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The role of consequence modeling in LNG facility siting☆

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Abstract

Liquefied natural gas (LNG) project modeling focuses on two primary issues, facility siting and the physical layout of element spacing. Modeling often begins with an analysis of these issues, while ensuring code compliance and sound engineering practice. The most commonly performed analysis involves verifying compliance with the siting provisions of NFPA 59A, which primarily concern property-line spacing (offsite hazard impacts). If the facility is located in the US, compliance with 49 CFR 193 is also required. Other consequence modeling is often performed to determine the spacing of elements within the facility (onsite hazard impacts). Often, many issues concerning in-plant spacing are addressed with the guidance provided in Europe's LNG standard, EN-1473. Spacing of plant buildings in relation to process areas is also a concern as analyzed using the approach given in API RP 752. Studies may also include probabilistic analysis, depending on the perceived risk and cost of mitigation.

Keywords: Liquefied natural gas; In-plant spacing; Consequence modeling; LNG

1. Introduction: using modeling for siting of a typical LNG facility

An example of consequence modeling used to locate and lay out an liquefied natural gas (LNG) liquefaction and export terminal illustrated in this paper is similar to many such facilities located around the world. The historical safety record of these facilities has been excellent—not a single member of the public has ever been fatally injured as a result of a spill, fire or explosion at any natural gas liquefaction/LNG export facility. This is due in part to the design codes followed by the designers, constructors, and operators of these facilities, as detailed in NFPA 59A (2001), *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*. This code contains requirements related to siting, design, construction, fire protection, and safety. This paper presents the application of a modeling study to provide project personnel with sufficient information to establish a process plant layout and then locate it such that the:

- Proposed facility design located at the proposed site meet the NFPA 59A requirements regarding thermal radiation protection distances and flammable vapor clouds. (These requirements primarily address concerns at the property line.)
- Layout and spacing of equipment within the facility boundaries meet the NFPA 59A prescriptive minimum spacing criteria.

The scope of this preliminary analysis covers the liquefaction process and LNG storage vessels, as well as any related impounding or drainage systems. Many of the design parameters for the facility are still subject to change. By referring to the study results, the project can use the information and tables to determine an optimal layout. Changes in these parameters could affect the results of this safety study and might require additional analysis.

2. Description of the LNG facility

The proposed site of the gas liquefaction and LNG storage and export facilities is at the coast. The liquefaction plant will include equipment that refrigerates a clean incoming gas stream, ultimately turning it into a liquid (LNG) so that it can be more readily stored and transported.

The liquefaction plant will have a nominal design capacity of 3.0 million tones per annum (mtpa). The proposed facility will include two 140,000 m^3 LNG storage tanks. The storage tanks will be single containment, with internal pumps and all LNG and vapor connections going through the roof (dome) of each tank.

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The facility will also include a jetty dedicated to loading LNG tank ships. Submersible pumps located within each LNG storage tank will pump LNG through one or two large-diameter pipes, from the tanks to the jetty head, where articulated loading arms will transfer the LNG cargo to the tank ship. The rate at which LNG will be transferred to the ship has been tentatively set at more than 10,000 m^3/h.

3. NFPA 59A LNG code guidelines

NFPA 59A is an internationally recognized standard for siting of LNG facilities. While not the only standard for LNG facilities, it makes numerous references to other NFPA standards, API standards and other internationally recognized standards that typically meet client requirements and are recognized by both financial institutions, such as World Bank and major underwriting agencies.

The value of using NFPA 59A lies with its world-wide recognition and extensive use of other internationally recognized standards. This section will discuss NFPA 59A requirements for siting.

3.1. Impounding system required by NFPA 59A

NFPA 59A requires any LNG container, process area, vaporization area or transfer area to have an impounding system capable of containing the quantity of LNG that could be released by an incident involving the component served by each particular impounding system. According to the definitions in the code, an LNG container is any vessel used for storing LNG. A transfer area is defined as any area where LNG or other flammable liquid is introduced to or removed from the facility. Transfer areas do not include permanent plant piping. Process areas include pump installations and process vessels that contain LNG but are not used for LNG storage. Thus, within the scope of this analysis of the proposed facility, LNG spill impounding systems should be provided for the following equipment:

- LNG storage tanks.
- LNG transfer pumps (between the liquefaction unit and the storage tanks).
- LNG cold boxes.
- Jetty head transfer arms.

Each of the areas listed above must have an LNG spill impounding system, although each one is not required to have a separate impounding system. One properly designed impounding system, can serve two or more areas. In such cases, spills of LNG would be directed to one or more shared impounding basins by the use of curbing and drainage trenches (channels).

Requirements for impounding systems for process areas and transfer areas are basically the same. Therefore, the following statement from NFPA 59A pertains to the impounding system for both areas.

> "Impounding areas, if provided to serve only vaporization, process, or LNG transfer areas, shall have a minimum volumetric capacity equal to the greatest volume of LNG, flammable refrigerant, or flammable liquid that could be discharged into the area during a 10 min period from any single accidental leakage source or a shorter time period based upon demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction."

