Develop a Risk-Based Approach and Criteria for Hazard Detection Layout

Blue Engineering and Consulting Company

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Executive Summary

Fire and gas detection systems are required to be installed at LNG facilities by NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*, however, no requirements or guidance for the location of hazard detection devices is provided [1]. Literature available in the public domain outlines key factors to consider in developing layouts for flame detectors (e.g. size of fire to be detected, fuel involved, sensitivity and field of view of detector, including obstructions, etc.) and gas detectors (e.g. pressure, temperature, density of the released material, topography, air movement and temperature effects, location of potential ignition sources, etc.), but a methodology to use this information in developing a detector layout is not clearly defined; instead, generic and non-quantifiable terminology such as "quick and reliable" is often used. Further, available guidance repeatedly calls for gas detectors to be placed in proximity to potential leak sources, which is often interpreted as placing point gas detectors right next to likely leak locations (e.g., flanges, valves, pumps or other equipment). This attempt at detecting the leak instead of the resultant gas cloud is known to be flawed and could result in a failure to detect the release in many cases, depending on factors such as release orientation and wind direction. It is also difficult to detect pressurized releases close to the source, where the cross-sectional area of the jet is quite small.

The lack of a consistent approach to developing hazard detector layouts for land-based LNG facilities and of a systematic method for regulators to evaluate these designs are of particular interest to the Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), which regulates numerous LNG facilities in the United States. PHMSA specifies the use of a 10-minute design spill duration in their hazard analyses if the process design includes acceptable detection, isolation, and shutdown, however, applicants are also permitted to evaluate a release duration shorter than 10 minutes based on demonstrable surveillance, shutdown and isolation design. Since there is currently no standard for the design of hazard detection systems at LNG facilities, it follows that there is no consistent methodology for demonstrating or evaluating successful detection, isolation, and shutdown provisions.

Blue Engineering and Consulting Company (BLUE) was commissioned by DOT-PHMSA to lead this research project to develop a risk-based approach and criteria for hazard detector layouts at LNG facilities. This project builds upon performance-based design principles outlined in NFPA 72 *National Fire Alarm and Signaling Code* [2] and the International Society of Automation (ISA) technical report 84.00.07 *Guidance on the Evaluation of Fire, Combustible Gas, and Toxic Gas System Effectiveness* [3]. The ISA guidance describes how the total effectiveness of a fire and gas detection system is based on three factors: safety availability, mitigation effectiveness and detector coverage. While consideration should be given to all factors in LNG facility design, the current analysis is focused on detector coverage.

The proposed methodology closely follows the performance-based design process outlined in ISA TR84.00.07 and is summarized in the figure below. The Fire and Gas Detection Philosophy should be developed prior to assessing the facility risk or performing the hazard detector layout so that objective and unbiased performance criteria are clearly established, and all forthcoming decision-making is based on the risk tolerability of the project stakeholders. The methodology then divides the LNG facility into Detection Areas based on the hazards present and the plant layout, identifies the appropriate hazard scenarios to evaluate the detector layout, assigns performance targets within each Detection Area, and quantifies hazard detector coverage. This methodology can be utilized to develop a hazard detector layout, as well as evaluate existing layouts.

Step 1: Fire and Gas Detection Philosophy

- Set detector coverage targets (e.g., 60-80-90%)
- Set detector voting criteria (e.g., 1ooN, 2ooN)

Step 2: Designate Detection Areas

- Group areas of the facility that contain similar hazards
- Carry out Detection Area Evaluations to characterize the hazards

Step 3: Identify Hazard Scenarios

- Perform a fire and explosion risk assessment using a full range of release categories
- Perform a hole size sensitivity to determine which scenarios to include in the detector evaluation

Step 4: Assign Performance Targets

- Establish detector coverage and voting criteria for each flammable inventory in each Detection Area

Step 5: Flame Detector Evaluation

- Assess the flame detector layout using the geographic coverage approach

Step 6: Gas Detector Evaluation

- Assess the gas detector layout using the scenario coverage approach

As part of this performance-based approach, risk tolerance and harm criteria are utilized to determine which scenarios need to be detected. However, it must be noted that the proposed methodology is independent of the risk tolerance and harm criteria. Therefore, users may choose to develop and/or apply different criteria but remain able to adopt this methodology as described.

Given the well-defined field of view of flame detectors, detector coverage can be evaluated using the geographic coverage concept, where the coverage is defined by the fraction of a given area or volume that is seen by one or more detectors. While this task is most accurately quantified using 3D models, a qualitative assessment can be performed by evaluating detector locations and orientations relative to large obstructions present.

Unlike flame detectors, gas detectors do not have a well-defined field of view. As a result, the cloud must migrate to the location of the gas detector at a sufficient concentration in order for the detector to activate. An evaluation of a gas detector layout using geographic coverage would require an array of gas detectors, which is impractical and not well-suited to LNG facilities. Therefore, gas detector coverage is best evaluated using scenario-based coverage, which is defined by the ratio of detectable releases to total credible releases.

Scenario-based coverage is most accurately quantified using dispersion modeling tools, however, a qualitative evaluation can be performed by considering the most likely release locations (i.e. flanges, piping connections and instrumentation, etc.), potential release directions (considering nearby obstructions to pressurized jets), and the physics of flammable cloud formation (e.g. pressure, temperature and density of the released material, topography, large obstructions, etc.) to understand where flammable clouds are most likely to accumulate.

While risk tolerance, harm criteria, and performance targets must be chosen for the purposes of the demonstratives included in this report, these targets should not be interpreted as requirements of DOT-PHMSA nor as acceptable to them.

1 Introduction

PHMSA's federal safety regulations for siting, design, construction, operation and maintenance of LNG facilities are codified in 49 CFR Part 193. Fire protection requirements are given in Subpart I (193.2801) which references sections 9.1 through 9.7 and section 9.9 of the 2001 edition of NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*; there are no additional requirements given by 49 CFR 193.2801. NFPA 59A requires LNG facilities to be outfitted with equipment to detect and control fires, leaks, and spills of hazardous materials, however, it does not provide any guidance or requirements for the locations of hazard detection devices. The full responsibility for developing a hazard detection layout rests on the individuals responsible for conducting "an evaluation based on sound fire protection engineering principles" (2001 NFPA 59A, section 9.1.2).

Further, NFPA 59A establishes qualifications for individuals performing plant activities such as inspections or welding, yet it does not establish qualifications for the individuals performing the fire protection evaluation. As a result, the LNG industry lacks a uniform approach to hazard detection layouts and there is no systematic method for authorities to evaluate these designs.

Six editions of NFPA 59A have been released since the 2001 edition referenced by 49 CFR 193. NFPA 59A has grown considerably over the years in response to the evolution of the US and worldwide LNG markets. With respect to gas detection, the current edition (2019) includes requirements for gas detection systems to activate a second alarm at not more than 50% of the lower flammability limit (LFL), and permits gas detectors to activate portions of the emergency shutdown (ESD) systems; by contrast, the 2001 edition only permitted flame detection to activate portions of the ESD system and did not grant this power to gas detection. This shift in code requirements is representative of the importance placed by industry experts on gas detection at LNG facilities.

A single LNG facility can have hundreds of detectors, covering a wide range of hazards: combustible gas, toxic gas, high/low temperature, flame, as well as smoke in select enclosed areas. For example, at Cheniere's Sabine Pass LNG Terminal in Louisiana, a single liquefaction train contains about 150 hazard detection devices [4]. Regulators and underwriters require hazard detection systems to be installed at LNG facilities, and facility owners desire robust hazard detection systems to protect their employees and equipment, however, there is no industry standard for developing a hazard detection layout. As a result, the LNG industry lacks a consistent approach to developing hazard detection layouts and there is no systematic method for authorities to evaluate these designs.

With the increasing number of LNG facilities in the US, it is imperative to provide designers, owners, and AHJ's with publicly available research and guidance on hazard detection layouts, which is the purpose of this research project and this report.

2 Literature Review

This section provides a summary of guidance and guidelines currently available in the public domain for developing a hazard detection layout at hydrocarbon processing facilities. While the focus of this research project is onshore LNG facilities, the literature review was expanded to include guidance from the offshore oil and gas industry, which has a longer history of research and development. It must be noted that offshore installations are much more compact and congested than onshore installations, and living quarters are located in proximity to process areas. Therefore, overpressure hazards are a leading concern and the onset of unacceptable damage occurs at much smaller size flammable clouds than onshore facilities.

The literature review found that many resources are available to outline key parameters that must be considered in developing a hazard detection layout, however, performance targets for the hazard detection system are not clearly stated. Furthermore, there is no clear methodology for applying these considerations to onshore LNG facilities in a consistent manner, on the basis of physical hazards or safety targets.

2.1 Detection Equipment Evaluated

The literature review included a variety of documents available in the public domain such as applicable industry standards, recommended practices, journal articles, and product data sheets related to the hazard detection devices described below. The current research effort is focused on flammable gas detectors (point and open path) and flame detectors, both of which are used to initiate alarms and emergency shutdowns in accordance with NFPA 59A.

The authors recognize that many other hazard detection technologies are available, such as low-temperature detectors for cryogenic liquid spills, electrochemical detectors for toxic releases, acoustic leak detectors for high pressure releases, and various gas cloud imaging technologies; however, these are not within the scope of the current study.

2.1.1 Gas Detectors

The most common combustible gas detector at LNG facilities in the US is the infrared (IR) point gas detector. This detector measures infrared absorption at two wavelengths: one calibrated to the target gas and one reference wavelength. Point IR combustible gas detectors measure the gas concentration at a discrete location with a reading in %-LFL (lower flammability limit). A point IR gas detector activates in a matter of seconds, however, it requires the flammable cloud to overlap its specific location. This often results in the need for an array of point gas detectors to monitor a specific region of the facility. Point gas detectors are effective for monitoring areas where flammable clouds are likely to accumulate, tracking cloud growth, and monitoring potential ignition sources.

Open path gas detectors (also referred to as line-of-sight) are the long-distance version of the point IR gas detectors. With the ability to separate the IR source and receiver by distances greater than 100 meters, a single open path detector can cover a much larger area, but only along a straight line (e.g., at a single elevation). The IR source and receiver must maintain line-of-sight connection, therefore they can be difficult to use in congested or high traffic areas. Open path gas detectors measure the integral of the gas concentration along the path and output the result in LFL-m, equivalent to a meter-long gas cloud at LFL concentration. Under this measurement scheme, the same reading would be given for a large cloud at low concentration and a small cloud at high concentration. As a result, these detectors are effective for perimeter monitoring to ensure flammable gas does not extend from one area of a plant to another and for general leak detection.

2.1.2 Flame Detectors

Flame detectors are used at LNG facilities to detect hydrocarbon flames, such as pool fires and jet fires, as well as major equipment fires. Flame detectors generally have a field of view that extends approximately 45 degrees off the center axis, resulting in what is referred to as a “cone of vision”. The listed maximum range of a flame detector is on-axis (i.e., the range decreases approaching +/- 45 degrees), fuel specific, and determined for an unobstructed fire source.

Combination UV/IR flame detectors are designed to filter out solar radiation and are suitable for outdoor applications, however, they can be impacted by heavy smoke and generally have an effective range of less than 100 feet. Triple/Multi IR flame detectors have the highest immunity to false stimuli and are available with a range beyond 200 feet (depending on the target fuel). IR flame detectors have different sensitivity settings which adjust the maximum detection range, in order to avoid nuisance sources of radiation such as a flare.

2.2 Summary of Main References

2.2.1 NFPA 59A

NFPA 59A requires LNG facilities to be outfitted with equipment to detect and control fires, leaks, and spills of hazardous materials. The responsibility for developing a hazard detection layout rests on the individuals responsible for conducting “an evaluation based on fire protection engineering principles” (2019 section 16.2.1). While NFPA 59A establishes qualifications for individuals performing plant activities such as inspections or welding, it does not establish qualifications for the individuals performing the fire protection evaluation.

Six editions of NFPA 59A have been released since the 2001 edition currently referenced by federal regulations (49 CFR 193). NFPA 59A has grown considerably over the years in response to the evolution of the US and worldwide LNG markets. With respect to gas detection, the current edition (2019) includes requirements for gas detection systems to activate a second alarm at not more than 50% of the lower flammability limit (LFL)[1], and permits gas detectors to activate portions of the emergency shutdown (ESD) systems; by contrast, the 2001 edition only permitted flame detection to activate portions of the ESD system and did not grant this power to gas detection. This shift in code requirements is representative of the importance placed by industry experts on gas detection at LNG facilities.

NFPA 59A requires fire protection for all LNG facilities and for detection systems to be designed, installed and maintained in accordance with NFPA 72 *National Fire Alarm and Signaling Code*, however, it does not provide detailed performance targets for determining the location of hazard detection devices.

2.2.2 NFPA 72

NFPA 72 covers the application, installation, location, performance, inspection, testing, and maintenance of fire alarm systems; this includes initiating devices such as smoke, heat, flame and gas detectors. It requires designers to be experienced in the design, application, installation, and testing of the systems, and to follow state or local licensure requirements.

NFPA 72 offers prescriptive methods for determining the location of initiating devices such as heat-sensing and smoke-sensing fire detectors for indoor application, however, it does not offer prescriptive methods for locating gas and flame detectors outdoors. Such detectors need to be located using a performance-based design approach, which requires the designer to document each performance objective and applicable scenarios, along with calculations, modeling or other technical substantiation that justifies adequate protection. Therefore, flame and gas detector layouts developed for LNG facilities need to meet these requirements for performance-based design analysis and documentation.

Similar to NFPA 59A, NFPA 72 calls for the location of flame and gas detectors to be based on an "engineering evaluation". It continues to list the following considerations for flame detectors:

1) Size of the fire that is to be detected
2) Fuel involved
3) Sensitivity of the detector
4) Field of view of the detector (with warnings for obstructions)

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[1] Audible and visual alarm required at not more than 25% LFL or 1 LFL-m. Second alarm required by 50% LFL or 3 LFL-m.

5) Distance between the fire and the detector
6) Radiant energy absorption of the atmosphere
7) Presence of extraneous sources of radiant emissions
8) Purpose of the detection system
9) Response time required

With respect to the location of gas detectors, the body of the code does not provide any further guidance; the annex material includes the considerations listed below. However, like much of the code, the annex guidance for the placement of gas detectors is geared towards indoor applications. As a result, this guidance has limited applicability to most LNG facilities, where combustible gas hazards are primarily outdoors.

1) Structural features, size, and shape of the rooms and bays
2) Occupancy and uses of areas
3) Ceiling heights
4) Ceiling shape, surface and obstructions
5) Ventilation
6) Ambient environment
7) Gas characteristics
8) Configuration of contents to be protected
9) Response time

2.2.3 NFPA 15

NFPA 15 *Standard for Water Spray Fixed Systems for Fire Protection* includes references to the location of gas and flame detectors, as they often serve as system initiating devices [5]. This standard requires flammable gas detector locations to be based on the density of the flammable gas and its temperature, as well as proximity to equipment where leakage is likely to occur. The annex offers additional information on recommended gas detector set points, with first alarm occurring between 10-25% LFL and second alarm (activation) occurring between 25-65% LFL. The annex also discusses avoiding inadvertent activation by requiring second alarm to be reached by any two (or more) detectors to trip the water spray system.

With respect to flame detectors, NFPA 15 requires them to be located in accordance with product listings and manufacturer recommendations. Similar to the other NFPA standards, there are no spacing requirements or performance metrics given for fire and gas detection.

2.2.4 European Standards

BS EN 1473 *Installation and equipment for liquefied natural gas – Design of onshore installations* recommends procedures and practices that will result in safe and environmentally acceptable design, construction and operation of LNG plants [6]. This standard requires continuously operating detection systems to be installed at every location, outdoors and indoors, where leaks are credible; however, credible leaks are not defined in the document.

With respect to emergency shutdown, the type, redundancy, number and location of detectors are to be studied to ensure "quick and reliable detection of a hazardous situation." Detector voting is permitted in the standard, but no guidance is given on voting criteria. The only specific requirement given for gas detection is placement at building air intakes, which is also regarded as a best practice for US LNG facilities. Otherwise, this standard only provides generic criteria and does not include specific performance targets.

