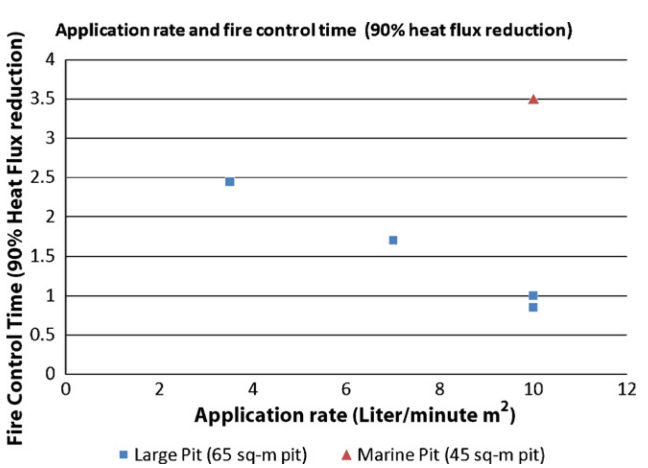


Fig. 9. LNG pool fire control time (90% heat flux reduction) at tested application rate.

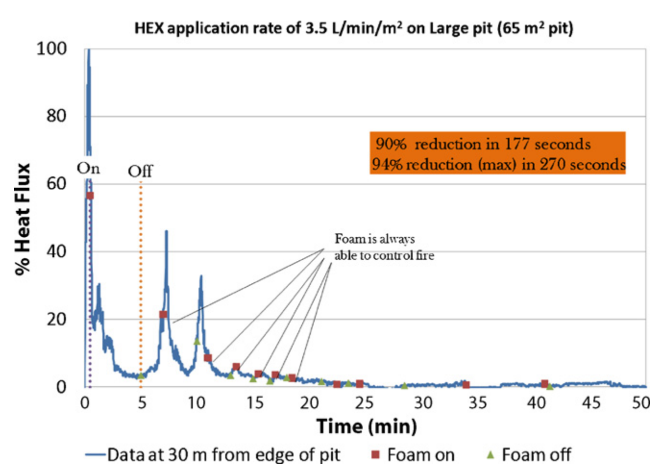


Fig. 10. Fire control time for pool fire in the 65 m^2 pit with foam application rate of 3.5 L/(min m^2) and showing the effect of re-topping.

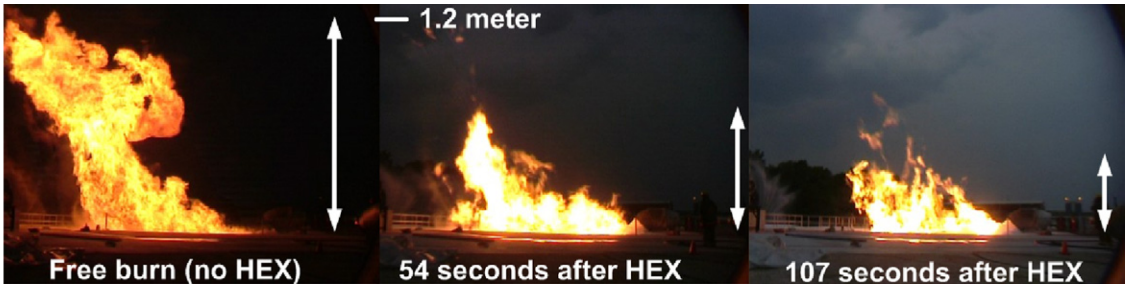


Fig. 11. Pool fire on the 65-m^2 pit before and after foam application rate of 7 L/(min m^2).

applications were on and off several times during the experiment. Whenever the foam was off, heat radiation increased while when the foam was on, foam layer is maintained and heat radiation we decreased. Thus, HEX re-topping is important.

4.1.2. HEX application rate of 7 L/(min m^2) in the 65-pit (Test 3)

From the data gathered on the foam application at 7 L/(min m^2) in the 65-^{2} pit, it is shown that the maximum heat radiation reduction by HEX application is 95% within 120 s at a distance of 30 m where the radiometer was placed. The 90% heat radiation reduction is achieved in 100 s, which seems quick but this was achieved in ideal conditions (experiment condition), with no allowance for adverse factors of higher wind speeds drifting foam off the pit or preventing all the foam entering, and no allowance for cooling sprays drifting water into the pit on the wind, or rain storms increasing the fire intensity.