Although NFPA 59A does not require providing impounding systems for permanent piping, the single accidental leakage source normally assumed for the purpose of computing the minimum acceptable volumetric capacity of an impounding system for process equipment is the full rupture of the largest diameter pipe connected to the process equipment.

When calculating the release rate from the ruptured pipe, simply setting the release rate equal to the normal flow rate is not sufficient; the arrangement of the piping system and the effect of decreased backpressure on the pumps must be taken into account.

For example, if a full rupture occurs in a piping system downstream of a pump, the flow rate of LNG will increase due to reduced backpressure on the pump. The total release rate in such a situation will certainly exceed the normal flow rate.

The liquid containment portion of an LNG spill impounding system required by NFPA 59A need not be located such that it surrounds the container or piece of equipment that is assumed to be the leak source; however, that container or piece of equipment should be surrounded by a drainage system that will direct any released LNG to an impounding area of sufficient volume. Such systems are often used for impounding spills from process or transfer areas. We have assumed that the following three such impoundment areas will be incorporated into the design of the proposed facility, one for spills in the liquefaction plant, one for the NFPA 59A 10 min design spill from each LNG tank (see Section 3.2), and one at the jetty head loading platform.

The impoundment sizing requirements for LNG containers (i.e., storage tanks) are very simple and are stated below:

> "Impounding areas serving LNG containers shall have a minimum volumetric holding capacity... [that] equals the total volume of liquid in the container, assuming the container is full."

The containment area surrounding each LNG storage tank must fulfill this requirement.

3.1.1. Spill impounding area

Each specified design spill must be contained within a spill impounding area. The volume of the impoundment must be large enough to contain the entire volume of the associated design spill. For design spills with unspecified release rates, Bechtel uses the software package, CANARY by Quest (Appendix A), to calculate the accidental release rate [2].

The minimum volumetric capacity of the associated impounding area and the duration of the release are set by this rate. Various combinations of length, width, and depth of the impoundment can provide the required minimum volumetric capacity. We typically attempt to limit the depth of impounding areas for design spills at less than 3 m where possible. (The reasons behind this are associated with cost of construction, water table issues, and safety and maintenance issues related to deep impounding areas.)

CANARY is used to calculate the rate at which the released LNG will vaporize from the spill impounding area. Depending on the authority having jurisdiction, vapor dispersion calculations are performed either with the CANARY model or DEGADIS. Section 2.2.3.3 recommends using DEGADIS, but allows the use of other models that meet certain requirements. (The dense gas vapor dispersion model in CANARY meets the requirements for such models in Section 2.2.3.3(c) of NFPA 59A.)

Whenever possible, we construct impounding areas (for design spills) from standard concrete. This is generally the lowest cost alternative. If initial vapor dispersion calculations indicate the vapor cloud exclusion zones are unacceptably large, we run a series of calculations with varying dimensions for the impounding area and varying densities for the concrete until we identify one or more combinations that meet code requirements regarding vapor cloud exclusion zones.

We do not calculate vapor dispersion distances for instantaneous releases of the entire contents of LNG storage tanks, unless directed to do so by the client. There are two primary reasons for not doing this calculation, as listed below:

1. This is not a design spill according to NFPA 59A. (LNG design/safety codes in use around the world do not require this calculation.)
2. The probability of a catastrophic failure of an LNG storage tank is very low, and, if such an event were to occur, the probability of immediate ignition of the released LNG is very high. Thus, the probability of a catastrophic tank failure occurring and producing a very large flammable vapor cloud is very small. (This is the same reasoning used by the Department of Transportation when it prepared 49 CFR 193, the U.S. federal code for LNG plants, which does not require consideration of this event.)

Additionally, with respect to full containment tanks, we do not calculate vapor dispersion distances for a sudden release of the entire contents of the inner tank into the outer tank (with resulting loss of the outer roof), unless directed to do so by the client. The reasons for this are the same as stated above for a catastrophic failure of the tank.

3.1.2. Fire radiation calculations for impounding areas

Section 2.2.3.2 of 59A specifies the required limits for fire radiation at property boundaries. Depending on the authority having jurisdiction, fire radiation calculations are performed either with the CANARY model or LNGFIRE III. (The pool fire radiation model in CANARY meets the requirements for such models in Section 2.2.3.2(b)(1) of NFPA 59A.)

If the fire radiation calculations are being performed to check compliance with Section 2.2.3.2 (which is concerned with the impact of fire radiation on areas outside the LNG plant), we use the three endpoints of 5, 9, and 30 kW/m^2, as specified by 59A. However, we do not limit calculations based solely on the atmospheric weather conditions prescribed in Section 2.2.3.2(a). Bechtel uses more conservative weather conditions than those prescribed in Section 2.2.3.2(a) when performing fire radiation calculations [4].