BS EN 50073 *Guide for selection, installation, use and maintenance of apparatus for the detection and measurement of combustible gases or oxygen* provides a comprehensive list of factors to consider in determining gas detector locations, most notably including [7]:

1) Indoor or outdoor site
2) Location and nature of potential leak sources (pressure, temperature, density, etc)
3) Jetting release vs. spillage
4) Topography
5) Air movement and temperature effects
6) Location and number of personnel in the plant
7) Location of potential ignition sources
8) Structures, such as walls or partitions

BS EN 50073 however does not provide a methodology for applying these considerations to an onshore gas facility, nor does it provide performance targets that could be used in developing and evaluating a hazard detector layout.

BS 60080 *Explosive and toxic atmospheres: Hazard detection mapping – Guidance on the placement of permanently installed flame and gas detection devices using software tools and other techniques* was first releases in 2020 [8]. This guidance document discusses two important concepts: (1) quantifying detector coverage by a percentage alone is not sufficient (e.g. a detector that adds 5% coverage and prevents a serious escalation is more valuable than a detector that adds 10% coverage in open area) and (2) gas detectors should not be located too close to leak sources. However, this document does not specify target coverage factors to use for evaluating a hazard detector layout. Low and high alarm thresholds are set at 10% LFL / 1 LFL-m and 25% LEL / 2 LEL-m, respectively, which are generally more conservative than NFPA 59A.

NORSOK Standard S-001 *Technical Safety* describes fire and gas detector requirements for offshore oil and gas installations and requires "reliable and fast detection" [9]. This standard permits both fire and gas detectors to initiate alarms and automatic mitigation measures. Recommendations are given for detector voting based on the number of detectors provided.

Leak detection is based on the smallest gas cloud that has the potential to cause unacceptable damage, as well as leaks down to 0.1 kg/s in naturally vented areas; such a small release would require an impractical number of detectors for an onshore LNG facility. Preference is given to open path detectors over point gas detectors in NORSOK S-001. Low and high alarm thresholds are set at 20% LEL / 1 LEL-m and 30% LEL / 2 LEL-m, respectively, which are generally more conservative than NFPA 59A.

NORSOK S-001 provides flame detector requirements based on fire size:

- A flame size of 0.5 m in diameter and length of 1 m shall be detected by at least one detector
- A flame size of 1 m in diameter and length of 3 m shall be detected by at least two detectors

While this offers specific fire sizes to be detected, such fires are unlikely to cause escalation for an onshore LNG facility and satisfying such criteria may require an impractical number of detectors.

2.2.5 HSE Guidance

The Health and Safety Executive (HSE) of the United Kingdom has published guidance on flammable gas detectors for both onshore and offshore installations. The HSE guidance on the selection, installation, use and maintenance of industrial flammable gas detectors recommends a warning alarm "as low as practicable", preferably no higher than 10% LFL, with a second alarm (including ESD) at no more than 25% LFL [10]. The guidance also discusses generic considerations for gas detector placement, such as the properties and dispersion characteristics of the target gas and detector redundancy, but does not provide detector spacing or coverage criteria.

An HSE investigation into offshore gas detector spacing resulted in guidance to locate detectors in a three-dimensional grid with 5 meter spacing, and alarm levels at 20% and 60% LFL [11]. This criterion was primarily based on experimental testing of stoichiometric methane-air and propane-air mixtures inside a 2.5 m diameter steel tube; the tube was closed on one end and fitted with annular rings to provide blockage and generate turbulence. The testing determined that a flammable gas cloud up to 6 meters in length will not produce flame speeds greater than 100 m/s for methane (125 m/s for propane) and will not produce damaging overpressures in excess of 150 mbar (2.2 psi). Therefore, it is expected that 5 meter gas detector spacing would provide detection prior to reaching a hazardous cloud size. For comparison, it should be noted that the degree of confinement in this test series is higher than typically seen at onshore LNG facilities. Additionally, the gas cloud will continue to grow for a period of time after detection during system isolation and de-inventory, which is important for onshore facilities with comparatively larger isolatable inventories.

2.2.6 ISA Guidance

The International Society of Automation (ISA) Technical Report TR 84.00.07-2018 *Guidance on the Evaluation of Fire, Combustible Gas, and Toxic Gas System Effectiveness* uses three main factors in evaluating fire and gas system performance: detector coverage (i.e. the gas cloud reaches required number of detectors), safety availability (successful detection activation), and mitigation effectiveness [3]. Two approaches for achieving effective detector coverage are defined in the technical report: geographic coverage and scenario coverage.

Geographic coverage is defined as the fraction of an area or volume that is covered by the detectors. Calculating geographic coverage is a straight-forward process with flame detection, where each detector has a well-defined field of view. With respect to gas detection, this method requires first establishing a dimensioning cloud size, which represents the threshold for unacceptable damage. As the dimensioning cloud is moved around the detection area, the detector layout must be such that at least the minimum required number of detectors is always within the dimensioning cloud; the most efficient way to comply with this requirement is with an evenly spaced grid of point gas detectors.

Scenario coverage is defined as the ratio of detected releases to total credible releases. Unlike geographic coverage, this method requires the evaluation of each credible release scenario. The scenario coverage approach provides the opportunity for the hazard detection layout to be optimized for the specific scenarios, weather conditions and configuration of a facility, however, it requires a much more detailed analysis.

Note that different detection methods may use different coverage schemes within the same facility; for example, flame detection may use geographic coverage, whereas gas detection may use scenario coverage.

The ISA technical report outlines a sample fire detection philosophy for onshore process plants as follows:

1) Identify leak sources and size
2) Locate detectors in proximity to leak sources
3) Alarm to evacuate personnel and initiate ESD
4) Supplement with perimeter gas detection

The report continues to provide examples of design hazards for both fire and gas detection. In addition to pool fires, jet fires down to 25 mm (1 inch) diameter are suggested. Heat flux thresholds for personnel safety and equipment are also provided. For flammable gas releases, the report proposes hole sizes from 1 to 25 mm diameter.

These hole sizes are notably smaller than release scenarios typically evaluated for PHMSA siting studies, which generally range from 2 to 4 inches (50 to 100 mm).

To detect flammable cloud accumulation early and prevent unacceptable overpressure hazards, the following criteria is given in terms of spherical clouds:

1) High congestion and confinement: 5 meters
2) Moderate congestion and confinement: 7-8 meters
3) Low congestion and confinement: 10 meters

ISA TR84.00.07 outlines a performance-based design process for fire and gas detection, and provides example criteria for various scenario parameters, however, it does not clearly state fire and gas detector performance requirements and release scenarios appropriate for onshore LNG facilities.

2.2.7 Center for Chemical Process Safety

The Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) publishes technical information for use in the prevention of major chemical accidents. Most notably, *Continuous Monitoring for Hazardous Material Releases* describes five methods for developing a gas detector layout [12]:

1) Source Monitoring
   This detection method is intended for moderate and large releases of flammable materials. The magnitude of the release is not specified, but it is assumed to be similar to the typical bounding scenarios for LNG facility siting studies. Computer modeling is utilized to determine detector set back distance (how far until the release reaches sensor height) and maximum distance between detectors (determined by cloud width at the set back distance).

   Commentary: The source modeling approach would prove difficult for an onshore LNG facility, where there are many potential leak points within a process area. This approach would be more appropriate for scenarios where leak points are sparse and well-defined.

2) Volumetric Monitoring
   Originally developed by BP Oil for offshore applications, this method assumes a vapor cloud explosion presents the greatest risk. A three-dimensional detector layout is developed to ensure that the dimensioning cloud size can be detected anywhere in the volume of interest. It is noted that the typical distance required for flame speeds to generate an overpressure is 5-6 meters. Gas detection is not recommended for open volumes with low congestion, unless there are pockets of higher congestion. In that case, it is recommended to use a spherical gas cloud of 10 meters in diameter across the entire volume, or to use 5 meters within the congested pockets. Additionally, for heavier-than-air releases, it is recommended

to include detectors arranged in a 5 meter triangular grid around the potential release point.

Commentary: Similar to 'geographic coverage' from the ISA guidance, this method requires the establishment of a dimensioning cloud size. Though references to values used for the offshore environment are often given, they do not translate well to the onshore environment. Additionally, a vapor cloud explosion may not present the greatest risk in all areas of an onshore LNG facility.

3) Enclosure Monitoring
Gas detection inside buildings is explicitly outside the scope of this project.

4) Path of Travel and Target Receptor Monitoring
Generally used for toxic gas detection and protecting personnel travel routes during normal operation and egress (outside the scope of this project).

5) Perimeter Monitoring
This method aims at protecting flammable clouds from migrating into an area with ignition sources and/or personnel, as well as beyond the facility property line. With respect to the latter, note that it may be more effective to locate the detection system between the release and the property line, rather than at the property line. This approach is often most efficient with use of IR or laser beam detection rather than point gas detectors.

Commentary: Perimeter monitoring is useful for ensuring flammable clouds do not migrate from one process area to another (or to known ignition sources), however, perimeter monitoring is unlikely to provide adequate protection on its own.

The mounting height for gas detectors in the presence of heavier-than-air clouds is given as 12-18 inches above grade. Gas detector set points are recommended to be no more than 20%-LFL for low-level alarm and 40%-LFL for high-level alarm. For detector voting, any system incorporating executive actions should be voted, requiring at least two detectors to activate.

2.2.8 Other References

Many other sources, not directly referenced herein, provide generic detector placement guidance like that summarized above. Additional sources referenced during this literature review are provided in the References section at the end of this report.

2.3 Literature Review Conclusions

Outside of NFPA 720 *National Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment*, there are no standards relating to the design of systems to detect combustible or toxic gases [13]. As described above, NFPA 72 requires a performance-based design to document each performance objective and applicable scenarios, along with calculations, modeling or other technical substantiation that justifies adequate safety. However, many fire protection design packages lack complete documentation in this regard, often with poorly detailed release scenarios (if any) and inadequate justification for hazard detector placement.

Several documents are available in the public domain that outline key factors to consider in developing fire and gas detector layouts, however, the literature review determined that performance criteria and a methodology for evaluating these layouts are not clearly defined. Generic terminology such as "quick and reliable" cannot be quantified in a way that could be effectively and consistently applied to the design or review of hazard detection layouts at LNG facilities. Further, available guidance repeatedly calls for gas detectors to be placed in proximity to potential leak sources. This is often interpreted as placing point gas detectors next to leak sources only. This attempt at detecting the leak instead of the resultant gas cloud is known to be flawed and could result in a failure to detect many leak scenarios, depending on factors such as leak orientation and wind direction.

If one were to consider a geographic or volumetric approach to gas detector spacing, a key factor that would have to be properly defined is the dimensioning cloud size. Dimensioning cloud sizes are often defined in terms of an equivalent stoichiometric cloud[2]. It is important to note that if an equivalent stoichiometric cloud is used, the size and shape of the cloud may be very different than the real gas cloud in the event of a release. Additionally, the output of two-dimensional dispersion models is often presented as a circle, which represents the greatest dispersion distance over all release and wind directions. If this composite hazard footprint is used for establishing hazard detector locations instead of considering the much smaller hazard footprint of individual release and wind direction combinations, the hazard detector layout will be misinformed.

There are many factors to consider when determining performance criteria for fire and gas detectors. The available literature does not define hazard detector performance targets or the scenarios that should be used to evaluate detector layouts in a way that can be consistently applied across the LNG industry. Therefore, such a methodology is developed and presented in this report.

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[2] In the event of a release, flammable clouds are continuously changing size, shape and concentration. The inhomogeneous cloud (within the flammability range) can be converted into a homogenous cloud at stoichiometric concentration, whose overpressure potential is 'equivalent' to the original. This technique is often used in overpressure hazard analysis.

3 Establishing Detector Performance Targets

Fire and gas detection (FGD) systems are critical to managing risk at LNG facilities. In most installations, these continuously monitoring systems not only notify personnel of hazardous conditions, but also perform executive actions including emergency shutdown, inventory isolation and depressurization. Fire and gas detection systems also serve as initiating devices to activate fire suppression and fire exposure protection systems.

The effectiveness of fire and gas detection systems can be characterized by three main factors: mitigation effectiveness, safety availability and detector coverage [3]. The effectiveness of mitigation measures employed after successful detector activation is often well understood through testing and analysis. Safety availability, or the reliability of the system, can be quantified by a thorough analysis of all system components, and is often high for fire and gas detection systems at LNG facilities. It should be noted that safety availability is analogous, but not equivalent to Safety Integrity Level (SIL) ratings. The goal of a fire and gas detection system is mitigation and not prevention. While SIL ratings correspond to an exact risk reduction in process safety, hardware failure is not directly proportional to the outcome in fire and gas detection because the hazard will still be present to a certain degree.

The leading challenge to FGD design is not in achieving sufficient detector coverage, but in defining what constitutes sufficient detector coverage. There are no design standards for determining the location of fire and gas detection devices at LNG facilities. There are a host of references with lists of factors to consider in developing a hazard detection layout (e.g. leakage source and rate, physical properties of the fuel, plant layout and topography, air movement, potential ignition sources, etc.), but quantifiable performance targets are not provided. As a result, fire and gas detection system layouts must be determined for each facility using performance-based design. The location of fire and gas detection devices is commonly determined by 'expert judgment' and often lacks reasonable levels of technical justification. In cases where a more detailed approach, such as a quantitative risk assessment (QRA) is taken, results can still vary since risk tolerance may differ between end-users and locations, and the use of different hazard thresholds impacts the results.

Therefore, there is a need to establish quantifiable performance criteria for fire and gas detection systems in the LNG industry. It is not possible to detect every conceivable leak or fire; therefore, minimum hazard thresholds must be established. This section presents a summary of the leading hazards at an LNG facility following the release of a flammable fluid and a methodology for evaluating fire and gas detection systems.

While risk tolerance, harm criteria, and performance targets must be chosen for the purposes of the demonstratives included in this report, these targets should not be interpreted as requirements of DOT-PHMSA nor as acceptable to them.

3.1 A Risk-Based Approach

Siting studies for LNG facilities in the US are currently based on maximum credible events (MCEs). NFPA 59A requires the evaluation of hazards from any single accidental leakage source (SALS) but does not prescribe the specific scenarios to be evaluated [1]. PHMSA provides guidance to determine the SALS for LNG facilities under their jurisdiction, generally requiring the evaluation of a 2-inch hole for piping 6 inches or larger in diameter, and a full-bore rupture for piping less than 6 inches in diameter, for a duration of 10 minutes[3]. These result in large hazard footprints that must be contained through a combination of land controlled by the facility owner and various mitigation strategies. The SALS prescribed by PHMSA are aimed at protecting the public and public property in the vicinity of LNG facilities.

The MCE approach can also be useful for a conservative analysis of onsite hazards (i.e. building siting studies), however, MCEs are generally not appropriate for evaluating a hazard detection layout. In fact, MCEs result in large hazard areas and therefore are 'easy' to detect; therefore, an FGD configuration that meets the MCE requirement could allow many smaller or shorter releases to go undetected. Since it is not realistic for every possible leak scenario to be detected, a minimum threshold must be established. Accordingly, a risk-based approach is necessary to be able to establish this minimum threshold and quantify the performance of the fire and gas detection system.

A risk calculation involves identifying possible release scenarios for the facility and calculating the likelihood and consequences for each individual scenario (i.e., Scenario Risk = Frequency x Severity). The risk can be evaluated qualitatively by use of a risk matrix (Figure 3-1), semi-quantitatively by use of a scoring system (detailed example provided in [3]), or by conducting explicit risk calculations, such as a Quantitative Risk Assessment (QRA). A risk-based approach to fire and gas detection layouts must therefore consider both the frequency of the event and the consequences of the event. This approach will optimize fire and gas detection layouts by focusing resources on the areas presenting the greatest risk within the facility and provide a method for quantifying system coverage.

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3 https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-plant-requirements-frequently-asked-questions. Accessed on June 4, 2020.

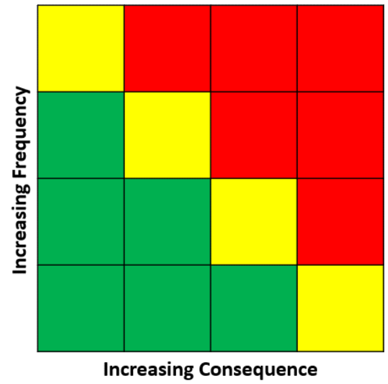

Figure 3-1: Generic example of risk matrix

The risk to personnel within the plant boundaries is often evaluated as Location-Specific Individual Risk (LSIR). LSIR is presented as 2D risk contours on the facility plot plan outlining areas where an event capable of causing the specified level of harm occurs at different frequencies, assuming someone is present to experience the risk. For example, Figure 3-2 shows contours for individual risk of fatality per year within a generic LNG facility. Similar contours could also be developed for specific hazards, such as frequency of experiencing a given heat flux from fire exposure, or a given overpressure from vapor cloud explosions. The LSIR contours identify which areas of the facility present the greatest level of risk; the application of fire and gas detection should be focused accordingly.