The experiment was conducted in the same conditions. Heat radiation emitted by the LNG pool fires depends heavily on the fire size (height, diameter), wind direction (tilting), atmospheric transmissivity, and distance to object. During this experiment and analysis, other factors were not changed too much while fire size was significantly reduced due to the foam application. Thus, it can be seen that fire size reduction is significantly related to the radiant heat flux. While fire size should be measured in the length of fire, Fig. 11 shows the reduction of fire size by comparing the vertical heights. This is an acceptable approach since this only represents fire size reduction and the wind speed did not change significantly during the free burn to 107 s after the HEX application.

The actual pool fire before and after the foam application is shown in Fig. 11 while the experiment results are presented in Fig. 12. As demonstrated in Fig. 11, the HEX is only intended to control the fire and permit a burn off of the LNG liquid pool through the foam blanket under controlled conditions and is not intended to extinguish the fire.

4.1.3. HEX application rate of 10 L/(min m^2) in the 65-m^2 pit (Test 4A)

The result for the foam application at 10 L/(min m^2) in the 65-m^2 pit is presented in Fig. 13. The 90% of heat reduction is achieved within 60 s of HEX application while maximum heat reduction is achieved after 70 s. This is significantly improved over the 7 L/(min m^2) HEX application rate since it provides a safety margin. This application might still give an effective result even under adverse conditions. The fire size reduction during this particular experiment is shown in Fig. 14.

4.1.4. Foam application rate of 10 L/(min m^2) in the 65-m^2 pit (Test 4B)

Test 4B was conducted on 20 April 2006. The foam generator was turned on and off twice. As shown in Fig. 15, the first cycle of on and off was between 26 (on) and 120 (off) seconds when the pit was full, while the second cycle was between 227 (on) and 275 (off) seconds. In the first cycle, foam is able to reach 90% heat reduction with the maximum reduction of 93%. It was found that maintaining a certain effective HEX depth was the best way to maintain maximum radiation reduction and also add sufficient water to provide controlled vaporization to safely burn off the residual pool. This practical 10 L/(min m^2) application rate coincides with the NFPA 11:2005 international standard recommendations of the National Fire Protection Association, which confirms under section A6.14.2.1 that "discharge rates per unit area shall be established by test" and section A6.14.2 that "tests often give minimum application rates, as conducted under ideal conditions with no obstructions or barriers to control. The final design rates are generally 3–5 times the test rates [6]". This recommended practical rate is also three times the minimum effective experimental test rate of 3.5 L/(min m^2). Despite the problem that occurred during experiment, the fire size was reduced, as shown in Fig. 16.

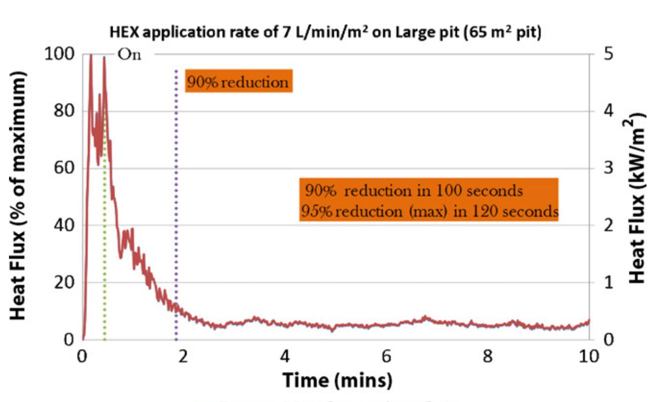


Fig. 12. Fire control time for pool fire in the 65-m^2 pit with foam application rate of 7 L/(min m^2).

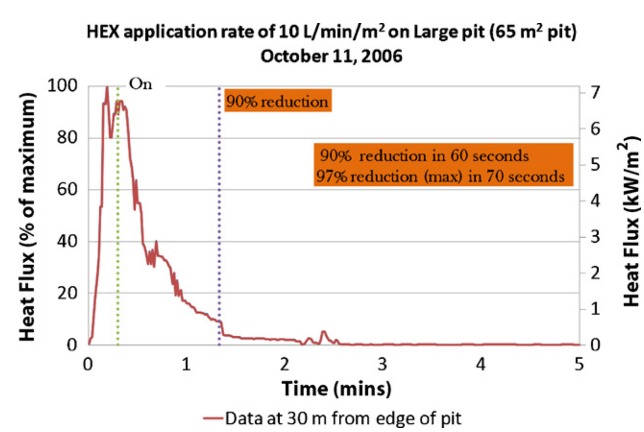


Fig. 13. Test 4A—Fire control time for pool fire in the 65-m^2 pit with foam application rate of 10 L/(min m^2).