NFPA 59A guidelines call for using zero wind speed when making fire radiation calculations. This can result in predictions that are not conservative since it ignores the influence of wind on flames. In nearly all cases, the predicted distances to the three endpoints of interest will increase as the wind speed used in the calculations is increased. Rather than use zero wind speed, we typically use 9 m/s if wind data are not available for the site. If wind speed data are available, we typically use the wind speed that is not exceeded more than 5% of the time.

The distances to specified fire radiation isopleths predicted with the pool fire model in CANARY compare well with those predicted by LNGFIRE III, with the predicted distances from CANARY exceeding those from LNGFIRE III in nearly all cases. However, the pool fire model in CANARY is much more versatile than LNGFIRE III. As a result, we tend to use CANARY rather than LNGFIRE III unless the authority having jurisdiction requires the use of LNGFIRE III.

3.2. NFPA 59A design spills

Section 2.2.3.5 provides a table that defines the design spill for LNG containers with over-the-top connections. The design spill is defined as:

> "...the largest flow from any single line that could be pumped into the impounding area with the container withdrawal pumps(s) delivering the full rated capacity: (1) for 10 min if surveillance and shutdown is demonstrated and approved by the authority having jurisdiction: (2) for the time needed to empty a full container where surveillance and shutdown is not approved."

For impounding areas serving only vaporization, process, or LNG transfer areas, the design spill flow rate and duration are defined as:

> "... the flow from any single accidental leakage source...for 10 min or for a shorter time based on demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction."

To maintain compliance with NFPA 59A, this LNG facility will be equipped with a comprehensive spill detection system, as well as a fire and gas detection system (FGS) that complies with NFPA 72. The FGS provides input to the Safety Instrumented Systems (SIS) to shutdown the process, isolate process elements and de-inventory.

In the event of a large LNG spill, these systems should be capable of detecting the spill and initiating an emergency shutdown in less than 3 min, thereby isolating the release source. Thus, the sizes of design spills and volumes of impounding systems for process and transfer areas could be based on a 3-min spill time.

When calculating the required size of the LNG spill impounding area for the liquefaction train, we assumed the leak rate from the LNG piping downstream of the LNG product pump would be 30% greater than the normal flow rate (which was supplied as 1219 m^3/h). The same assumption was made when calculating the size of the LNG spill containment sump for the 10-min design spill from the LNG storage tanks. (The actual difference between the normal flow rate and the spill rate for each of these releases will depend on the pump curves. If necessary, the release rate calculations can be corrected once the pumps have been specified.)

For an LNG spill from one loading arm at the jetty head, it was assumed that Powered Emergency Release Couplings (PERCs) and a comprehensive spill detection system will be installed. With these devices, a leak or rupture within the transfer system can be shut down quickly. Because this area is continuously manned during transfer operations, and the PERC or other shutdown devices can be triggered based on several signals (e.g., fire, gas detection, low temperature), we assumed a maximum release time of 1 min. Thus, the spill rate for a loading arm failure consists of one-half the maximum loading rate for 1 min. A corresponding impoundment was sized based on the assumption of containing the amount of released LNG that reaches the loading platform. Because of the physical and process conditions of LNG at the jetty head, only about 60% of the released liquid will fall to the loading platform. (This assumes a 1-m release height.) The remaining 40% will form an aerosol cloud that moves downwind. When this behavior is accounted for, the 29 m × 15 m loading platform requires a 4.5-in. curb to contain the LNG released over a 1-min period.

NFPA 59A Section 2.2.3.1 excludes transfer areas at the water's edge of marine terminals from the flammable vapor and fire radiation siting provisions. This area must still include an impoundment for liquid spills, but the vapor dispersion and fire radiation hazards following that spill do not need to be used in the layout and spacing of the facility.

Table 1 presents the sizing and modeling parameters associated with the three NFPA 59A design spill impoundment areas. Each single-containment LNG storage tank will be required to have a spill containment sump (size based on the 10-min pumpout design spill) in addition to the diked area that forms the secondary tank impoundment.

3.3. NFPA 59A LNG vapor dispersion scenarios

For each design spill specified in Section 2.2.3.5, Section 2.2.3.4 requires calculation of flammable vapor dispersion distances in order to "minimize the possibility of a flammable mixture of vapors from a design spill... reaching a property line that can be built upon and that would result in a distinct hazard." Thus, a vapor dispersion calculation for each of the spill impoundment areas is required, based on the parameters defined in Sections 2.2.3.4 and 2.2.3.5.

The model used to predict the flammable vapor dispersion must also take into account the physical factors that affect LNG, must have been validated by experimental data, and must be acceptable to the authority having jurisdiction.

3.3.1. Assumptions utilized in vapor dispersion calculations for design spills

Section 2.2.3.3 of NFPA 59A requires modelers to perform vapor dispersion calculations for a set of specified LNG design spills.