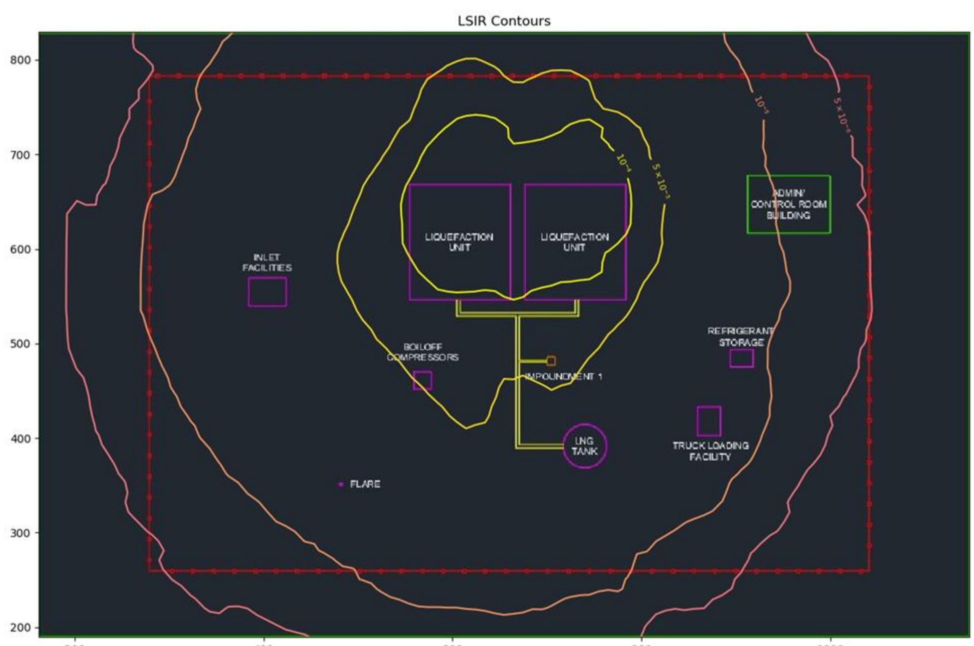

Figure 3-2: Example of LSIR risk contours

3.1.1 Methodology

Though risk can be quantified, it is still a matter of perspective; each stakeholder in a project may have a different risk tolerance. It is important to note that, in order to demonstrate the application of this methodology, risk tolerability criteria (section 3.1.2) and a set of hazard thresholds and associated harm criteria (section 3.3) had to be specified; however, the methodology is independent of the chosen criteria – that is, users may choose to apply different criteria but remain able to adopt this methodology as described. The risk tolerability thresholds used in this analysis were chosen as minimum requirements for the safety of plant personnel in order to demonstrate a methodology for evaluating hazard detection systems at onshore LNG facilities. Similarly, this demonstration is based on individual risk of fatality, however, owners or operators may choose to incorporate financial risk parameters (e.g. property damage, business interruption, image, etc.) or apply an established corporate risk profile more stringent than required by regulators.

3.1.2 Risk Tolerability Criteria

The UK Health and Safety Executive (HSE) defines three regions for the tolerability of risk: broadly acceptable, tolerable, and unacceptable [14]; this concept is commonly represented as a triangle as shown in Figure 3-3. The broadly acceptable region at the bottom of the triangle represents very low risk where no further action is needed. The HSE considers an individual risk of death of 1 in 1,000,000 (10^{-6}) per year to represent the maximum broadly acceptable risk (green dashed line in Figure 3-3), noting that the activities people perform in their daily lives, such as using gas and electricity, entail a similar level of risk. The unacceptable region at the top of the triangle requires design modifications and/or mitigation strategies to reduce the risk. Daily life includes various kinds of risk, which averaged over a lifetime was estimated as a risk of death of 1 in 100 (10^{-2}) per year [14]. The HSE maximum tolerable risk for workers is one order of magnitude lower at 1 in 1,000 (10^{-3}) fatalities per year. HSE considers a risk tolerance threshold of 1 in 10,000 (10^{-4}) for the general public, one order of magnitude lower than workers, in acknowledgement that the associated risk has been imposed upon them involuntarily.

The region between the broadly acceptable and unacceptable risk tolerance thresholds is the tolerable region. It is not sufficient that a risk simply fall within the tolerable range; it requires that all practical design modifications and mitigation strategies have been utilized in an effort to reduce the risk to a level 'as low as reasonably practicable' (ALARP). In this case, it must be demonstrated that the cost of further reducing the risk is 'grossly disproportionate' to the cost associated with the calculated risk. This is achieved through a cost benefit analysis that calculates the ratio of the cost of mitigation per year to the cost of loss per year.

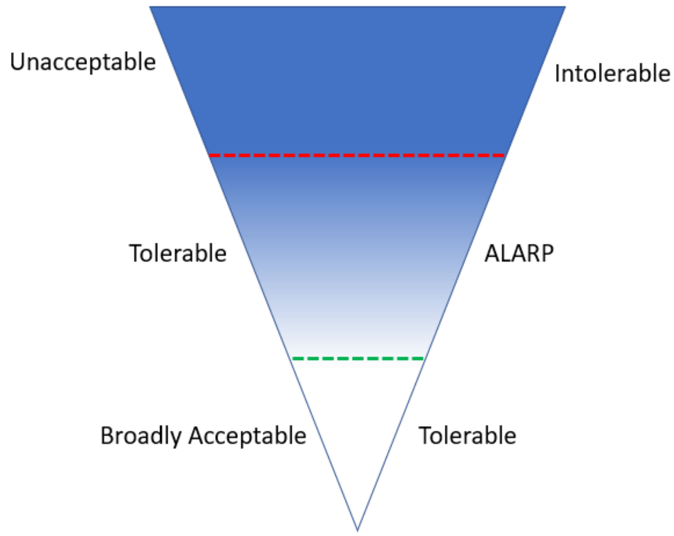

Figure 3-3: Risk Regions, with terminology from HSE [14] (left) and NFPA 59A [1] (right)

NFPA 59A adopted the HSE risk philosophy using terminology such as "risk tolerance" instead of "risk acceptance". However, NFPA 59A applies to plant siting and therefore focuses on offsite impacts; as such, it does not set risk tolerance thresholds within the plant. NFPA 59A sets the intolerable threshold for individual risk of fatality to 5×10^{-5} per year outside plant boundaries (with further restrictions on sensitive establishments) and the tolerable threshold to 3×10^{-7} per year. Assuming one order of magnitude higher risk tolerance for workers within the plant boundaries would yield individual risk of fatality criteria of 5×10^{-4} per year for 'intolerable risk' and 3×10^{-6} per year for 'tolerable risk'.

This project will use terminology consistent with NFPA 59A and set the threshold for 'intolerable risk' at an individual risk of death of 1×10^{-4} per year and 'tolerable risk' at 1×10^{-6} per year for personnel within the plant boundaries. These values were chosen as order of magnitudes consistent with NFPA 59A and HSE philosophies, as well as decision criteria from NORSOK Standard Z-013 for limiting risk of escalation to 1×10^{-4} per year[4] [15]. Additionally, areas subject to individual risk of fatality greater than 5×10^{-5} per year must remain within plant boundaries per NFPA 59A. The risk thresholds used for this project are summarized in Table 3-1.

[4] A threshold of Individual Risk of Fatality of 1×10^{-4} is commonly used in risk assessments

Table 3-1: Risk Thresholds

Individual Risk of Fatality (per year)	Risk Classification
IR ≥ 1 x 10^{-4}	Intolerable
IR > 5 x 10^{-5}	Permitted within plant boundaries[5]
IR < 1 x 10^{-6}	Tolerable

3.2 Description of Hazards

A loss of containment could occur at any point along piping and equipment in an LNG facility. Potential leak points include piping failures (i.e. corrosion), flanges, valves, pumps, compressors, vessels, instrument connections, etc. The risk associated with a loss of containment is a combination of the likelihood of the event (i.e. leak frequency) and the consequences of each potential hazardous outcome. Leak frequencies can be determined from failure rate data available in the literature[6]; the consequences need to be calculated for each scenario based on facility specific process data, plant layout and local weather conditions. This analysis will focus on process related hazards (i.e. loss of containment of flammable streams from facility piping and equipment). Consideration should also be given to non-process and electrical fires as required by NFPA 59A [1].

It should be noted that while toxic gases are outside the scope of the current project, an evaluation of toxic gas detection could be performed in a similar methodology as presented for flammable gas detection, with the establishment of separate toxic gas hazard thresholds.

Figure 3-4 shows an event tree for the range of potential hazard scenarios arising from the loss of containment of a flammable stream. Without immediate ignition, the release of a flammable material within an LNG facility will result in the formation of a flammable cloud. This could be the result of a pressurized gas release, a pressurized liquid release (flashing and jetting), or a liquid spill. The fuel concentration of the cloud will vary over space and time. The fuel concentration in air must be between the lower and upper flammability limits for ignition to be possible; this portion is referred to as the flammable cloud.

[5] 2019 edition of NFPA 59A, Table 19.10.1(a) Criteria for Tolerability of Individual Risk of Fatality – Zone 1

[6] Reference DOT PHMSA Research & Development Project No. 731 "Consistency Review of Methodologies for Quantitative Risk Assessment" for a summary of failure rates applicable to LNG facilities.

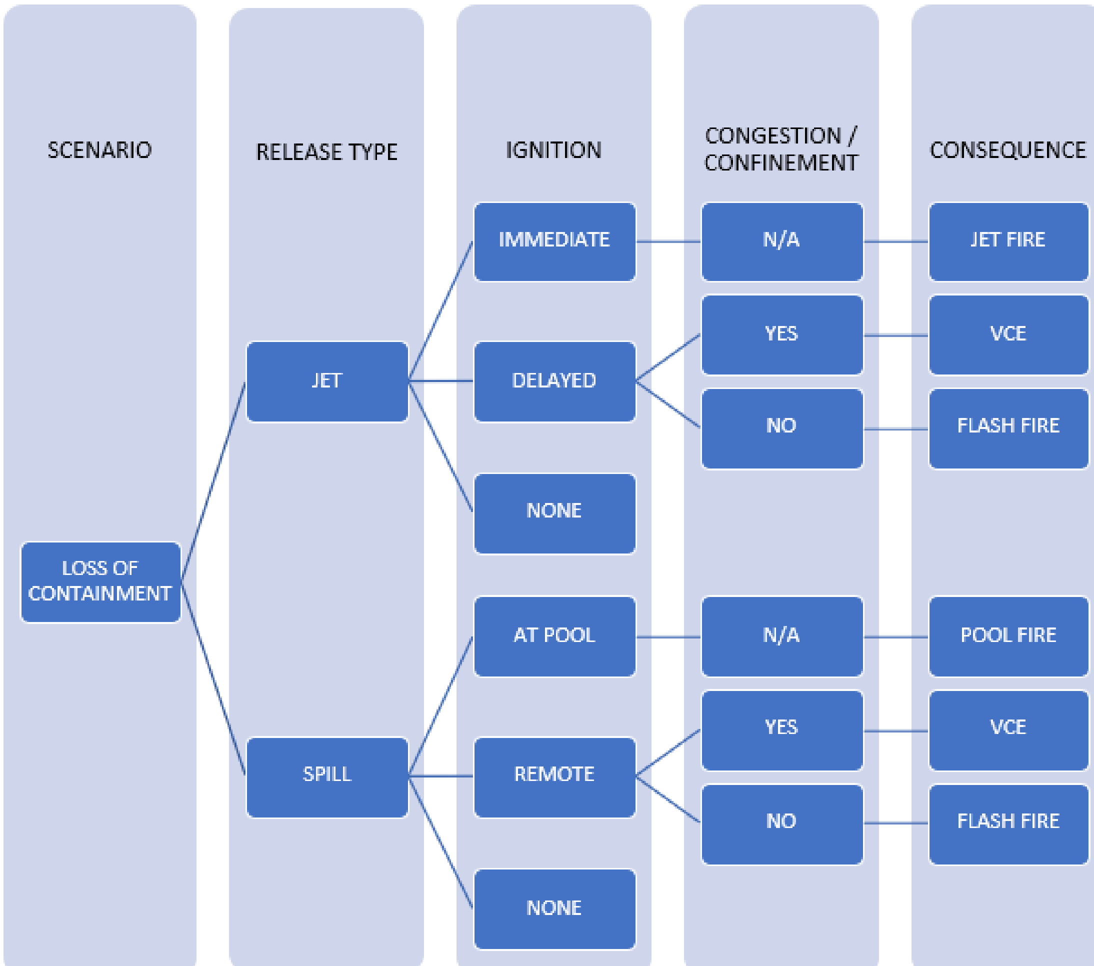

Figure 3-4: Event tree for loss of containment of a flammable stream.

3.2.1 Flash Fire

If the flammable cloud is ignited in open space, or in the presence of low congestion and confinement, flame speeds will not accelerate to the point of generating an appreciable overpressure – this hazard is referred to as a *flash fire*. An example of a flash fire is shown below in Figure 3-5. It is commonly assumed that any person caught within a flash fire envelope will be a fatality; however, given the short duration of flash fires, no equipment damage or escalation is considered to occur from a flash fire.

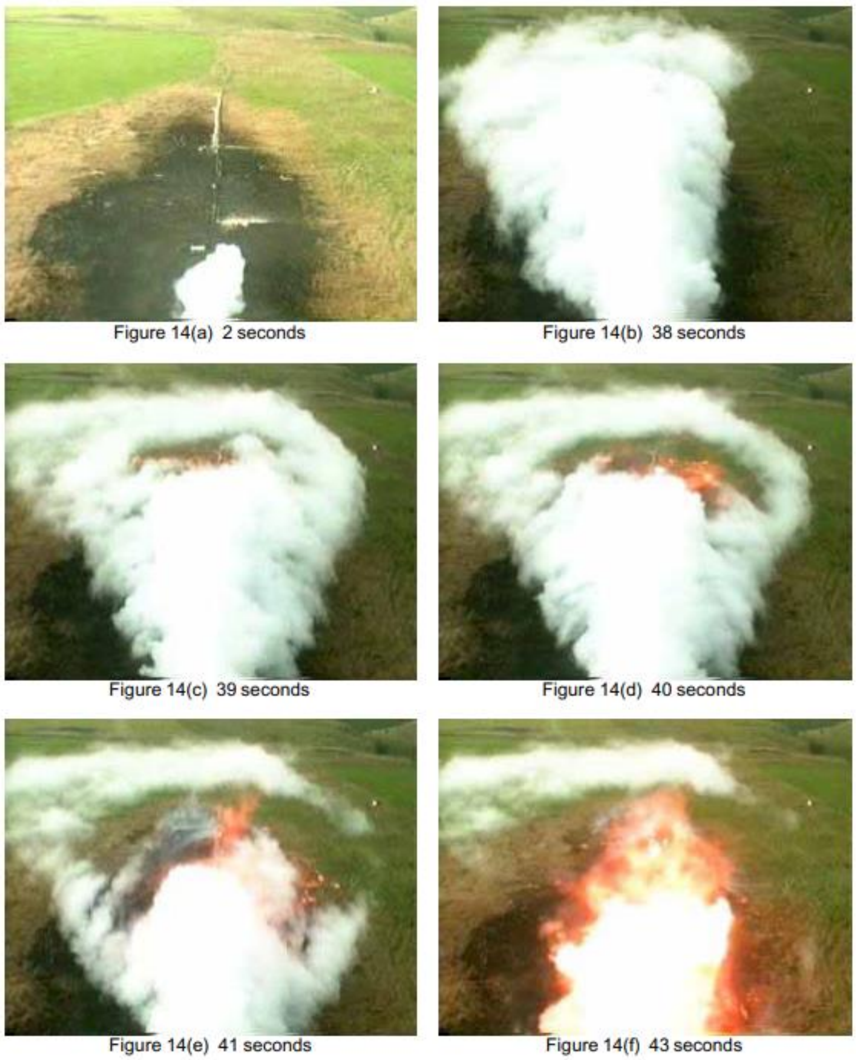

Figure 3-5: Flame progression through a flammable cloud [16]

3.2.2 Vapor Cloud Explosion (VCE)

If the flammable cloud is allowed to accumulate to a sufficient size in the presence of congestion and/or confinement and is ignited, the cloud combustion will result in an overpressure – this hazard is referred to as a *vapor cloud explosion (VCE)*. Confinement is given by a planar obstruction that restricts expanding gas and flame propagation in one or more directions, such as a wall or a solid deck. The level of congestion is defined by the number and size of objects in a given volume, which generate turbulence, increase flame speeds, and lead to the development of damaging overpressures. The fuel composition and levels of congestion and confinement will determine the minimum size of the flammable cloud required to develop damaging overpressures. Figure 3-6 shows the damage resulting from a vapor cloud explosion following a leak (likely mixed refrigerants) at an LNG facility in Skikda, Algeria in 2004.