Fig. 14. Fire at 65 m2 pit.

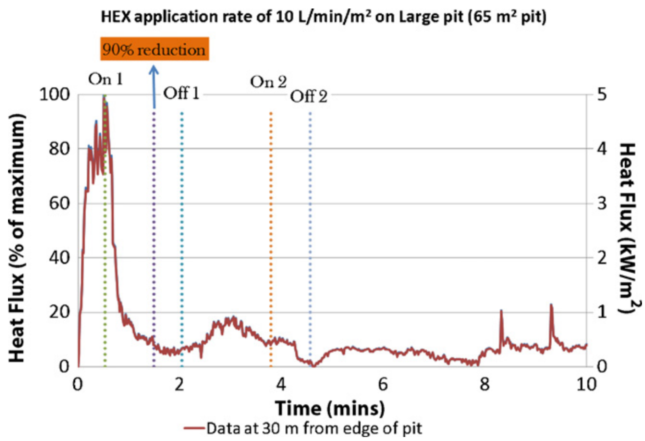


Fig. 15. Test 4B—Fire control time for pool fire in the 65-m^2 pit with foam application rate of 10 L/(min m^2).

Between the first and second cycle, the radiant heat increases but not as high as without the foam, so even the residual frozen foam layer has an impact, while the pit is topped up with fresh foam. This shows that while foam is still covering the LNG surface, it does provide a level of control on the fire. And when the second cycle starts, the combination of the newly sprayed HEX and the first cycle HEX reduces the heat radiation faster and further.

4.1.5. Experiment on the 45-m^2 pit

Two foam generators were provided, one as back-up knowing that a low rate was probably going to be insufficient on this pit. One foam generator, the LNG Turbex FT1 unit, was located downwind and another LNG Turbex FT2 unit was located perpendicular to the wind direction. Both units were fed by fire hoses for flexibility and ease of providing water, although in operational installations, rigid metal piping would be used to supply foam solution to each LNG Turbex foam generator. The plan was to use only one foam generator, the FT1, to achieve a 5-L/(min m^2) application rate.

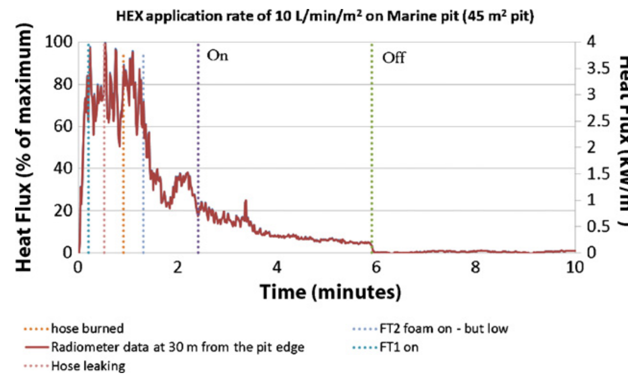


Fig. 17. Fire control time for pool fire in the 45 m^2 pit with foam application rate of 10 L/(min m^2)—Test 1.

However, between 16 s to 1 min after the FT1 was turned on, its hose continued flowing foam solution even though it caught light with direct flame impingement. The flames created a small burst in the hose and it slowly burned away and fell onto the ground while still discharging the foam solution. To continue the experiment, it was necessary to open the control valve to allow foam solution to the FT2 unit. At $t = 1.3–2.4$ min, the FT2 was operating but due to existing open ended flow at FT1, FT2 did not have enough pressure to reach 7 bar gauge line pressure and deliver the expected 10 L/(min m^2). At $t = 2.4$ min, the valve on FT1 was closed and FT2 achieved an application rate of 10 L/(min m^2), which controlled the intense fire despite the long pre-burn time.

The effectiveness of the foam application is therefore analyzed starting from the data of $t = 2.4$ min, as shown in Fig. 17. 90% heat reduction was achieved after 3.5 min while the total heat reduction before the fire was extinguished by using a dry chemical is 91% after 3.6 min.