Assumptions used during these calculations include the following: the LNG tank contains internal pumps; all its connections pass through the roof of the tank (over-the-top connections); the design spill duration is 10 min; the release rate equals the largest flow from any single pipe at the tank; and the pumps deliver LNG at their full rated capacity. These assumptions are often referred to as the full pumpout rate spill. Subsequent calculations generally identify the largest potential design spill at an LNG liquefaction/export facility.

Assumptions related to release durations vary. Typically modelers utilize a release duration of only 1 min for a spill from a cargo transfer arm since cargo transfer operations are monitored closely and incorporate sophisticated hazard detection and emergency shutdown systems. For spills of LNG from process equipment and pumps in liquefaction trains, they typically assume a release duration of from 3 to 10 min. The latter assumption is based on the ability of facility personnel to quickly detect a spill and activate the emergency shutdown systems, which then closes isolation valves and opens depressuring valves, thereby limiting the amount of hydrocarbons released.

3.3.2. Vapor cloud explosions

None of the codes/standards/guidelines for LNG make any specific reference to or requirement for vapor cloud explosion (VCE) modeling. However, Bechtel performs a series of VCE calculations for confined or congested locations where flammable vapors could accumulate within the facility. These calculations by CANARY are based on the Baker-Strehlow explosion model [5].

This information is then used according to API RP 752 guidelines detailed in "Management of Hazards Associated with

Table 1
Spill impoundment modeling parameters

Description	Normal flow rate (kg/s)	Duration (min)	Impoundment size (m)	Basis
Release from one LNG loading arm	600	1	15 × 29 × 0.1143	1/2 Maximum loading rate (5000 m^3/h)
Release of LNG from liquefaction train into process impoundment	147	3	5 × 6 × 7	LNG liquefaction rate
Release of LNG from storage tank pumpout line	600	10	10 × 14 × 5.5	Maximum pumpout rate from one tank

Location of Process Plant Buildings” to locate occupied process buildings and determine the various buildings’ design criteria. The subject using dispersion modeling to locate all types of buildings based on an occupancy criteria (per API RP 752), and other buildings based on risk assessment of business interruption loss and capital costs are beyond the scope of this paper. To date, the Occupational Safety and Health Administration (OSHA) has issued 93 citations for improper siting, but has provided almost no guidance related to proper siting.

3.4. NFPA 59A LNG pool fire scenarios

Section 2.2.3.2 of NFPA 59A requires calculation of thermal radiation protection distances for each impounding area required by Section 2.2.2.1, and for ignition of the design spills defined in Section 2.2.3.5. Impounding area calculations are based on the assumption that the LNG is burning and the impounding area contains a volume of LNG equal to the minimum volume computed in accordance with Sections 2.2.2.1, 2.2.2.2, or 2.2.3.5, whichever is applicable. In addition, if the plant design employs spill drainage trenches and impounding systems that are not required by the code, it is standard practice to calculate thermal radiation protection distances for those systems as well.

NFPA 59A requires calculation of all thermal radiation distances by using a model that considers impoundment configuration, wind speed, humidity, and atmospheric temperature, which have been validated with experimental data and are acceptable to the authority having jurisdiction.

4. Consequence modeling

The focus of this analysis was to estimate potential hazards resulting from design spills specified by NFPA 59A. Each design spill is a release of LNG into a specific impounding area. For each impounding area, vapor dispersion and/or fire radiation calculations are done. These types of releases generally represent specific scenarios that control the spacing of plant equipment in relation to the facility boundaries (i.e., the public).

All calculations for this analysis were performed with the CANARY by Quest® consequence modeling package. When performing a site-specific consequence analysis, the ability to accurately model the release, dilution, and dispersion of gas is important to attain an accurate assessment of potential impact. For this reason, Bechtel uses the CANARY modeling package, which contains a set of complex models that calculate release conditions, initial dilution of the vapor (dependent upon the release characteristics) and the subsequent dispersion of the vapor introduced into the atmosphere. The models contain algorithms that account for thermodynamics, mixture behavior, transient release rates, gas cloud density relative to air, initial velocity of the released gas and heat transfer effects from the surrounding atmosphere and the substrate. The release and dispersion models contained in the QuestFOCUS package (the predecessor to CANARY by Quest) were reviewed in a United States Environmental Protection Agency (EPA) sponsored study ([3]) and an American Petroleum Institute (API) study [2]). In both studies, the QuestFocus software was evaluated on technical merit (appropriateness of models for specific applications) and on model predictions for specific releases. One conclusion drawn by both studies was that the dispersion software tended to over predict the extent of the gas cloud travel, thus resulting in a cloud that is larger than shown by the test data (i.e., a conservative approach).

A study prepared for the Minerals Management Service [1] reviewed models for use in modeling routine and accidental releases of flammable and toxic gases. CANARY by Quest received the highest possible ranking in the science and credibility areas. In addition, the study recommends CANARY by Quest for use when evaluating toxic and flammable gas releases. Specific vapor dispersion models (e.g., SLAB) contained in the CANARY by Quest software package have also been extensively reviewed. These models account for the parameters required by NFPA 59A.