Figure 3-6: Damage after vapor cloud explosion at LNG plant in Skikda, Algeria (Right – maintenance building near liquefaction train) [17]

3.2.3 Jet Fire and Pool Fire

If a flammable cloud is ignited and burns back to the source of the release, it could result in a *jet fire* or *pool fire*. Either hazard could also result from an ignition source near the release point or near the liquid pool surface. A jet fire is a turbulent diffusion flame fed by the release of a flammable material under pressure as shown in Figure 3-7. Extinguishment is commonly achieved by emergency shutdown procedures to end the flow of fuel to the fire. A pool fire is self-sustaining in that radiation from the fire heats the pool surface, increasing vaporization from the pool and fueling the fire. Mitigation measures such as high expansion foam and insulating floating foam blocks can be employed to reduce the size of a pool fire and provide more favorable conditions for manual firefighting with a dry chemical extinguisher (see Figure 3-8). Alternatively, a pool fire may be allowed to burn to extinction.

Figure 3-7: Jet Fire (leak source right side of image)[7]

Figure 3-8: LNG pool fire (Left – unmitigated, Right – with high-expansion foam) [18]

Both jet fires and pool fires can result in high thermal radiation exposures to personnel and equipment. If the plot plan allows, impoundments can be located remote of major equipment and personnel to reduce the risk of pool fire exposures. Jet fires, however, could conceivably occur anywhere along a pressurized line containing a flammable material. As a result, exposure protection is often necessary for key pieces of equipment, such as passive fire protection (PFP) or cooling water from fire water monitors or a fixed water spray system.

[7] https://www.dnvgl.com/training/lng-hazard-awareness-training-1-day--58023

3.3 Hazard Thresholds

The hazards outlined in the previous section define situations where a loss of containment of a flammable stream can cause harm to an individual. Determining the level of risk for an individual requires defining the probability of a hazard occurring and the severity of being exposed to a hazard. Therefore, in order to develop a performance-based approach to fire and gas detection at LNG facilities, thresholds must be established to define the severity of exposure for each potential hazardous event. The thresholds must be quantifiable in both the magnitude of the hazard and the consequences (i.e., probability of fatality from exposure to the hazard). This section demonstrates a methodology for establishing thresholds for each hazard that may result from a loss of containment of flammable streams at an LNG facility.

While the methodology would remain the same, it does not preclude regulators, owners or operators from applying different risk criteria as appropriate.

3.3.1 Flash Fire

As described above, the ignition of a flammable cloud outside of a congested area will result in a flash fire and will not cause notable damage to structures and equipment. The outer limits of the flammable cloud, representing the volume of gas at and above the lower flammability limit (LFL), are referred to as the flash fire envelope. Personnel located within the flash fire envelope are typically considered to be fatalities due to direct flame exposure.

Occupied buildings at LNG facilities are often noncombustible construction and equipped with gas detectors at air intakes that close ventilation systems once gas is detected, preventing a flammable atmosphere from migrating inside the building. However, it must be considered that a portion of incident radiation from an outdoor flash fire would be transmitted through building windows, particularly in the case of a building located inside the flash fire envelope. Previous analysis performed for the HSE has shown that an individual would need to be standing less than 1 meter from a window in order to experience a hazardous dose of thermal radiation from a flash fire, suggesting that occupants would be protected as long as they were not standing at the window to observe the event [19]. There is also potential for personnel to attempt to escape the area prior to ignition of the flammable cloud, and hazards associated with secondary fires that may follow the initial flash fire. Additionally, a goal of a gas detection system would be to detect a leak prior to a flammable concentration reaching an occupied building. As a result, for the purpose of this study, personnel inside buildings found to be within the flash fire envelope will also be considered fatalities [20].

The flash fire hazard levels are summarized below in Table 3-2. The LFL will be used as the hazard threshold for dispersion calculations as prescribed in NFPA 59A; note that safety factors or model validation correction factors will not be applied. This is consistent with standard risk calculation procedures in the petrochemical industry, as well as current procedures in the LNG industry for determining the volume of flammable cloud accumulation within congested regions. Additionally, imposing a validation factor on the dispersion results, such as ½ LFL, would increase the size of the hazard footprint, thereby requiring fewer detectors for activation.

Table 3-2: Flash Fire Hazard Levels (Outdoors and Indoors)

Within Flash Fire Envelope	Fuel Concentration	Fatality [%]
No	< LFL	0
Yes	≥ LFL	100

3.3.2 Vapor Cloud Explosion (VCE)

The blast impact from a vapor cloud explosion is commonly evaluated by the peak overpressure as a function of distance[8]. There are many references available in the public domain that detail human injury and property damage based on overpressure. Direct blast effects on humans are often characterized by impacts to the ear drums and lungs. A review of the data reveals that the human body can handle an appreciable overpressure before experiencing fatal consequences. For example, NFPA 921 *Guide for Fire and Explosion Investigations* reports 10 psig as the threshold for lung hemorrhage and 14.5 psig as the threshold for fatality from direct blast effects [21]. Comparatively, the threshold for the failure of reinforced concrete structures is reported as 4.8 psig. Therefore, the threat to personnel from indirect hazards (flying objects, body displacement, building collapse) must be considered in addition to direct blast effects.

The evaluation of risk requires the consequences to be coupled with a likelihood of fatality. This is a fairly simple process for flash fires as outlined above: 100% fatality inside the flash fire envelope; no fatality otherwise. However, the consequences of a vapor cloud explosion vary based on the peak overpressure. Therefore, probit functions are often used to determine the probability of death based on a given exposure. Several probit functions have been developed for damage caused by overpressure hazards, therefore the appropriate probit function must be determined for each application.

The main overpressure hazard for personnel indoors is building collapse. Eisenberg developed a probit function for probability of total structural damage as given by [22]:

$$Pr = -23.8 + 2.92 \ln p_s$$

[8] Overpressure hazard thresholds are usually reported as a static load. Detailed structural analyses may employ the pressure-impulse to better characterize the duration of the blast loading.

Where p_s is the peak overpressure in Pascals [Pa]. The probability of the effect can be determined from the probit as given by:

$$P = 50\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right]$$

Where

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\, dt$$

Assuming structural damage to a building results in fatalities inside the building, the probability of fatality for personnel indoors due to overpressure hazards is given in Figure 3-9 and Table 3-3, with damage criteria associated with the given overpressure in the last column for context.

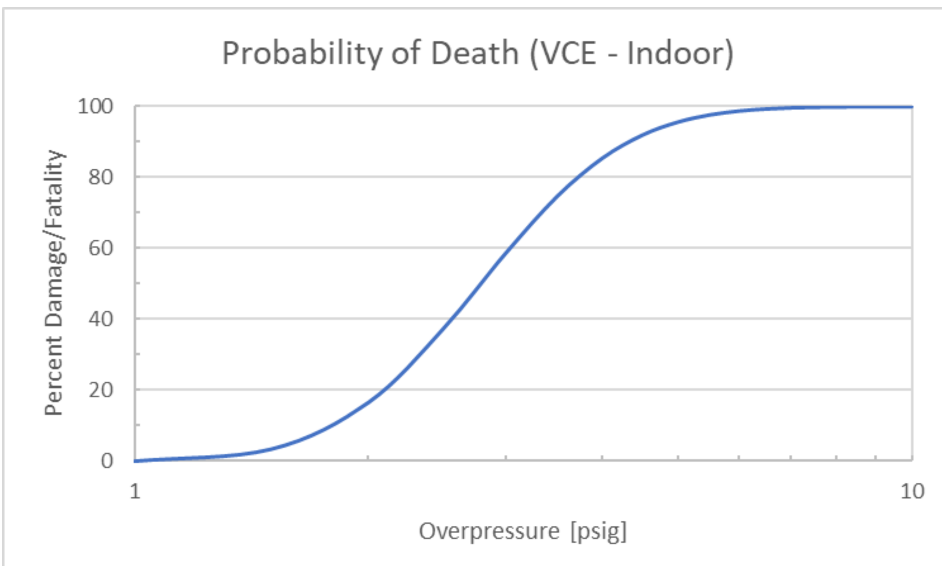

Figure 3-9: Eisenberg probit for structural damage

Table 3-3: Overpressure Hazard Levels (Indoors)

Overpressure [psig]	Probit Value	Fatality [%]	Damage Criteria [21][9]
1.3	2.67	1	Steel frame of clad building slightly distorted
2.8	5.00	50	Shattering of nonreinforced concrete
4.9	6.64	95	Failure of reinforced concrete structures

[9] Calculated threshold similar to reported values

The TNO "Green Book" also contains probit equations for structural damage to houses, however, the overpressures required to achieve the damage criteria are notably higher than the Eisenberg probit [23]. Comparatively, the Eisenberg probit is more conservative and better aligned with available data for overpressure damage criteria.

Outdoor hazards to personnel from a VCE include both direct and indirect blast effects. Compared to probits developed by Eisenberg and TNO, direct blast effects (death due to lung hemorrhage) are most conservatively captured by the HSE probit function below [24]:

$$Pr = 1.47 + 1.37 \ln p_i$$

Where p_i is the peak overpressure in psig.

With respect to indirect blast effects, the TNO Green Book provides probit functions for death due to full body displacement (head impact and whole body impact), as well as flying fragments. While death due to flying fragments is a potential hazard in the event of a VCE at an LNG facility, definition of this scenario has many variables, such as the weight and velocity of the fragment. Therefore, the probit for death due to head impact was chosen for indirect effects [23]:

$$Pr = 5.0 - 8.49 \ln\left(\frac{2.43 * 10^3}{p_s} + \frac{4.0 * 10^8}{p_s * i}\right)$$

Where p_s is the peak overpressure in Pascals [Pa] and i is the impulse of the shock wave[10].

These probit functions for outdoor blast effects are plotted below in Figure 3-10 to demonstrate when the probability of death from indirect effects exceeds that of direct effects. Therefore, this project considers a combination of the two probits as outlined in blue. The resulting overpressure hazard thresholds are summarized below in Table 3-4, with damage criteria associated with the given overpressure in the last column for context.

[10] Duration of overpressure assumed 70 ms

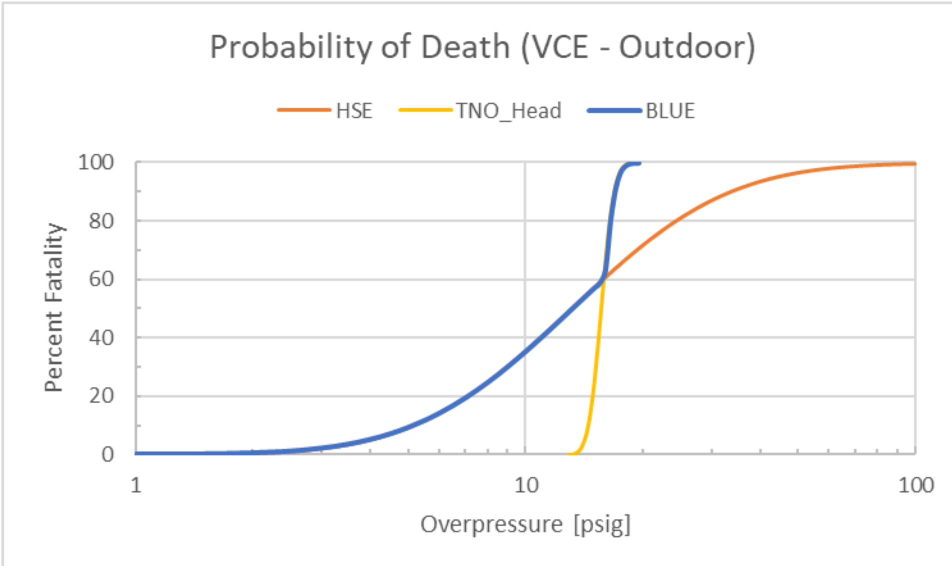

Figure 3-10: Probits for outdoor blast effects

Table 3-4: Overpressure Hazard Levels (Outdoors)

Overpressure [psig]	Probit Value	Fatality [%]	Damage Criteria [21][11]
2.4	2.67	1	Threshold for eardrum rupture
13.1	5.00	50	Below fatality threshold for direct blast effects
17.3	6.64	95	10% probability of fatality from direct blast effects

It should be noted that NFPA 59A includes overpressure hazard thresholds of 1 psig for fatality of persons inside a building that is not blast resistant and 3 psig for fatality of persons outdoors [1]; these values are consistent with the onset of the probability of fatality in Table 3-3 and Table 3-4, however, based on associated damage criteria available in the literature, such thresholds were deemed overly conservative for higher probability of fatality.

[11] Calculated threshold similar to reported values

3.3.3 Jet Fire and Pool Fire

The consequences from a jet fire and pool fire can both be quantified by prolonged heat flux exposure to personnel and equipment. Unlike overpressure damage, which occurs over a span of milliseconds, thermal radiation requires longer exposure times to cause damage. Steel structures and equipment can sustain flame impingement for several minutes before failure, but severe injury and fatality to people can occur for elevated heat fluxes in a matter of seconds.

Thermal radiation damage thresholds are therefore often expressed in terms of "dose" (combination of heat flux and a duration) rather than just heat flux intensity. The thermal radiation dose (tdu) is defined as [23]:

$$tdu = I^{4/3} * t$$

Where I is the incident thermal flux (W/m^2) and t is the exposure time (seconds).

Eisenberg developed a thermal dose probit by analyzing fatalities from the nuclear bomb event at Hiroshima. This function was then modified by Tsao and Perry to account for the increased intensity of hydrocarbon flames (infrared radiation) over that of a nuclear event (ultraviolet radiation), and further modified by TNO to adjust for protection from normal clothing, resulting in the following probit [25]:

$$Y = -37.23 + 2.56 \ln(tdu)$$

Where tdu is based on the incident thermal flux in W/m^2.

The results using this probit are shown below in Figure 3-11 compared to HSE offshore criteria, which are based on the ignition of clothing [26], demonstrating that the TNO probit is more conservative. The thermal radiation hazard levels for outdoor exposure are summarized in Table 3-5. Note that the heat flux values are given for reference only and are based on a 30 second exposure (i.e. the heat flux necessary to achieve the same percent fatality would be higher for a shorter exposure, but the thermal radiation dose would remain the same).

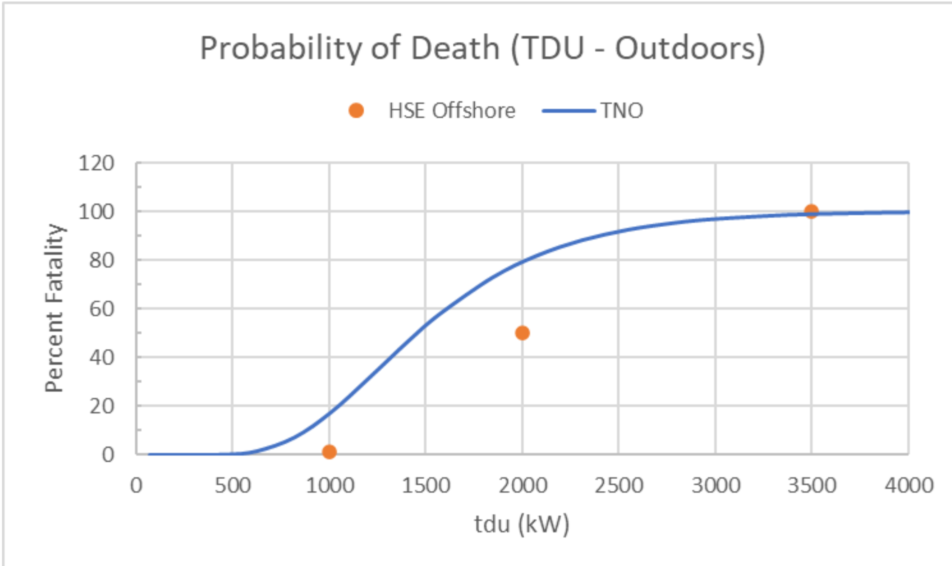

Figure 3-11: TNO probit compared to HSE offshore criteria for thermal radiation dose

Table 3-5: Thermal Radiation Hazard Levels (Outdoors)

Heat Flux for 30 second exposure [kW/m^2]	tdu [kW/m^2]$^{4/3}$ s	Probit Value	Fatality [%]
9.3	587	2.67	1
18.4	1457	5.00	50
29.8	2772	6.64	95

NFPA 59A uses a radiant heat flux of 9 kW/m^2 as the threshold for fatality of persons outdoors without personal protective equipment, however, this endpoint does not consider the duration of exposure [1]. A radiation intensity of 9.5 kW/m^2 is documented to cause pain in 8 seconds and second degree burns after 20 seconds [27]. Therefore, it is reasonable to assume most individuals would be capable of escaping the area of exposure to a heat flux of 9.5 kW/m^2 prior to fatality, however, a longer exposure could result in increased levels of harm. This is consistent with the onset of fatality in Table 3-5.