The experiment results were obtained for an LNG pool depth of 6 in. The experiments were not to determine the expansion foam effectiveness on deeper LNG pools nor were they to determine the total amount of expansion foam necessary to sustain an LNG pool

Fig. 16. Fire at 45 m^2 pit.

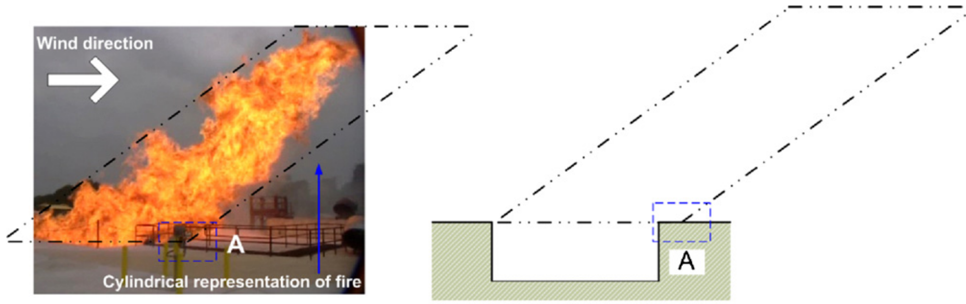


Fig. 18. Flame drag at below the ground pit.

fire's control for a certain amount of time. Re-topping has been shown as a good strategy. It maintains the pool fire control, and is one of the determinants in specifying the total amount (not application rate) of expansion foam applied. Thus, good engineering judgment should be used in applying the results of this research.

4.2. LNG pool fire characteristics on different types of LNG spill containment pits

Three experiments have been conducted with the foam application rate of 10 L/(min m^2) on the 65 m^2 pit (Test 4A and B) and the 45-m^2 pit (Test 1). The data shows that heat radiation reduction for the 65-m^2 pit is better and that fire control time is better than that of the 45-m^2 pit. This contradicts common sense that dictates that smaller LNG pool surface areas are easier to control than the bigger ones.

There are several explanations behind these phenomena. The fire control time on the 45-m^2 pit does take into account the extra heated concrete area attacking the foam, the "chimney effect" of the raised walls, and the amount of un-burned LNG-rich vapor in the pit as follows:

- The time is higher compared to 65 m^2 pit because although the LNG or pit surface area is smaller, the 45 m^2 pit has a larger area of concrete wall (61 m^2 compared to 35 m^2 on 65 m^2 pit). Thus, more heat built up in the concrete walls, which destroyed the initial HEX application before it started to work effectively.
- It is estimated that ignition occurs at the top of the pit. This is because LNG vapors in the pit do not meet limiting oxygen concentration (LOC) to sustain the combustion process while at the same time the LNG-rich vapor is above its flammable region. Thus, the pit is filled with vapors that are ready to burn. There is an estimated 103 m^3 of hot vapor in 45 m^2 pit, which is 1.4 times more compared to the 65-m^2 pit, which has 72 m^3 of hot LNG vapor. This leads to two things: chimney effect and foam damage. Higher walls in the 45-m^2 pit create a chimney effect that happens when hot vapor is forced to move upward. This means that the 45-m^2 pit provides more fuel to burn outside the pit faster. At the same time, the volume of hot vapors represents the amount of heat that the HEX must endure during its travel from the top of the pit to the LNG pool surface to create a blanket. Contact with hot vapors breaks or damages some of the HEX; thus, it requires more time to build a HEX blanket in the 45-m^2 pit.
- It took more time to reach the required depth than to cover the whole surface. In addition, the vertical distance travelled by the foam, which was 7.5 ft, was doubled compared to the one in the 65-m^2 pit, which was 3.5 ft. During the travel, the HEX was exposed to the hot vapors longer than in the 65-m^2 pit. Thus,