CANARY also contains a model for pool fire radiation. This model accounts for impoundment configuration, material composition, target height relative to the flame, target distance from the flame, atmospheric attenuation (includes humidity), wind speed and atmospheric temperature. It is based on information in the public domain (published literature) and has been validated with experimental data.

4.1. Modeling parameters

The wind speed and atmospheric stability to be used when calculating the extent of each flammable vapor cloud are specified in NFPA 59A 2.2.3.3. These include “the combination of wind speed and atmospheric stability that can occur simultaneously and result in the longest predictable downwind dispersion distance which is exceeded less than 10% of the time” or, alternatively, Pasquill-Gifford stability Category F with a 2.0 m/s (4.5 mph) wind speed. For this study, the following conditions were used for all vapor dispersion calculations.

Wind speed	2 m/s
Atmospheric stability	Pasquill-Gifford Class F
Air temperature	24 °C
Relative humidity	90%

NFPA 59A 2.2.3.2 requires the calculation of fire radiation based on the assumption of zero wind speed. Flames above pool fires will rise vertically if there is no wind, but will be tilted from vertical if the wind is blowing. Tilting of the flame can cause the distance to a specified thermal heat flux to increase, particularly in the direction downwind of the pool. Thus, the assumption of zero wind speed is most often not the conservative assumption. Consequently, the distances to the heat fluxes specified in NFPA 59A were calculated twice; once using the parameters prescribed by NFPA 59A, and once with site-specific, high wind conditions. Fire radiation modeling parameters are listed in Table 2.

The site-specific values were taken from weather data spanning several years. The wind speed value of 7 m per second represents a wind speed that is exceeded only a small percentage

Table 2
Fire radiation modeling parameters

Parameter	NFPA 59A	Site-specific
Wind speed (m/s)	0	7
Air temperature (°C)	21	24
Relative humidity (%)	50	90

of the time at this site. It therefore represents a credible worst-case scenario for fire radiation. The values of air temperature and humidity are simple averages from the provided weather data. These conditions are more accurate representations of the actual conditions at the proposed site, with a worst-case wind speed.

4.2. Hazard endpoints

For the LNG tank design spills defined in Section 2.2.3.5 of NFPA 59A, Section 2.2.3.3 requires the average concentration of methane in air not to exceed 50% of the lower flammable limit at the property line that can be built upon. For the LNG design spills specified in Section 2.2.3.5, Section 2.2.3.4 states “provisions shall be made to minimize the possibility of a flammable mixture of vapors from a design spill. . . reaching a property line that can be built upon and that would result in a distinct hazard.” This appears as though the restrictions are only on vapor clouds from tank design spills. However, Tentative Interim Amendment 01-2(NFPA 59A) deletes Section 2.2.3.4. In its absence, according to the NFPA, the wording in Section 2.2.3.3 is to be applied to all LNG design spills, not just the tank design spill. The objective of the flammable vapor calculations is to find the distance to 1/2 of the lower flammable limit (1/2 LFL) for each of the design spills.

4.3. Results for LNG storage and impoundment scenarios-vapor clouds

The size of the flammable vapor cloud created by a release of LNG depends on several factors, including the rate at which LNG vapor is introduced into the air and weather conditions. The rate at which LNG will vaporize upon release is the sum of the vaporization rate due to flashing and the rate of vaporization due to heat transfer from the impounding system. The vaporization rate due to flashing is controlled by the LNG release rate and the temperature of the LNG prior to its release. If the LNG is superheated, some of the released LNG will flash to vapor.

Table 4
Flammable dispersion distances

Description	Maximum downwind distance (m) to	
	LFL	1/2 LFL*
10-min spill from LNG tank pumpout line into spill containment diked area	**	**
	**	**
3-min spill from liquefaction process into impoundment	70	115

* These values are to be used for siting purposes.
** Vapor cloud does not leave the main diked area.

Table 5
LNG fire radiation scenarios—NFPA 59A conditions

Description	Maximum downwind distance (m) from center of impoundment to thermal radiation endpoint		
	30 kW/m²	9 kW/m²	5 kW/m²
Spill containment sump for 10-min LNG tank spill (14 m × 14 m)	20	45	60
Liquefaction process impoundment (5 m × 6 m)	6	15	22
Fully-involved LNG tank impoundment fire (140 m × 210 m)	180	310	400

As the amount of superheat increases, the percentage of LNG that will flash to vapor upon release also increases. The rate of vaporization due to heat transfer depends on the release rate, the amount of Flash vaporization, the size and shape of construction materials and surface temperature of the impounding system. Table 3 represents the end points and their correlating descriptions as defined in NFPA 59A.

Table 4 presents the computer-generated flammable mixture dispersion distances for the three NFPA 59A design spills considered in this study. The vapor dispersion calculations were based on the construction of impounding areas of low density concrete that is suitable for cryogenic service. In our example, the onshore flammable dispersion vulnerability zones (defined by the 1/2 LFL hazard distance) from Table 4 could be superimposed on a proposed plot plan.