Personnel indoors are generally considered protected from thermal radiation hazards arising from pool and jet fires, as most occupied buildings at LNG facilities are made of noncombustible construction. The TNO Purple Book sets the threshold for ignition of buildings at a sustained heat flux of 35 kW/m^2 [20]. Therefore, the following thermal radiation hazard levels are considered for personnel indoors:

Table 3-6: Thermal Radiation Hazard Levels (Indoors)

Heat Flux [kW/m^2]	Building Ignition	Fatality [%]
< 35	No	0
≥ 35	Yes	100

3.4 Approaches to Detector Layouts

There are many factors to consider when determining performance criteria for fire and gas detection for an onshore facility. The type of hazard presenting the most risk varies between different areas of an LNG facility, according to flammable materials present, typical levels of congestion, time personnel is present in the area, equipment subject to cascading hazards, etc. Therefore, detector performance targets may also vary between different areas of an LNG facility.

As mentioned previously, ISA TR 84.00.07 evaluates the effectiveness of fire and gas detection systems by three main factors: detector coverage, safety availability, and mitigation effectiveness [3]. The report uses an event tree to demonstrate that no matter how high safety availability and mitigation effectiveness are rated, a detector coverage factor less than 90% will result in an overall risk reduction factor of less than 10 (i.e., less than one order of magnitude). Since the goal of a fire and gas detection system is to reduce risk, this has led to 90% detector coverage being used as a minimum criterion for hazard detector placement. Table 3-7 summarizes detector coverage criteria included in ISA TR 84.00.07.

Table 3-7: Sample Fire and Flammable Gas Detection Coverage [3]

Detection Coverage	Fire Detection	Flammable Gas Detection
90%	Potential for severe consequences	High frequency release sources or high degree of congestion/confinement
80%	"Normal" risk with moderate to low likelihood of fire	Moderate degree of congestion/confinement
60%	"Low" risk areas, such as those with high flash point fuels	Open areas with well-controlled ignition sources

However, simply achieving 90% detector coverage may not reduce overall risk to a tolerable level; additional criteria must be placed on the undetected release scenarios. Otherwise, for example, the undetected 10% could contain scenarios that present a significant risk to the facility and personnel, or the undetected 10% could be concentrated in a single area of the facility; neither of these outcomes should be acceptable. The detector coverage fraction is also highly dependent on the number of scenarios evaluated; therefore criteria would also need to be established to define an appropriate set of release scenarios (e.g., achieving 90% detector coverage for MCE scenarios would translate to a much lower detector coverage once the sample size was expanded to include the many, more likely smaller releases) and release locations.

3.4.1 Flame Detector Layout

Flame detectors have a well-defined field of view which simplifies the process of detector coverage mapping[12]. Additionally, flame detectors are tested against relatively small sources of radiation, such as a 1-ft x 1-ft heptane pan fire [28]; using a point source model, the heat flux 1 meter away would be approximately 9.7 kW/m^2. Therefore, flame detectors are assumed capable of detecting any size pool or jet fire that could reach the hazard levels identified in Section 3.3. It is important to note that the goal is to detect the presence of a flame, therefore in the case of a jet fire, a flame detector may alarm if the radiation from a flame enters its field of view, even though the source of the fire may not be within the field of view; this may be lead to nuisance alarms, for example, where a flame is present during normal operation (e.g., flares).

Given the well-defined field of view, it is reasonably straightforward to perform a flame detector layout based on geographic coverage, where the coverage is defined by the fraction of a given area that is seen by one or more detectors. An example of flame detector mapping is provided in Figure 3-12; areas covered by one detector are shown in yellow, areas covered by two or more detectors are shown in green, and areas outside the field of view for all detectors are shown in red. Due to equipment obstructions and the size of the protected area, four flame detectors were required to achieve coverage by two or more detectors.

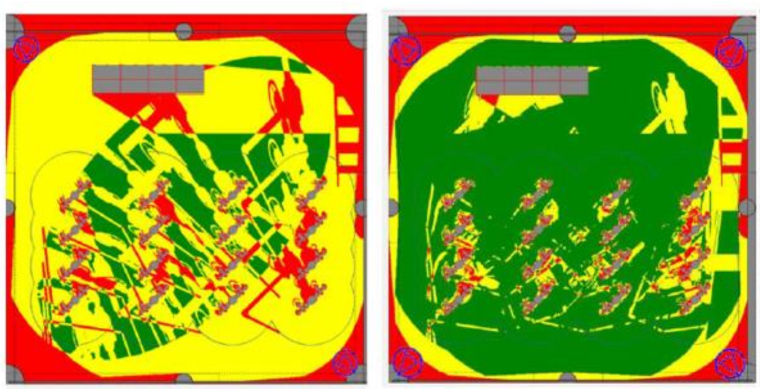

Figure 3-12: Flame detector coverage with two (left) and four (right) detectors [3].

A simple metric of 90% coverage would likely be insufficient over the entire facility; for example, the 10% undetected area could contain a pressure vessel subject to BLEVE hazards, or an area commonly occupied by plant personnel. Therefore, if a geographic coverage approach is taken, areas with a high risk of escalation should be subject to higher coverage requirements than areas with low or no risk of escalation. As a result, areas where flame detection needs to initiate ESD or activate suppression systems should

12 Flame detectors are line-of-sight, therefore 3D coverage mapping is helpful for identifying obstructions

consider voting by two or more (2ooN) detectors to confirm flame detection prior to taking executive action [29], whereas an area that just needs notification for personnel to evacuate or operators to intervene may find one detector activation (1ooN) to be sufficient. If there is a scenario where emergency shutdown by plant personnel is preferable to automatic shutdown by flame detection, the facility would need to evaluate the reliability of human intervention, as well as the impact of the additional time required for human intervention.

A more detailed approach to flame detection layout, such as scenario coverage where success is based on the ratio of detectable releases to total possible releases, is unlikely to yield a vastly improved flame detector layout. Jet fires could conceivably occur anywhere along pressurized piping and equipment containing flammable fluid streams, therefore, the result of the more computationally intensive scenario-based coverage would be similar to geographic coverage; the scenario-based approach may place greater emphasis on locations with multiple leak points, but these areas would also be covered under the geographic approach. Additionally, both methods would still require an evaluation for the potential of cascading effects, which is a deciding factor for the need of automatic ESD. Therefore, the added computational time and cost associated with the scenario coverage approach will not be proportional to the benefit.

Geographic coverage is recommended for flame detection, with performance targets based on the need for notification and/or executive action within each individual Detector Area. A risk-based approach will focus flame detection on areas presenting the highest risk to personnel and equipment, while ranking areas not requiring executive action accordingly.

3.4.2 Flammable Gas Detector Layout

Unlike flame detectors, gas detectors do not have a well-defined field of view; point gas detectors require the flammable cloud to migrate to their fixed location, or through their linear observation path for the open path detectors. As a result, a discrete coverage area cannot be defined for any single detector or set of detectors. Additionally, with flame detection, the hazard is generally considered already present to the full extent and mitigation is geared towards reducing the likelihood or impact of cascading effects. With gas detection, the goal is to detect the release and formation of a flammable cloud prior to the realization of the ultimate hazard (i.e. flash fire or VCE).

In order to consider a geographic approach to gas detector spacing (truly a volumetric approach as gas cloud formation and migration occurs in three dimensions), a key factor that would have to be properly defined is the dimensioning cloud size, which is the maximum cloud size allowed to accumulate under the facility risk criteria. This approach has been commonly applied in the offshore oil and gas industry where vapor cloud explosions are a major concern for personnel safety, given high levels of congestion, limited egress ability, and living quarters in close proximity to process equipment.

However, compared to offshore installations, onshore facilities are often less congested, equipment and personnel have greater separation, and evacuation to a safe location is more easily achieved. As a result, VCEs will generally not present the highest risk in most Detection Areas and the dimensioning cloud sizes used for offshore installations would not translate directly to the onshore environment. Further, extensive quantitative analysis would be required across a large sample size in order to properly calibrate such criteria. Additional considerations include:

- Flammable clouds from pressurized releases do not grow as a sphere radiating from the source
- Isolatable inventories at LNG facilities can be quite large, therefore, the cloud size will continue to grow after detection (during isolation and de-inventory)
- The large size of onshore LNG facilities would result in an impractical number of gas detectors using a uniform grid layout

Therefore, the concept of using a dimensioning cloud for onshore LNG plants is inadequate and needs to be replaced by different criteria. While VCE hazards are limited to congested areas in LNG facilities, flash fires can occur anywhere with equal consequences within the flash fire envelope. Therefore, scenario coverage is well suited to evaluating gas detector layouts. This approach incorporates site-specific operating and weather conditions, as well as the plant layout. By evaluating a range of release rates, locations, directions and weather conditions, and having each scenario tied to a likelihood, the overall risk profile is clearly captured. In so doing, the effectiveness of the gas detector layout can be more stringently quantified. This approach will also optimize the gas detector layout for the specific installation, rather than relying on a dimensioning gas cloud template or expert judgment alone.

Therefore, the scenario coverage approach is recommended for determining and evaluating flammable gas detector layouts. Scenario coverage can be evaluated using 2D modeling tools, however, the user must be aware of key limitations: (1) 2D models do not account for obstructions and may not accurately represent the size and shape of the flammable cloud in congested areas, and (2) 2D models reach steady-state very quickly.

For the purpose of this study, in all areas, gas detection will be assumed to activate first alarm at 20% LFL and second alarm at 40% LFL for point gas detectors [12], and at 1 LFL-m and 2 LFL-m for open path gas detectors [30][13]. It is generally accepted as best practice to require more than one detector activation for confirmation of hazard before initiating executive actions, therefore this study will require 2ooN [29].

[13] NFPA 59A requires first alarm at not more than 25% LFL (1 LFL-m) and second alarm at not more than 50% LFL (3 LFL-m). The activation thresholds chosen are consistent with recommendations in the literature and current practice in the LNG industry.

3.5 Individual Detection Area Assessments

This proposed methodology divides an LNG facility into Detection Areas based on similar hazards and the overall layout of the facility to assess fire and gas detection systems, similar to establishing Fire Areas as part of a NFPA 59A fire protection evaluation. This section will evaluate five Detection Areas common to LNG facilities (Pretreatment, Liquefaction, LNG Storage, Refrigerant Storage, and LNG Transfer) and establish fire and gas detector performance targets for each area. Note that this is not an exclusive list of areas that may require hazard detection: for example, vaporization areas also require flame and gas detection coverage. The approach outlined in this section can easily be applied to any other area not explicitly discussed here.

In the following subsections, each Detection Area will be evaluated against the criteria in Table 3-8 to establish detector performance targets. An assessment of the fuel reactivity and typical level of congestion is used to determine if VCE hazards should be considered for a given Detection Area. The assessment is based on the Baker-Strehlow-Tang (BST) method for predicting blast loads, which is widely used to evaluate VCE hazards in the petrochemical industry. The BST method uses nondimensionalized blast curves to predict the blast load for a given source energy and standoff distance [31]. Congestion is characterized by the volume blockage ratio (VBR); a visual representation of the volume blockage ratios provided in Table 3-8 are shown in Figure 3-13 for a 6-foot cube with vertical 2-inch pipes.

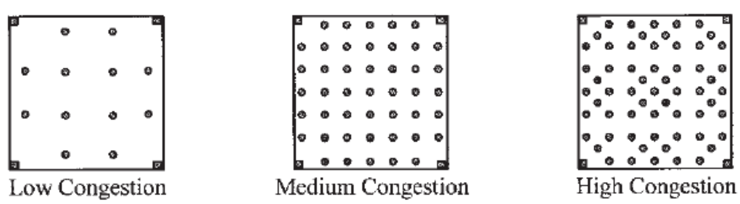

Figure 3-13: Comparison of congestion levels for BST [31].

Reference values of the VBR for each congestion level are 1.5%, 4.3% and 5.7% for Low, Medium and High, respectively. In general, most areas in an onshore LNG facility are considered 'Low' or 'Medium' congestion. Reference fuels for reactivity are methane for Low and ethylene for High, with other hydrocarbons and mixtures present at LNG facilities qualifying as Medium reactivity. Based on BST overpressure calculations, it was determined that a combination of 'Low fuel reactivity' and 'Low' or 'Medium congestion' would not result in an appreciable overpressure, therefore, VCE hazards will not be considered for Detection Areas meeting those criteria[14].

[14] For the purpose of this study, appreciable overpressure is defined as 2.8 psig, which is the hazard threshold identified in section 3.3 for 50% probability of indoor fatality .

The "Cascading Damage" criterion in Table 3-8 is intended to detail specific events that could lead to escalation and further hazards that are not captured in the initial risk calculation and/or require special treatment by the fire detection system. NFPA 59A includes the following equipment under cascading damage evaluation: LNG storage containers, LNG marine carriers, refrigerant storage vessels, buildings, or equipment required for the safe shutdown and control of the hazard [1]. For example, jet fire calculations will determine the risk for high heat flux exposure across the facility, but the location of pressurized vessels subject to BLEVE hazards must be identified and evaluated against those results. The "Cascading Damage" criterion is not intended to include hazards common to the entire facility, such as jet fire impacts on structural steel.

Table 3-8: Detection Area Evaluation Criteria

Flammable Streams	List of flammable streams present in the area
Potential Leak Scenarios	Define type of release scenarios that may occur (i.e. gas release, flashing and jetting, liquid spill)
Flash Fire	Can a flammable cloud be generated?
VCE	Is there sufficient congestion in the presence of a reactive fuel to generate an appreciable overpressure?
Jet Fire	Is operating pressure higher than 10 psig for flammable streams [32]?
Pool Fire	Can a flammable fluid accumulate on the ground or in an impoundment?
Cascading Damage	Is there potential for escalation of events (e.g. jet fire on pressurized vessel may result in BLEVE)

3.5.1 Pretreatment

The Pretreatment process removes acid gas and moisture from the feed gas in preparation for liquefaction. Depending on the size and configuration of the facility, the Pretreatment area may be in the same section of the plant as the Liquefaction area or standalone. It should be noted that while toxic gases are outside the scope of the current project, an evaluation of toxic gas detection could be performed in a similar methodology as presented for flammable gas detection, with the establishment of separate toxic gas hazard thresholds.

A summary of the hazards presented by a loss of containment of flammable fluid streams in the Pretreatment area is provided in Table 7-3. Feed gas from the pipeline is approximately 95% methane, therefore feed gas in the pretreatment area is evaluated as pure methane, consistent with current PHMSA procedures for hazard modeling.

Table 3-9: Pretreatment Evaluation

Flammable Streams	Natural Gas (methane)
Potential Leak Scenarios	The feed gas lines operate at high pressure, therefore a leak would result in a high velocity flammable gas release.
Flash Fire	Yes
VCE	No (low reactivity fuel; low/medium congestion)
Jet Fire	Yes
Pool Fire	No (gaseous inventories)
Cascading Damage	None

3.5.2 Liquefaction

There are several liquefaction technologies available in the LNG industry, mainly depending on the desired production rate of the facility. Many small-scale LNG facilities use a closed loop nitrogen refrigerant liquefaction system; though a nitrogen release presents an asphyxiation hazard in the vicinity of equipment, this hazard is often bounded by flammable gas hazards from the natural gas and LNG lines. Facilities needing a larger production rate often utilize a mixed-refrigerant liquefaction process.