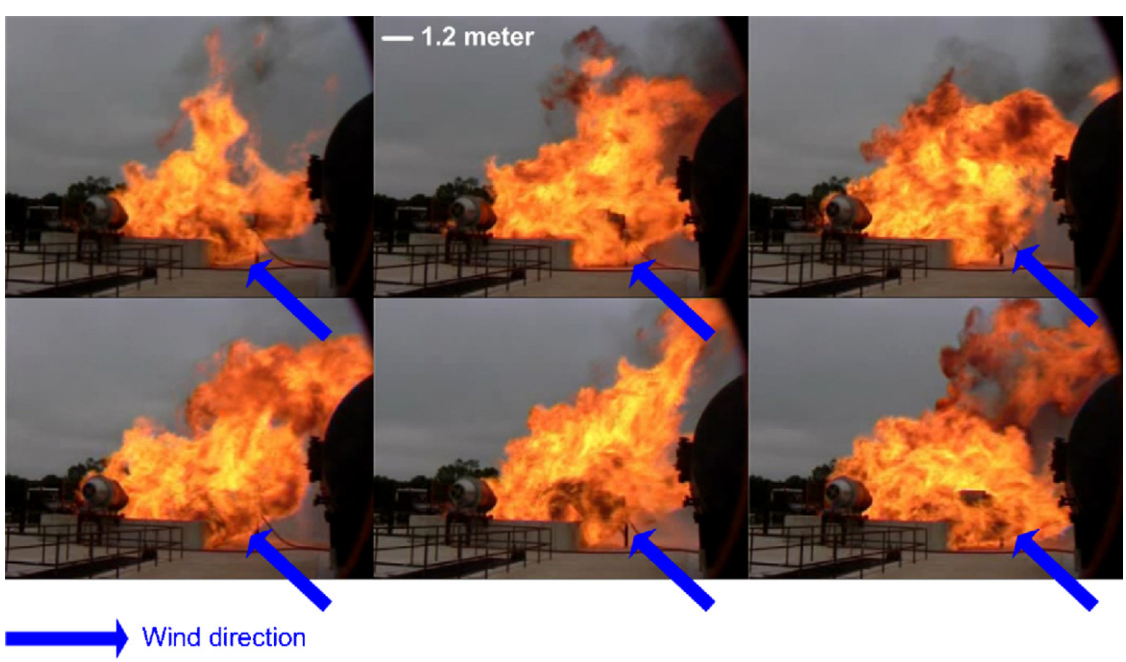


Fig. 19. Fire turbulence at 45 m^2 containment pit.

longer contact time with fire broke down the HEX by evaporation of water content in the HEX and the bond between HEX solution and air in the HEX.

- As mentioned above, the LNG pool fire is heavily affected by the wind. Wind tilting occurs when the wind blows the fire, thus tilting it and creating an angle between the fire and the ground. One of the results of this phenomenon is flame drag. Flame drag is a well-known phenomenon in which the wind drags some part of the fire outside the pit, as shown in Fig. 18.

The 45-m^2 (Marine) pit showed different behavior of flame drag, as shown in Fig. 19. This type of pit has 1.2 m-of-above-the-ground walls. As a result, the flame drag effect drags some part of the flame outside the pit, and the flame eddies down to ground level. At the same time, fire warms the surrounding air and creates air entrainment and large eddies, as shown in Fig. 3.

This phenomenon of flame extending down to the ground level and air entrainment in limited volume space in between the ground and pit wall creates fire turbulence, as illustrated in Fig. 19. While this fire turbulence becomes smaller when the fire size is smaller during HEX application, this part itself is not covered by HEX. In addition, it freely emits radiant heat. Any object in the down wind direction might be affected by the intensity of this fire turbulence. The HEX foam generator (FT1) was engulfed in flame the entire time and the solution hose was burned by this effect during the experiment. This part of the experiment showed that LNG pool fires behave differently depending on the design of the containment pit. Therefore, facility siting and mitigation system placement around an LNG containment pit should incorporate this pool fire's behavior.

Had the foam application rate been lower, it is questionable whether it would have achieved effective fire control, as there is a point where the generator is producing foam, but the foam is being destroyed as fast as it builds up. Hence, radiation levels do not drop to acceptable levels, the pit never fills with foam, and the resulting extra radiant heat can cause danger to personnel and plant structures. Additionally, there is an increased risk of incident escalation. It is, therefore, important that a safety margin is built into the designed system application rate to cover unexpected factors and adverse operating conditions, should an incident occur.