Tables 5 and 6 detail the predicted fire radiation hazard distances for the LNG pool fire scenarios considered in this study,

Table 3
Maximum heat flux levels

Flux level (kW/m²)	Description
30	Maximum flux at a property line that can be built upon for an impounding area fire whose size is determined by Section 2.2.2.1
9	Maximum flux at the nearest point on a building or structure outside the property line used for assembly, education, health care, detention or correction or residence, for an impounding area fire whose size is determined by Section 2.2.2.1
5	Maximum flux at the nearest point outside the property line used for outdoor assembly by groups of 50 or more persons, for an impounding area fire whose size is determined by Section 2.2.2.1
	Maximum flux at a property line that can be built upon for ignition of a design spill defined in Section 2.2.3.5

Table 6
LNG fire radiation scenarios—site-specific conditions

Description	Maximum downwind distance (m) from center of impoundment to thermal radiation endpoint		
	30 kW/m^2	9 kW/m^2	5 kW/m^2
Spill containment sump for 10-min LNG tank spill (14 m × 14 m)	45	60	75
Liquefaction process impoundment (5 m × 6 m)	20	25	30
Fully-involved LNG tank impoundment fire (140 m × 210 m)	240	360	435

under the two sets of weather conditions presented in Table 2. The fire radiation exclusion zones for fires in the tank 10-min pumpout containment sump and the process impoundment area required by NFPA 59A would then be superimposed on the plot plan. Tables 5 and 6 show the 5 kW/m^2, 9 kW/m^2, and 30 kW/m^2 vulnerability zones for the fully-involved LNG tank impoundment fire.

Table 5 lists the code-defined fire radiation exclusion zones (5, 9, or 30 kW/m^2) that identify the limits of a property line that can be built upon. The 5 kW/m^2 exclusion zone could extend over the ocean because the shoreline is not a property line that can be built upon. Thus, the facility would be in compliance with the NFPA 59A thermal radiation siting criteria.

5. Acceptability of proposed site

With regard to public safety, NFPA 59A would judge a proposed site for an LNG facility as acceptable if the proposed facility can be placed on the site without violating any of the siting restrictions, particularly those related to flammable vapor clouds and fire radiation hazard zones. This section discusses the acceptability of a proposed site.

5.1. Adjacent activities and land use

It will be important for project personnel to ensure that sufficient land over which the operator can exert control is identified. This includes not only the plant proper but also the required space for the jetty, storage and accessibility for personnel and equipment.

5.2. Flammable mixture dispersion distances

Table 2 illustrates the 1/2 LFL vulnerability zones associated with design spills, as required by NFPA 59A. The 1/2 LFL zones from the 10-min tank pumpout design spill are not presented because they are contained within the main dike wall for each LNG tank. Because the 1/2 LFL zones from the tank pumpout spill impoundment and the liquefaction process area impoundment cannot extend beyond the fence line, the facility must ensure that it complies with the NFPA 59A vapor dispersion siting provisions.

5.3. Thermal radiation protection distances

To be in compliance with the siting requirements of NFPA 59A, the impacts of thermal radiation heat flux must be considered for the following cases:

- Design Spills specified by Section 2.2.3.5.
- A fully-involved LNG tank impounding area fire.

5.3.1. Design spills

The thermal radiation heat flux associated with a fire involving design spills specified in Section 2.2.3.5 of NFPA 59A cannot exceed 5 kW/m^2 at any onshore portion of the facility's property line.

5.3.2. Fully-involved LNG tank impounding area fire

Section 2.2.3.3 requires that the radiant heat flux from any LNG tank impoundment area fire (in this case, a fully involved fire over the diked area) cannot exceed the following limits:

- 30 kW/m^2 at any onshore portion of the facility's property line;
- 9 kW/m^{2}at the nearest point of any building used as a residence, or special occupancy, such as a school, prison, hospital, or place of worship; or
- 5 kW/m^2 at any area used as an outdoor point of assembly by groups of 50 or more persons.

6. General site layout

NFPA 59A siting requirements related to LNG vapor clouds and fires are intended to help prevent injuries or fatalities to persons outside the LNG facility boundary. These requirements affect the layout and spacing of equipment within the facility boundary only to the extent that LNG spill impounding systems must be located far enough from the boundary to ensure that the radiant heat flux levels from fires and vapor concentration levels due to dispersion of flammable vapors do not exceed acceptable values at the plant boundary. In addition, NFPA 59A contains several requirements pertaining to layout and spacing that are not based on model calculations. Some of those that apply to the proposed LNG facility are paraphrased below.

2.2.3.8 In no case shall the distance from the nearest edge of impounded liquid to a property line that may be built upon, or the near edge of a navigable waterway, be less than 15 m.

2.2.4.1 The minimum distance between the shell of an LNG storage tank and the facility property line is 70% of the tank diameter or 30 m, whichever is greater. The minimum distance between outer walls of two adjacent LNG tanks is 1/4 of the sum of the diameters of the two tanks.