This analysis considers an LNG facility with a mixed-refrigerant liquefaction process, which introduces hazards from additional flammables such as ethylene, propane, and butane[15]. These refrigerants are more reactive than methane and present increased hazard potential from VCEs. Though ethylene is considered a 'high' fuel reactivity, it usually makes up less than half of the mixed refrigerant streams, therefore the highest fuel reactivity for the Liquefaction area is considered 'medium'. Additionally, the Liquefaction area tends to be the most congested area of an LNG facility.

Table 3-10: Liquefaction Evaluation

Flammable Streams	Natural Gas and LNG (methane) Refrigerants (Ethylene, Propane, Butane and mixtures)
Potential Leak Scenarios	Flammable gas releases from 'clean gas' lines from the Pretreatment area or mixed-refrigerant vapor lines. Flashing and jetting releases of LNG or liquid mixed-refrigerant inventories. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	Yes (medium reactivity fuel; medium congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	BLEVE of pressurized vessels

[15] Pentane is also commonly used

3.5.3 LNG Storage

LNG is commonly stored in above ground atmospheric storage tanks or horizontal pressure vessels. Piping in this area includes LNG rundown lines from the Liquefaction area, LNG sendout lines to the vaporization or transfer areas, and boil off gas (BOG) lines. Safety standards and regulations require impoundments for the collection of liquid spills in this area; whenever possible, these should be located remote of the LNG storage tanks to limit thermal radiation impacts from a pool fire.

Table 3-11: Liquefaction Evaluation

Flammable Streams	LNG and BOG (methane)
Potential Leak Scenarios	Flashing and jetting releases of LNG from rundown or sendout lines. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment. Flammable vapor releases from boil off gas lines.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	Thermal radiation exposure to the LNG storage tanks, including BLEVE of pressurized vessels

3.5.4 Refrigerant Storage

Facilities utilizing refrigerants for liquefaction typically store make-up quantities of those refrigerants (or their components) on site. The Refrigerant Storage area is usually remote from the Liquefaction area to limit hazardous exposure to the pressurized storage vessels. Refrigerants are delivered to the facility via truck, requiring personnel to be in the refrigerant storage area during unloading operations. Some facilities have 'mounded' storage tanks that are covered by earthen berms to protect the vessels from thermal radiation and mitigate BLEVE hazards, however, this is not considered in the current analysis.

Table 3-12: Refrigerant Storage Evaluation

Flammable Streams	Refrigerants (Ethylene, Propane, Butane)
Potential Leak Scenarios	Flashing and jetting releases from liquid piping or transfer hose. Liquid spill from large-bore piping or hose ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	Yes (medium/high reactivity fuels; low/medium congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	BLEVE of pressurized storage vessels

3.5.5 LNG Transfer Areas

Some small-scale LNG facilities supplement LNG production by receiving LNG from truck shipments, while some peakshaving facilities receive their entire inventory via truck. Truck loading and unloading operations require personnel to be present. During loading operations, any boil off gas (BOG) generated is often directed through low pressure vapor lines to be used as fuel gas. While this analysis considers truck loading to represent the LNG Transfer area, ship loading or vaporization and sendout areas could be evaluated similarly.

Table 3-13: LNG Transfer Evaluation

Flammable Streams	LNG and BOG (methane)
Potential Leak Scenarios	Flashing and jetting releases of LNG from liquid piping or truck hose. Liquid spills from a large-bore LNG line ruptures flowing into the facility trenches and impoundment. Flammable vapor releases from boil off gas lines.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	Thermal radiation exposure to LNG Trailer

3.6 Parameters for Detector Performance Targets

The leading challenge to FGD design is not in achieving sufficient detector coverage, but in defining what constitutes sufficient detector coverage. ISA TR 84.00.07 demonstrates that a risk reduction of one order of magnitude requires at least 90% of the releases to be detected, which is sometimes adopted as a performance target for hazard detection systems at LNG facilities. However, this criterion alone is insufficient to evaluate hazard detector layouts for several reasons, such as:

- The percentage of successful release detection is highly dependent on the release scenarios evaluated (hole size, orientation, locations, etc.)
- The undetected 10% may include scenarios that present a significant risk to the facility and personnel
- The undetected 10% could be concentrated in a single area of the facility
- Uniform application of a single criterion for individual areas of the facility may be overly burdensome in low-risk areas
- Not all areas within an LNG facility will require a risk reduction factor greater than 10 (basis for the 90% target in the ISA TR 84.00.07) from the fire and gas detection system. In fact, there may be no areas requiring a risk reduction factor greater than 10.

Therefore, a performance-based approach is required to determine what level of detection is appropriate for each Detection Area within an LNG facility. Rather than a blanket requirement of detecting a given percentage of potential release scenarios, the proposed methodology will optimize the fire and gas detection system by focusing resources on the scenarios that present the greatest risk.

In order to establish detector performance targets, the following parameters should be defined in the Fire and Gas Detection Philosophy:

- Risk tolerability (i.e., intolerable and tolerable risk levels)
- Hazard thresholds (i.e., probability of fatality from exposure to the hazard)
- Use of geographic coverage or scenario-based coverage
- Detector coverage criteria based on different risk classifications (e.g., High-Normal-Low) and corresponding detector coverage targets (e.g., 90-80-60%)
- Detector voting criteria (i.e., how many detectors must activate to initiate executive actions)

It should be noted that the detector coverage method, detector coverage criteria, and voting criteria may be different for flame and gas detection. Sections 6 and 7 of this report present two case studies which demonstrate two separate ways to establish detector coverage criteria; one using Individual Risk of Fatality thresholds and one using more general risk classifications.

4 Identifying Hazard Scenarios for Detection

A risk-based approach to fire and gas detection requires developing a list of potential hazard scenarios that can be used to assess detector coverage. Fire and explosion risk assessments typically include a range of potential releases, varying from pinhole leaks to full-bore ruptures. It is not feasible to design a fire and gas detection system capable of detecting every conceivable leak. Therefore, the list of potential hazard scenarios used to evaluate fire and gas detection systems should exclude scenarios with minor risk contributions and focus on scenarios that require mitigation, otherwise the cost of detection would be disproportionate to the benefit.

With respect to gas detection and scenario-based coverage, the achieved detector coverage is highly dependent on the number and location of scenarios evaluated. For example, achieving 90% detector coverage for release scenarios typical to facility siting studies (i.e. hole sizes on the order of 2-4 inches evaluated at release points closest to the property line) would translate to a much lower detector coverage once the sample size was expanded to include all isolatable inventories and multiple release locations for each.

This section discusses the information needed to develop a list of potential hazard scenarios at an LNG facility and a methodology for identifying the scenarios that should drive the fire and gas detection layout. As noted previously, toxic gas detection is outside the scope of the current project, however, a toxic gas detector evaluation could be performed using a similar methodology.

4.1 Required Information

The documents required to conduct this analysis are consistent with those required for a Design Spill Package prepared for LNG facilities under PHMSA jurisdiction as defined by PHMSA's LNG Plant Requirements: Frequently Asked Questions (FAQs) [16] and include:

- Plot plans
- Process Flow Diagrams (PFD)
- Piping and Instrument Drawings (P&ID)
- Heat and Material Balance Sheets (H&MB)
- Process Datasheets
- Site specific weather data

[16] https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-plant-requirements-frequently-asked-questions

Sample documents for the generic LNG facility used in this report include a plot plan, PFDs, and H&MBs, which are included as appendices to this report. Preparation of detailed engineering documents, such as P&IDs and process datasheets, is outside the scope of the current project, therefore parts counts and process inventory are estimated based on the experience of the project team[17].

4.2 Potential Hazard Scenarios

The first step in identifying potential hazard scenarios is to define isolatable inventories. Each isolatable inventory represents a section of the overall process (located between control or emergency shutdown valves) where the process conditions are the same; connecting areas between process areas are also separated to avoid an over estimation of risk where the only failure points are those associated with piping. Isolatable inventories can be identified by reviewing PFDs and P&IDs. Failure rates for each isolatable inventory can then be determined based on parts counts and data available in the literature[18].

For the purpose of applying the detector layout methodology to a generic LNG facility, this project primarily relies upon the process release frequencies contained in the International Association of Oil & Gas Producers (IOGP) Risk Assessment Data Directory, which utilizes the release categories given in Table 4-1 [33]; these categories are consistent with guidelines from the Center for Chemical Process Safety (CCPS) [32]. The total probability of ignition is also based on IOGP data and is subdivided into a 30% probability of immediate ignition (jet fire) and 70% probability of delayed ignition (flash fire or vapor cloud explosion, VCE) [34]. It should be noted that different sets of failure rate or ignition probability data can be used without invalidating the basis of the proposed methodology.

Table 4-1: Release categories

Type	Hole Size [mm]	Hole Size [in]
Pinhole	< 3	< 0.1
Small	3-10	0.1-0.4
Medium	10-50	0.4-2
Large	50-150	2-6
Rupture[19]	> 150	> 6

[17] Note that conservative estimates of parts counts were made for this demonstrative.

[18] Reference DOT PHMSA research project No. 731, "Consistency Review of Methodologies for Quantitative Risk Assessment" for a summary of failure rates applicable to LNG facilities.

[19] Based on equipment diameter

Using the harm criteria established in Section 3 of this report, the risk associated with a loss of containment is calculated for each isolatable inventory, and the location-specific individual risk (LSIR) contours are calculated and plotted as summarized in Table 4-2; note that the contour for individual risk of fatality of 1×10^{-5} per year (midpoint of the Tolerable Range) is plotted in addition to the risk criteria established in Section 3.

Table 4-2: Risk Thresholds

Individual Risk of Fatality (per year)	Risk Classification
IR ≥ 1×10^{-4}	Intolerable
IR > 5×10^{-5}	Permitted within plant boundaries[20]
IR > 1×10^{-5}	*ALARP Midpoint*
IR < 1×10^{-6}	Tolerable

4.3 Unmitigated Risk

The process outlined above was carried out to calculate the 'unmitigated risk' for the generic LNG facility. The unmitigated risk assumes no detection by the fire and gas system and subsequent ESD procedures. All consequence modeling was performed with the 2D hazard modeling software Phast (version 8.22). The release duration was assumed to be one hour (unmitigated case), though the Phast calculations usually reach a steady-state within the first few minutes.

The risk calculations require ambient conditions to be defined, since the hazard footprint from each release scenario depends to some extent on the wind speed and direction and, to a lesser extent, on the ambient temperature. Weather data from an unspecified location were used for the calculations in this report; the ambient temperature was set to 70 °F and the wind data is represented by the wind rose shown in Figure 4-1.

[20] 2019 edition Table 19.10.1(a) Criteria for Tolerability of Individual Risk of Fatality – Zone 1

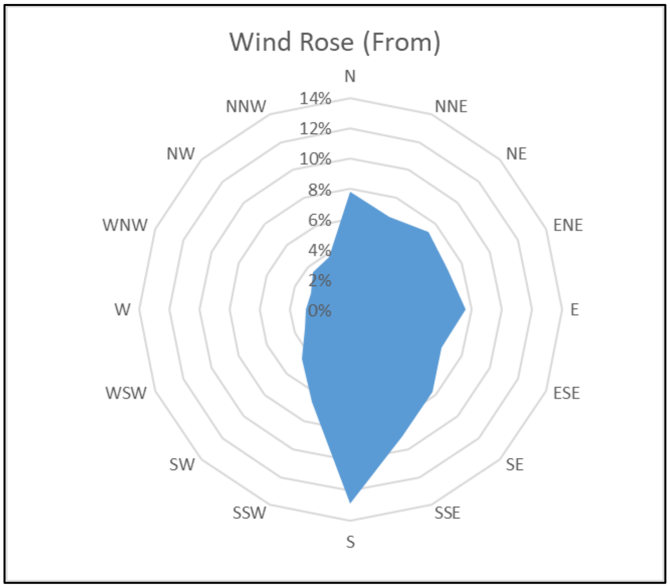

Figure 4-1: Wind rose for generic LNG facility.

The unmitigated individual risk for the generic LNG facility is shown in Figure 4-2. Note that the red box indicates the facility property line and the weather data had a prevailing wind from plan south, which explains why the risk isopleths are shifted north relative to the piping and equipment. The LSIR contours show that risk is concentrated near the liquefaction units, which include the Pretreatment (north end) and Liquefaction (south end) areas; these areas fall in the 'intolerable' risk category. The 'tolerable' LSIR contour extends offsite and the full extent is not shown.

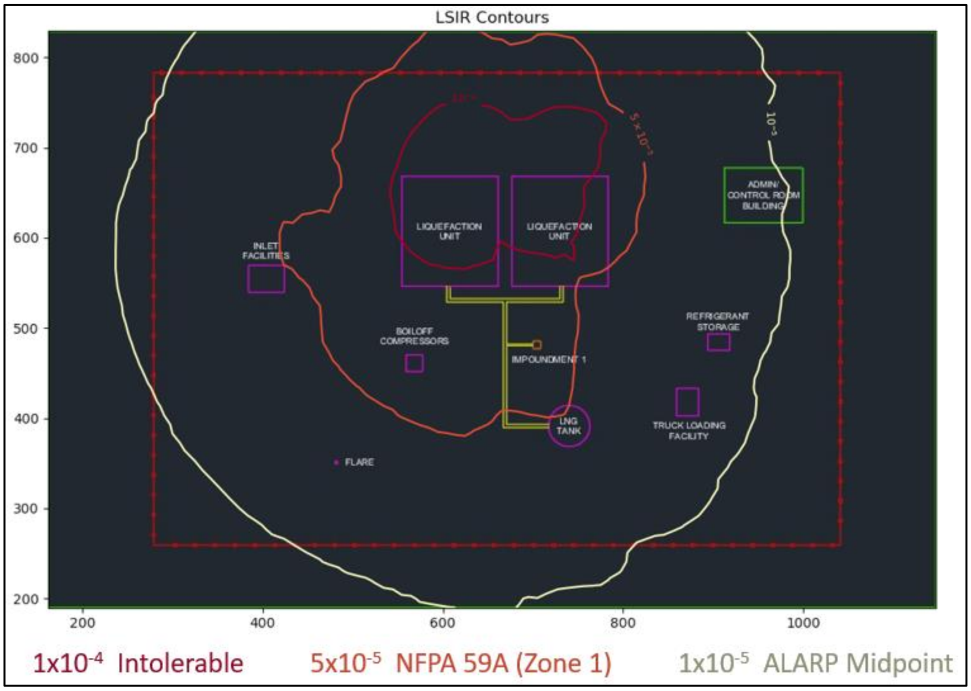

Figure 4-2: Unmitigated risk (baseline).

4.4 Hole Size Sensitivity

The fire and gas detection system can be evaluated and optimized by focusing on the hazard scenarios that contribute the highest level of risk to the facility. Though smaller releases are more likely to occur, attempting to detect these releases would require a significant increase in the number of hazard detection devices, without appreciably reducing the individual risk. Therefore, the proposed methodology includes performing a sensitivity study to identify the minimum leak size required to be included.

Figure 4-3 through Figure 4-6 compare the baseline unmitigated risk contours (which includes all release categories) with the unmitigated risk including only subsets of releases. Specifically:

- Figure 4-3 compares the baseline LSIR with the LSIR from releases larger than 6 inches only
- Figure 4-4 includes releases 6” and larger in the comparison subset
- Figure 4-5 includes releases 2” and larger
- Figure 4-6 includes releases 0.4” and larger

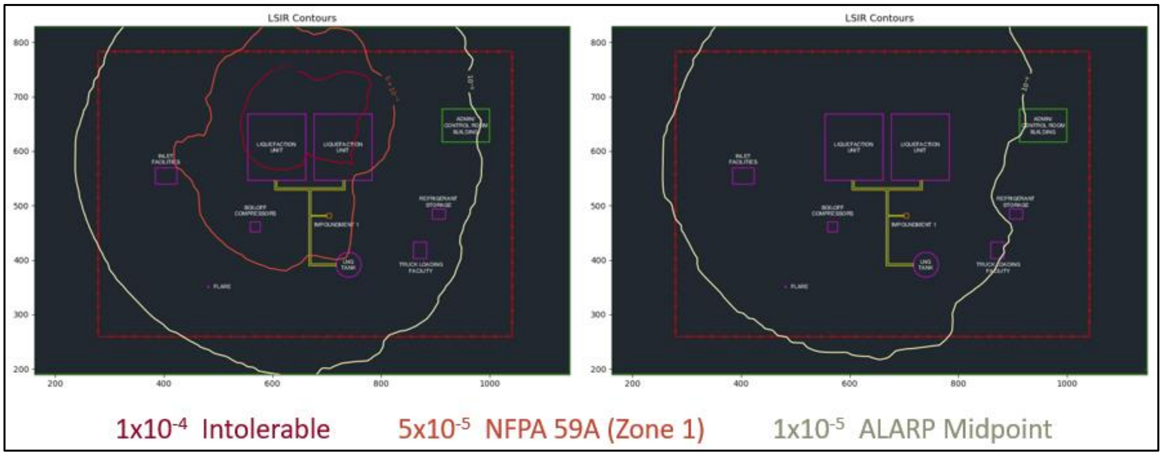

Figure 4-3: Unmitigated risk: baseline (left) and releases larger than 6 inches (right).