In summary, those phenomena illustrated in Fig. 20 do not happen during the HEX application in the 65-m^2 pit. It is also interesting to note that in Fig. 17, the limited foam application from the LNG Turbex FT1 unit has a significant effect in reducing radiation

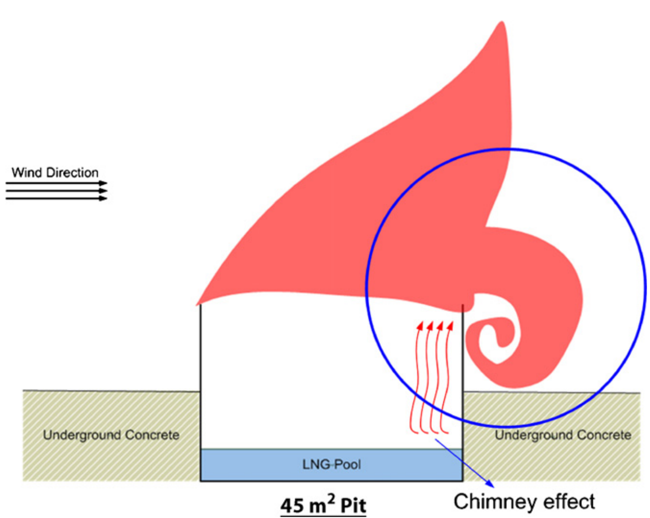


Fig. 20. LNG Fire phenomena in the 45-m^2 pit.

despite operating pressure problems. But very quickly when the foam application stops, the foam begins to be destroyed by the heat and flames. This is reflected by the climbing radiation levels; they reach 40% before new foam from the FT2 unit, which is operating correctly, reverses this trend and regains fire control.

5. Conclusions and recommendations

From the above experiment results discussion, the following conclusions are made:

1. This detailed testing on LNG has established that practical foam application rates of 10 L/(min m^2) are effective on modern concrete LNG containment pits when LNG Turbex foam generators and Expandol high expansion foam concentrate at 3% induction rates are used on the tested containment pits. This is based on the experiment using a HEX application rate of 3.5 L/(min m^2) under ideal (experiment, not incident scenario) conditions. NFPA 11:2005 international standard recommendations of the National Fire Protection Association, which confirms under section A6.14.2.1 that “discharge rates per unit area shall be established by test.” In addition, NFPA 11:2005 section A6.14.2 states that “tests often give minimum application rates, as conducted under ideal conditions with no obstructions or barriers to control. The final design rates are generally 3–5 times the test rates” [6]. Therefore, the recommended practical application rate is 10 L/(min m^2), which is three times of the minimum effective experimental test rate of 3.5 L/(min m^2). It should be noted that this experiment was conducted at wind speed of 3.7 m/s.
2. The fire control time in Fig. 9 has been defined as the time required for achieving the 90% heat radiation. Fig. 9 shows that the pool fire control time is reduced with increasing HEX application rate as expected, but this provides an important built in safety factor against unexpected adverse conditions at the time the systems are activated in an incident. It is clear that the foam controls the fire by blanketing the LNG pool surface, thus the faster the blanketing time, the faster the foam controls the pool fire, and thus greatly reduces back radiation into the pool.
3. The 45-m^2 pit, with twice the depth of the 65-m^2 pit (2.64 m versus 1.32 m) with no significant difference in LNG pool depth of 6 inches in both pits, showed different fire control behavior at the same 10 L/(min m^2) application rate. The 45-m^2 pit has significantly more hot concrete and hot LNG vapors to attack the foam and a seemingly more intense fire from the chimney effects, which made it harder to control. Experiment results show that it required more time for the foam to form an adequate depth, thus increasing the time to reduce heat radiation on the 45-m^2 pit.
4. The location of foam generators around larger pits and relative to the wind direction is important as large highly radiant flames may burn the generators and cause units to fail unless the foam generators have been specifically designed and tested to withstand these tough conditions. Constructing a line of foam generators could be a good solution to reduce foam transit distance, travel time, and time to achieve required depth.
5. Foam will stay on the surface of pool fire for a certain time (depending on the foam break down) so that even as the foam flow is stopped, foam is still functioning and later foam addition will help reduce heat radiation further until maximum heat radiation reduction is achieved.
6. It is important to design the LNG pool fire suppression system as one system. The containment dike should be designed to maximize the HEX application and vice versa. Separate design involving the two might bring drawbacks.

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Glossary

BFTF: Brayton Fire Training Field.
ESTI: Emergency Services Training Institute.
FT1: LNG Turbex foam generator 1.
FT2: LNG Turbex foam generator 2.
HEX: High expansion foam with expansion ratio of 500 to 1 produced by Angus Fire's Expandol foam solution with LNG turbex foam generator.
L: liter.
LNG: Liquefied natural gas.
m: Meter.
min: Minute.
TAMU: Texas A&M University.
TEEX: Texas Engineering Extension Service.