2.2.6.1 Process equipment containing LNG, flammable refrigerants, flammable liquids or flammable gases must be located at least 15 m from:

- Sources of ignition.
- Facility property line that can be built upon.
- Control room, offices, shops, and other occupied structures.

2.2.6.2 Fired equipment and other sources of ignition must be located at least 15 m from any impounding area or spill damage system.

The proposed facility layout must meet all of the NFPA 59A spacing requirements above. The liquefaction process layout should be reviewed to ensure compliance with Section 2.2.6.2.

Once code compliance issues have been satisfied, the Plant Layout and Design (PL&D) staff can start to optimize the equipment arrangement to meet operating and maintenance requirements. Historically, much has been published on optimization of plant layouts, and such guidelines as the Dow Index and the MOND Index have been used extensively. In addition, many operators have their own standards as well as guides published by underwriting agencies.

Bechtel uses these sources, along with the results from the CANARY modeling program, to identify the boundaries of vapor dispersion and heat flux from major hydrocarbon sources to attain optimal facility layout. Utilizing the information in Tables 7 and 8, PL&D staff can continually refer to site compliance issues and consider their effects on loss prevention to assess various proposed process equipment locations and identify the most cost effective operational design.

6.1. In-plant layout and spacing

NFPA 59A does not require the use of vapor dispersion or fire radiation models for resolving layout issues within LNG plants. Instead, it contains a simple set of prescribed minimum separation distances, such as requiring process equipment to be at least 15 m from control rooms, offices, shops, etc.

The European code for land-based LNG plants (EN 1473) provides guidance on using fire radiation calculations to identify minimum separation distances within LNG plants. The recommended maximum allowable radiation flux on the unprotected concrete outer surface of an adjacent LNG tank is 32 kW/m^2, or behind thermal protection on such a tank.

The recommended maximum allowable radiation flux on the unprotected metal outer surface of an adjacent LNG tank is 15 kW/m^2.

EN 1473 lists LNG-tank-related pool fire scenarios that could be considered in a hazard assessment. It recommends including a pool fire within the full tank impounding area when single containment tanks are used. For double containment tanks and full containment tanks with metal roofs, EN 1473 recommends consideration of a roof collapse, leading to a fully-involved pool fire in the secondary containment (i.e., a tank-top fire). Roof collapse is not considered for full containment tanks with concrete roofs, thus there is no pool scenario for such tanks.

We typically model the fire radiation from a tank-top fire unless the roof is concrete. The design basis for a full contain-

Table 7
Vapor dispersion

Case	Description	Hole size	Distance		
			LFL	50% LFL	25% LFL
1a	Release from liquefaction discharge line	Rupture	490	645	860
		Puncture	170	250	355
1b	Release from liquefaction discharge line near storage	Rupture	270	495	895
		Puncture	130	210	325
2a	Release suction line outside cold box	Rupture	335	445	780
		Puncture	100	160	255
3a	Release from propane accumulator	Rupture	965	1270	1660
		Puncture	260	370	520
3c	Release from propane accumulator inlet line	Rupture	810	1065	1395
		Puncture	260	365	510
5a	Release from transfer line to Jetty (spill onto soil)	Rupture	1045	2185	4570
		Puncture	235	325	450
5b	Release from transfer line to Jetty (spill onto water)	Rupture			
		Puncture			
6a	Release from propane storage drum	Rupture	300	405	540
		Puncture	165	230	320
7a	Release from ethylene storage drum	Rupture	375	495	655
		Puncture	220	295	415
8a	LNG tank top failure	Rupture	380	580	1415
		Puncture			
10a	Release from ethylene storage drum	Rupture	745	975	1285
		Puncture	305	425	590

Rupture = full-bore rupture. Hole size equals pipe diameter. Puncture = hole size equals 2-in. diameter.

Table 8
Fire radiation

Case	Description	Hole size	Distance (m)		
			30 k W/m^2	15 k W/m^2	5 k W/m^2
1a	Release from liquefaction discharge line	Rupture	95	110	130
		Puncture	30	35	45
1b	Release from liquefaction discharge line near storage	Rupture	55	60	75
		Puncture	25	30	35
2a	Release suction line outside cold box	Rupture	120	140	165
		Puncture	20	25	30
3a	Release from propane accumulator	Rupture	320	385	460
		Puncture	50	60	75
3b	BLEVE of propane accumulator	BLEVE			
3c	Release from propane accumulator inlet line	Rupture	250	300	345
		Puncture	50	60	75
5a	Release from transfer line to Jetty (spill onto soil)	Rupture	140	175	215
		Puncture	30	35	40
5b	Release from transfer line to Jetty (spill onto water)	Rupture			
		Puncture			
6a	Release from propane storage drum	Rupture	85	100	125
		Puncture	45	55	65
	BLEVE of propane storage drum	BLEVE	325	495	710
7a	Release from ethylene storage drum	Rupture	85	105	130
		Puncture	65	80	100
	BLEVE of ethylene storage drum	BLEVE	110	165	240
8a	LNG Tank top failure	Rupture	190	255	330
10a	Release from ethylene storage drum	Rupture	210	235	295
		Puncture	50	60	70

ment tank is partly based on the requirement for the outer tank to be capable of withstanding the effects of a release of LNG from the inner tank into the outer tank, including the pressure increase that would occur as the released LNG vaporizes.