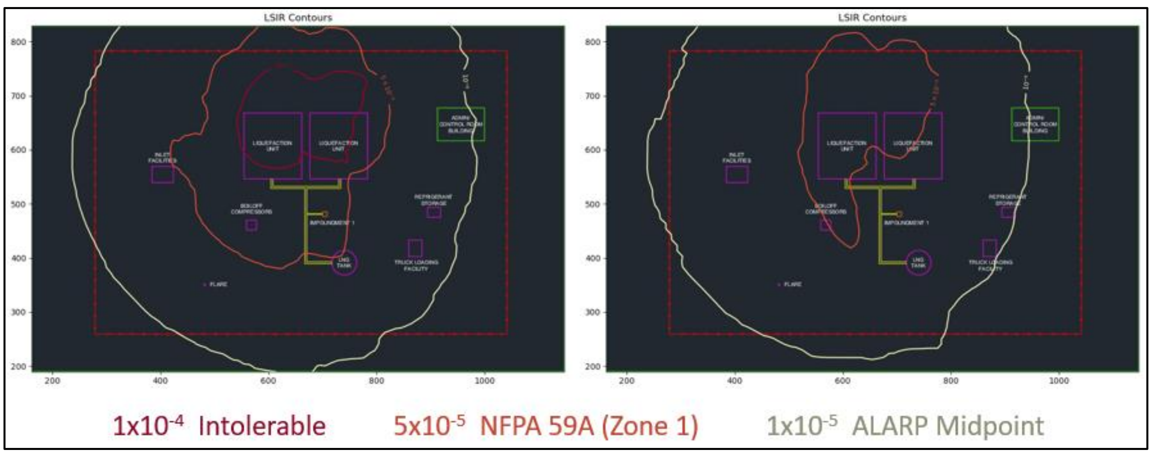

Figure 4-4: Unmitigated risk: baseline (left) and releases 6 inches & larger (right).

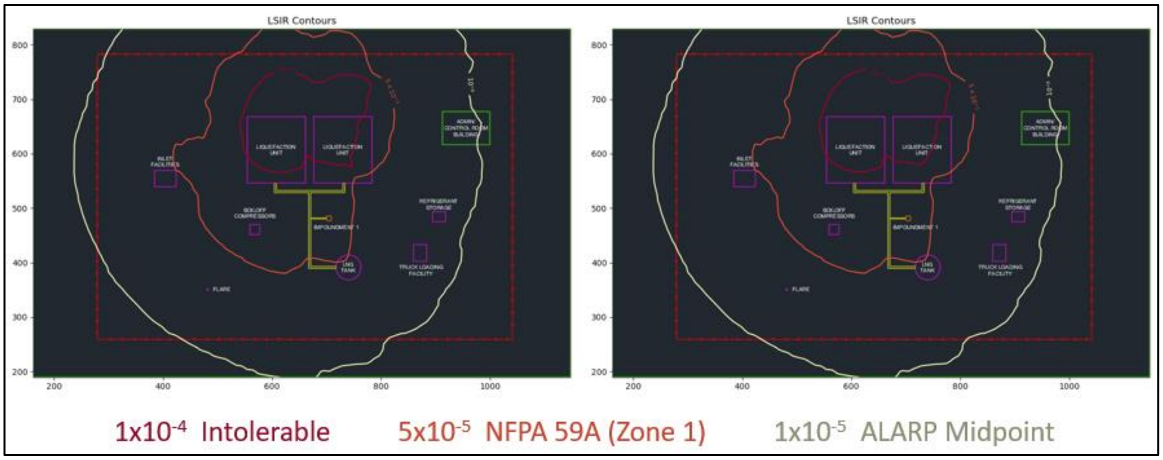

Figure 4-5: Unmitigated risk: baseline (left) and releases 2 inches & larger (right).

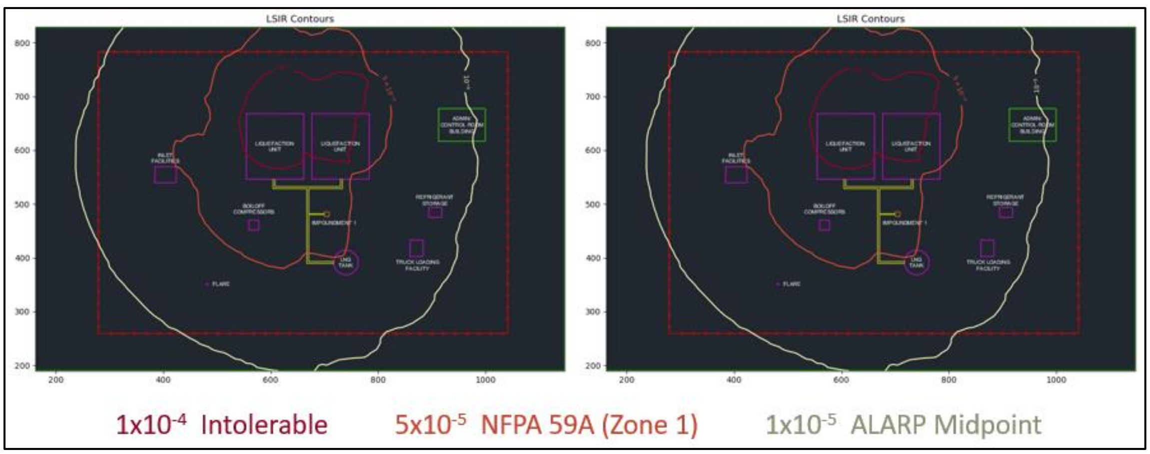

Figure 4-6: Unmitigated risk: baseline (left) and releases 0.4 inches & larger (right).

The comparisons show that, for this specific case, releases smaller than 2" diameter do not contribute appreciably to the individual risk at the specified tolerability thresholds. Therefore, the performance-based flame and gas detection layout review (or design) for this specific case can be limited to evaluating detection of releases 2" and larger, without affecting the results.

It is important to note that the results of the sensitivity study are case-specific; they should not be considered generally applicable to other facilities. For each facility, a hole size sensitivity analysis should be performed to determine the minimum hole size to be considered.

It should also be noted that, while the example presented in this section did not consider buildings or enclosed equipment, either can be included in the LSIR calculation as needed on a case-by-case basis.

4.5 Hazard Scenario Selection Summary

In order to evaluate a fire and gas detection layout, a proper set of hazard scenarios needs to be developed. This section outlines a methodology for determining which hazard scenarios are driving the risk profile for the facility, thereby providing guidance on how to allocate hazard detection resources.

The unmitigated risk calculated for this facility is based on the generic facility information included as appendices to this report, sample weather data, estimates for parts counts, and the risk tolerability criteria specified in Section 3. It is important to note that the conclusions regarding evaluating releases 2 inches in diameter and larger for hazard detection layouts are based on these study-specific inputs and assumptions; they should not be considered generally applicable to other facilities. For each facility, a site-specific hole size sensitivity analysis should be performed to determine the minimum hole size to be considered.

The methodology presented in this report is independent of the exact facility layout, process areas, process conditions, weather conditions, parts count, etc. Therefore, the same methodology can be applied to any LNG facility. In order to establish a minimum hole size that must be considered for hazard detection, this methodology would need to be performed for each facility or carried out on a representative sample size to be found reliable.

With the documentation listed in section 4.1, the process is as follows:

1) Specify risk criteria
2) Define isolatable inventories
3) Determine failure rates based on parts counts and data from the literature
4) Set criteria for ignition probability
5) Calculate the consequences associated with a full range of release categories
6) Calculate and plot LSIR contours (Unmitigated Risk – Baseline)
7) Perform hole size sensitivity to determine which release categories are driving the facility risk profile; smaller hole sizes will not need to be considered when evaluating the hazard detector layout
8) Compare LSIR contours to risk classification criteria and assign minimum detector coverage requirements

5 Consequence Modeling

Federal regulations for the siting of LNG facilities specify design spills to have a 10-minute duration if the process design includes acceptable detection, isolation and shutdown, however, applicants are also permitted to evaluate release durations shorter than 10 minutes based on *demonstrable* surveillance, shutdown, and isolation design[21]. Since there is currently no standard for the design of hazard detection systems at LNG facilities, it follows that there is no consistent methodology for demonstrating successful detection, isolation, and shutdown provisions.

The hazard modeling tools used for facility siting studies are often employed to evaluate the performance of hazard detection layouts and quantify the reduction in consequences associated with shortened release durations. Therefore, it is necessary to understand the use and limitations of such models.

The first model evaluation protocol used to determine the acceptability of dispersion models for LNG facility siting studies (commonly referred to as the "LNG MEP") was released in 2007 and was updated in 2016 [35]. This model evaluation protocol is geared towards far-field dispersion and maximum gas concentration, which are the main parameters of concern with respect to facility siting studies. Therefore, the experimental data used to evaluate the models is comprised of LNG spills with gas cloud data tracked at measurement arcs 150 ft or more from the spill location; additionally, model performance is based on the ability to predict peak gas concentration at specific points or arcs, without regard for timing. A new MEP for flammable dispersion was developed by BLUE and released in 2020 that includes pressurized releases, however, the purpose of the MEP and the target variables (e.g. far field dispersion) remain the same [36].

When evaluating detector layouts, the time to detection and isolation of an accidental release is a critical target, therefore there is a need to focus on near-field dispersion and the results are very time sensitive. This section presents a comparison of dispersion models commonly used for LNG facility siting studies and how their respective results would impact the scenario-based coverage of a gas detector layout[22]. This report is not a dispersion model validation effort.

21 https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-plant-requirements-frequently-asked-questions, DS8

22 Evaluating flame detector layouts by geographic coverage does not require hazard modeling, therefore, flame detection will not be addressed in this section.

5.1 Dispersion Models

There are currently two models approved by PHMSA for dispersion analysis: Phast (versions 6.6 and 6.7) and FLACS (version 9.1).

Phast incorporates the Unified Dispersion Model (UDM) to model two-phase jet, heavy and passive dispersion including droplet rainout and pool spreading/evaporation. This allows for an unmitigated representation of the hazards associated with a hazardous fluid release. Phast calculates dispersion for an unobstructed cloud over flat terrain; it does not take into account site features (such as elevation changes, buildings, berms, etc.) or the effect of common dispersion mitigation measures (such as vapor fences, barriers, etc.). A single dispersion scenario can be set-up in Phast with basic process and weather data; calculations are complete in a few seconds. This allows a large number of scenarios to be run in a relatively short time frame.

FLACS is a computational fluid dynamics (CFD) code for the modeling of ventilation, gas dispersion and vapor cloud explosions in complex process areas. FLACS is not a general-purpose CFD model, but a model specifically developed to perform consequence modeling studies in an accurate yet efficient manner. Though it is computationally more intensive than Phast, FLACS allows the consequence modeling to consider the interaction of gas flows with site-specific features (terrain, obstacles and obstructions) as well as common mitigation measures (walls, vapor barriers, etc.). As is the case for most CFD tools, FLACS simulations take more time and expertise to set-up than Phast. Additionally, the run time for a single scenario can vary from a few hours to a few days depending on the size of the simulation grid and the duration of the release.

While Phast only requires process conditions and hole size to calculate the dispersion scenario, the source term for the accidental release must be defined in a FLACS simulation. In FLACS, all releases need to be in the vapor phase, therefore the jet emerging from a liquid release needs to be converted to a vapor "pseudo-source". This process can be completed by the Flash utility supplied with the FLACS package, or by use of another model such as Phast. In both instances, the result is a "displacement" distance between the actual leak source and the modeled vapor source, as shown in Figure 5-1 by the yellow and green arrows, respectively. The pseudo-source reconciles the initial jet expansion from the system pressure to ambient pressure (including flashing of superheated releases), the droplet size distribution for the atomized jet, the air entrainment, and the vaporization of the liquid droplets. For typical LNG facility siting scenarios, the pseudo-source displacement distance ranges approximately 40-80 ft (13-25 m) for 2-inch holes, and generally increases with hole size.

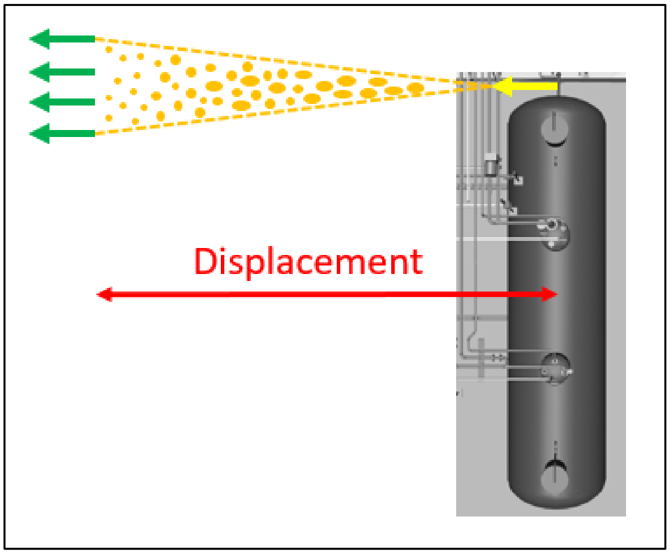

Figure 5-1: Displacement for modeling a liquid release in FLACS; actual source in yellow and modeled source in green.

The FLACS geometry developed for the generic LNG facility used in this analysis is shown in Figure 5-2. Though the model does not include a detailed piping layout, piping was distributed within the liquefaction area to represent a ‘medium’ congestion level as defined in Section 3.5.

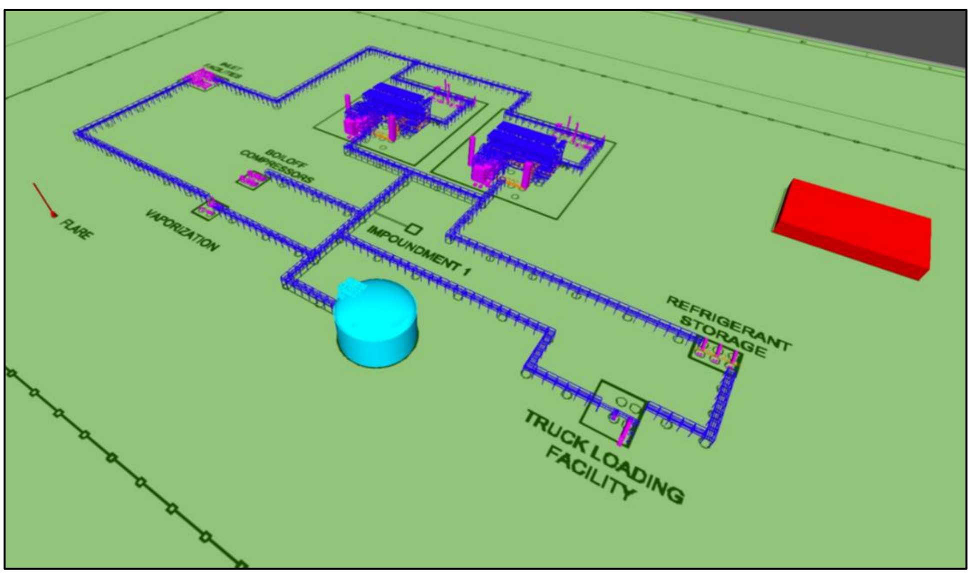

Figure 5-2: FLACS geometry for the generic LNG facility.

5.2 Hazard Scenarios

The analysis conducted in Section 4 demonstrated that releases 2-inches in diameter and larger are driving the risk for the generic LNG facility developed for this project. Therefore, the model comparison was based on 2-inch release scenarios. A wind speed of 4.5 mph (2 m/s) was used for the model comparison.

After a review of the hazard scenarios identified for the generic LNG facility, 18 scenarios were chosen for conducting the model comparison as detailed in Table 5-1 and Figure 5-3. Note that the release locations and directions are given by color-coded arrows and labeled by Inventory number; releases for Inventories 5 and 19 occur at the same location.