The size of the release that must be considered is not specified, but left to the tank designers, plant owners, etc. Since the basis for the release size is arbitrary, we believe it is prudent to assume a larger release is possible, thus making failure of the roof on a full containment tank a possibility.

When single containment tanks are selected, we typically model the fire radiation from a full impounding area fire. Some clients choose to locate the liquefaction plants outside the 15 kW/m^2 vulnerability zones associated with this fire. Other clients allow parts of process areas (such as liquefaction trains) to be located within the 15 kW/m^2 vulnerability zones, based on the very low probability of a fully involved impounding area fire and additional measures intended to mitigate excessive heat flux.

Another use for the 15 kW/m^2 isopleth is to consider the effect of a fire when looking at the spacing of major pieces of process equipment. Typically, when more likely scenarios indicate the possibility of heat flux in excess of 15 kW/m^2, a Fire Hazard Assessment (FHA) will be initiated (in compliance with Chapter 9 of NFPA 59A) to determine the most effective means of protecting exposed equipment. This will require passive protection in the form of drainage, fire/cold proofing and additional spacing.

The same dispersion models and heat flux models are used for the location of fire water underground piping, fixed system risers, hydrants and monitors. All of these play an important role when considering the possible effects and subsequent mitigation of an accidental release of LNG or flammable refrigerants.

NFPA 59A also references NFPA 72, which addresses the design, installation and operation of fire and gas detection systems. The CANARY modeling confirms the types of detection devices, their required response times and their physical location.

Using consequence modeling allows a well-documented, comprehensive evaluation of more likely events, which allows the most cost-effective design, safest layout, optimal site selection and passive/active safety systems possible.

This approach also allows exploration of various options to reduce risk and improve operability without resorting to “Tribal Knowledge” or guesswork. By specifically identifying more likely scenarios and modeling the consequences of various mitigating approaches, such as SIS, isolation, spacing, inventory reduction and depressuring, the results can be used to determine the safest, most cost effective solution.

6.2. Probability arguments

Much of the siting work for LNG facilities concerns code compliance and does not directly address the probability of the events that are modeled. Code compliance is not often thought of as a risk issue, but the siting portion of the codes can be interpreted as a backwards risk analysis. If one complies, the hazards will be in the acceptable range and thus the risk is usually acceptable. Many of the design spills required by NFPA 59A and other scenarios modeled for inner-plant spacing are rare events.

The probability of occurrence for major failures, such as full pipe breaks or tank-top fires is very low. These events are not expected to occur in the entire LNG industry during the lifetime of any one facility. Thus, if the plant is designed to withstand these types of events, the overall risk can be thought of as low. Of course, this does not quantify the risk. Risk quantification requires a much more detailed study.

Probability is also addressed through the selection of accidents for non-code scenarios. For example, a 2-in. hole size may be selected as the largest hole to be modeled for inner-plant spacing issues. Since it is an established fact that small release sizes occur more often than large ones, this type of accident is considered a more likely event and is used for the basis of design. In this way, probability is brought into the analysis. Furthermore, if the large, highly unlikely, catastrophic events were used to determine plant spacing, LNG facilities would be prohibitively expensive to locate due to the extensive land requirements.

One of the side issues that touches on probability is the use of site-specific weather conditions. The codes specify certain parameters that should be used in modeling, but this can give an artificial, worst-case bias to the cases modeled. Oftentimes, project personnel elect to address all of the cases using average wind speeds or temperatures, or with a prevailing wind direction. This better describes the more likely outcome due to environmental conditions should a release occur.

7. Conclusions

By using this analysis, the proposed LNG facility can meet the thermal radiation and vapor dispersion exclusion zone requirements of NFPA 59A. None of the exclusion zones from the code-defined spills can extend beyond a property line that can be built upon.

This analysis was performed assuming the project would strictly adhere to the prescriptive requirements of NFPA 59A relative to siting. The separation distances provided by the analysis identify all the selected facility layout parameters to meet all applicable NFPA 59A spacing criteria. Once equipment arrangement drawings and the site location plan have been finalized, further studies will be used to verify the location and design criteria for process buildings according to API RP 752.

The results presented in this paper are based on typical project information and would be subject to change if the process conditions or certain design parameters were modified. In addition to using consequence modeling to address code-imposed site selection and plant layout, modeling is used extensively in the detailed layout studies and FHAs conducted. Use of modeling expedites the process of determining the most cost effective and safest LNG plant possible.

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