These scenarios were chosen to provide a range of fuels and evaluate three obstacle conditions:

1) *Unobstructed*: Dispersion over flat terrain with little to no obstacles downstream[23].
2) *Obstructed near Modeled Source*: Scenarios where there are obstructions immediately downstream of the modeled source[24].
3) *Obstructed Downstream*: The Modeled Source is located in open space, but flammable cloud formation is impacted by obstacles downstream of the leak.

[23] The case of a single piperack in open-flat terrain was included in the Unobstructed scenario set.

[24] For gas releases, the modeled source is at the actual source location. For liquid releases, the modeled source has a displacement distance from the actual source in FLACS (Figure 5-1).

Table 5-1: Release scenarios for model comparison.

	Inventory	Fuel	Description	Release Direction
Unobstructed	1	Natural Gas	Inlet Metering	East
	4	LNG	From Coldbox	South
	5	LNG	Single Train Rundown	South
	19	Propane	Makeup to Train	South
	14	LNG	LNG Tank to Truck Loading	West
	15	LNG	Truck Loading	North
Obstructed near Modeled Source	1	Natural Gas	Inlet Metering	South
	3	Natural Gas	Pretreatment	East
	12	Mixed-Refrigerant – Liquid	Liquid to Coldbox	West
	13	Mixed-Refrigerant – Vapor	Vapor to Coldbox	North
	15	LNG	Truck Loading	East
	31	LNG	LNG Sendout / Vaporization	South
Obstructed Downstream	3	NG	Pretreatment	South
	4	LNG	From Coldbox	West
	5	LNG	Single Train Rundown	North
	12	Mixed-Refrigerant – Liquid	Liquid to Coldbox	East
	19	Propane	Makeup to Train	North
	26	Ethylene	Storage Vessel	East

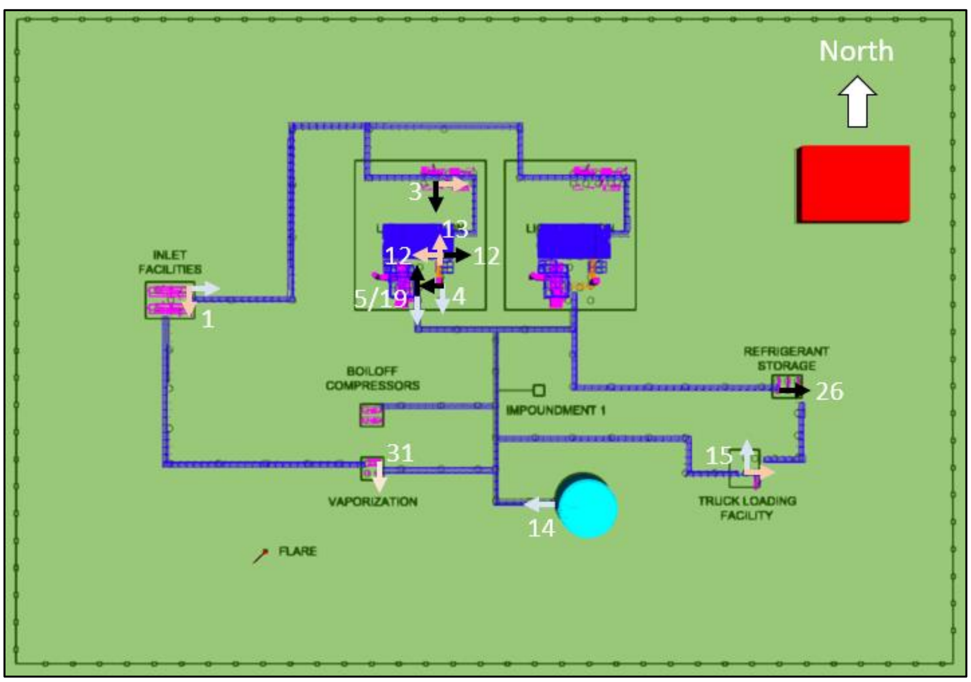

Figure 5-3: Release locations and directions for model comparison (arrow colors refer to Table 5-1).

5.3 Model Comparison

Scenario-based detector coverage is expressed as the percentage of the total number of release scenarios that is successfully detected. Therefore, each individual scenario (combination of inventory, hole size, release location and direction, wind conditions, etc.) needs to be evaluated against the detector layout. For this project, successful detection is defined as two detectors (2ooN) reaching the activation threshold.

This model comparison assumed detector activation to occur at a gas concentration of 40% LFL. It should be noted that some facilities use a detector activation threshold of 20% LFL; by selecting the higher concentration threshold for this project, the size of the detectable cloud was smaller and therefore provided a more rigorous test of the detector layout. Additionally, it should be noted that a safety factor was not applied to these modeling results; any such requirements would be subject to the Authority Having Jurisdiction.

Open path gas detectors, which separate the IR source and receiver to provide coverage over large distances, report gas concentration as LFL-m rather than %-LFL. These detectors measure the integral of the gas concentration along the path between the transmitter and receiver, where 1 LFL-m is equivalent to a meter-long gas cloud at LFL concentration. Under this measurement scheme, the same reading would be given for a large cloud at low gas concentration and a small cloud at high gas concentration. While open path gas detectors are commonly utilized at LNG facilities, a reading of LFL-m is not easily compared across different hazard scenarios and dispersion models. Accordingly, open path gas detectors were included in the case studies conducted under this project, but are not addressed in this section.

Interactions with obstacles or obstructions can slow down and redirect cloud growth, ultimately changing the shape of the gas cloud that must be detected. This section includes visual and numerical comparisons of the selected dispersion models to compare cloud shape for different fuels and obstacle layouts, demonstrating how model selection will impact an evaluation of gas detector coverage.

5.3.1 Visual Comparison

The brief introduction of Phast and FLACS in Section 5.1 should be sufficient to intuitively understand that different dispersion models may result in different evaluations of a given detector layout, due to their respective treatment of the cloud-obstruction interaction. A clearer demonstration of the difference can be obtained by comparing graphically the cloud sizes at the elevation of the detectors. This model comparison will focus on cloud width at 1.5 ft (0.5 m) above grade, consistent with point gas detector mounting heights for heavy gases available in the literature [27], [12].

In this section, snapshots of the Phast and FLACS clouds at 30 seconds into the release are compared for side view and elevation view (at 0.5 m above grade). The Phast plots are located at the top of each figure, with blue and red contours indicating the extent of the cloud to 40% and 100% LFL, respectively; note that the aspect ratio is not 1:1 as the vertical axis is automatically stretched to increase readability. The FLACS images are located below the Phast plots in each figure, with the blue area indicating cloud concentrations at or above 40% LFL, and the red area indicating the same for 100% LFL.

The FLACS images were scaled and aligned with the Phast plot according to the downstream distance (i.e., the release occurs at zero on the horizontal axis). The vertical axis on the FLACS images is not scaled to match the Phast plots, and the coordinates of the release were not adjusted from the simulation (i.e., the release does not occur at zero on the vertical axis in FLACS). Additionally, note that the Phast calculations assumed the wind to be aligned with the release direction; the FLACS simulations show different wind directions, as indicated by the blue arrows. Since the wind direction varies in the FLACS simulations, the advancement of the cloud front is referred to as ‘downstream’ of the release point, rather than ‘downwind’.

A comparison of the Phast and FLACS output for an unobstructed natural gas release (Inventory 1 – NG) is shown below in Figure 5-4 and Figure 5-5. The results show a similar downstream distance to the concentration thresholds and a slightly wider cloud in FLACS. Wind direction does not have a significant impact on cloud width in the vicinity of this high-pressure release.

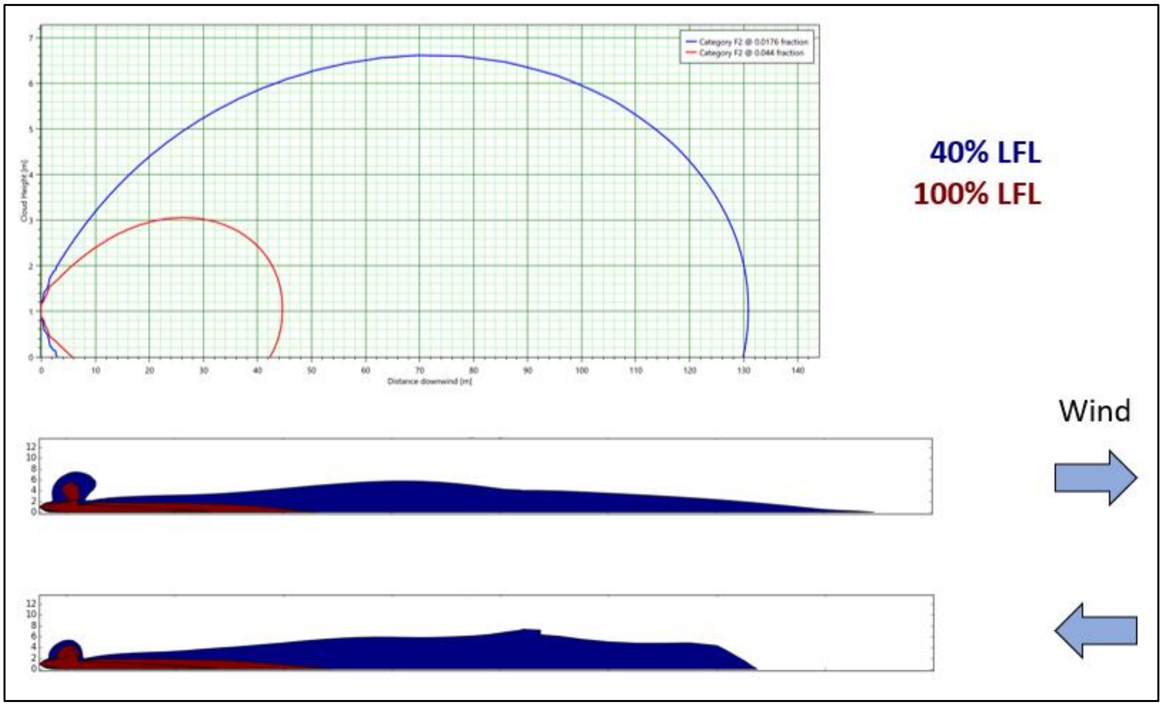

Figure 5-4: Inventory 1 – NG – Unobstructed – Side View.

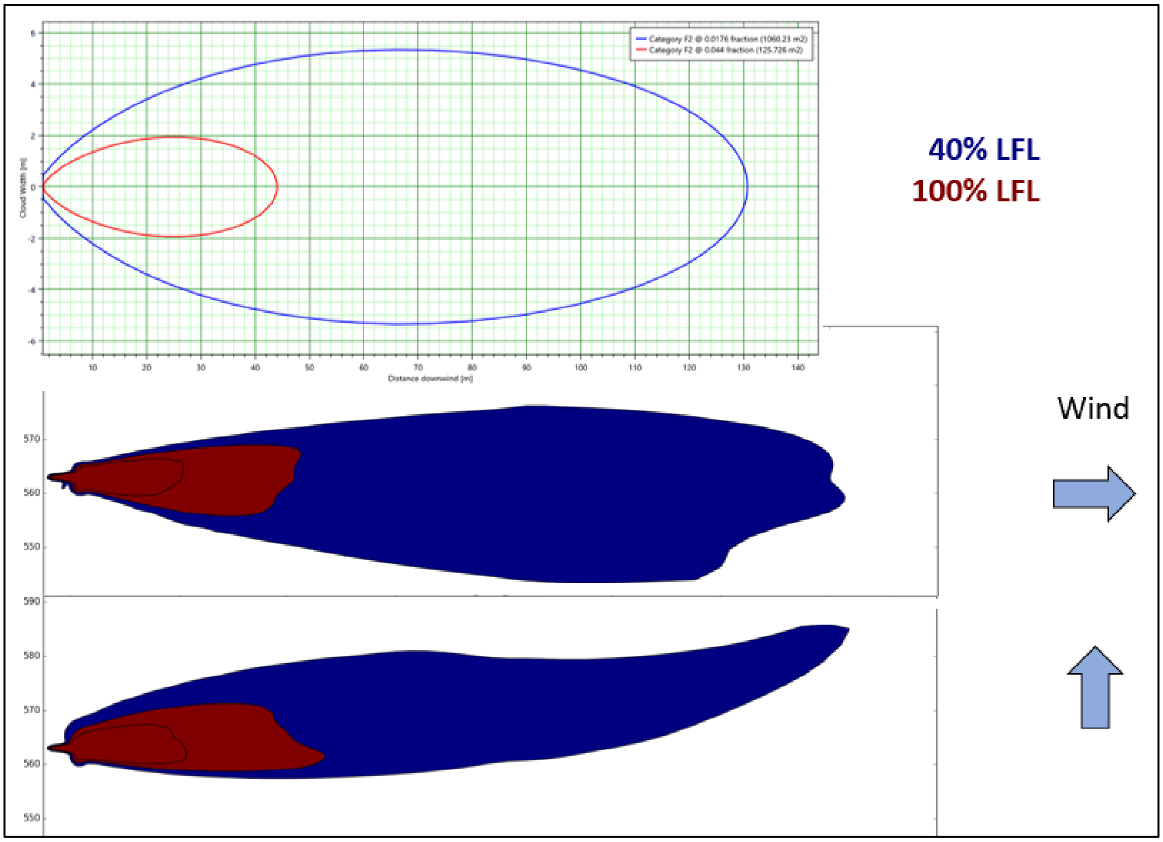

Figure 5-5: Inventory 1 – NG – Unobstructed – Plan View at 0.5m.

The same release is shown in Figure 5-6 and Figure 5-7 where the jet hits large-bore piping in the FLACS model approximately 2 m downstream of the release. The side view shows 100% LFL extending farther in FLACS than the Phast calculation, and a reduced distance to 40% LFL. The plan view shows a significant increase in cloud width: 5m vs. 61m at 10m downstream, 7m vs. 44m at 20m downstream, for Phast and FLACS, respectively.

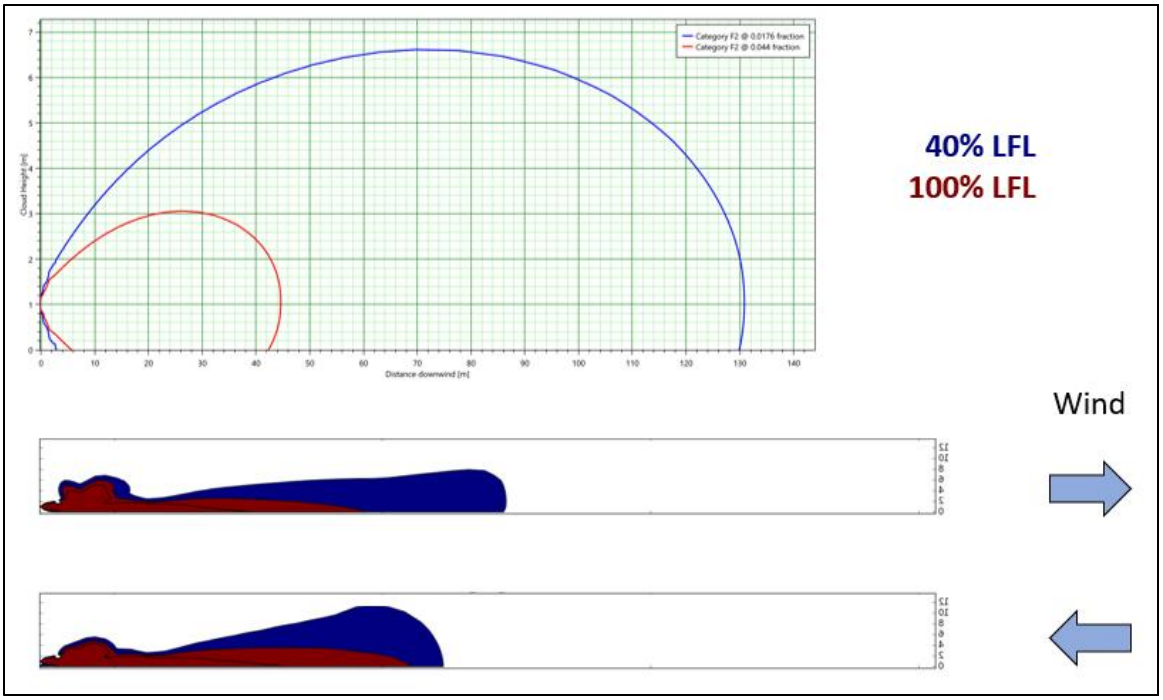

Figure 5-6: Inventory 1 – NG – Obstructed near Source – Side View.

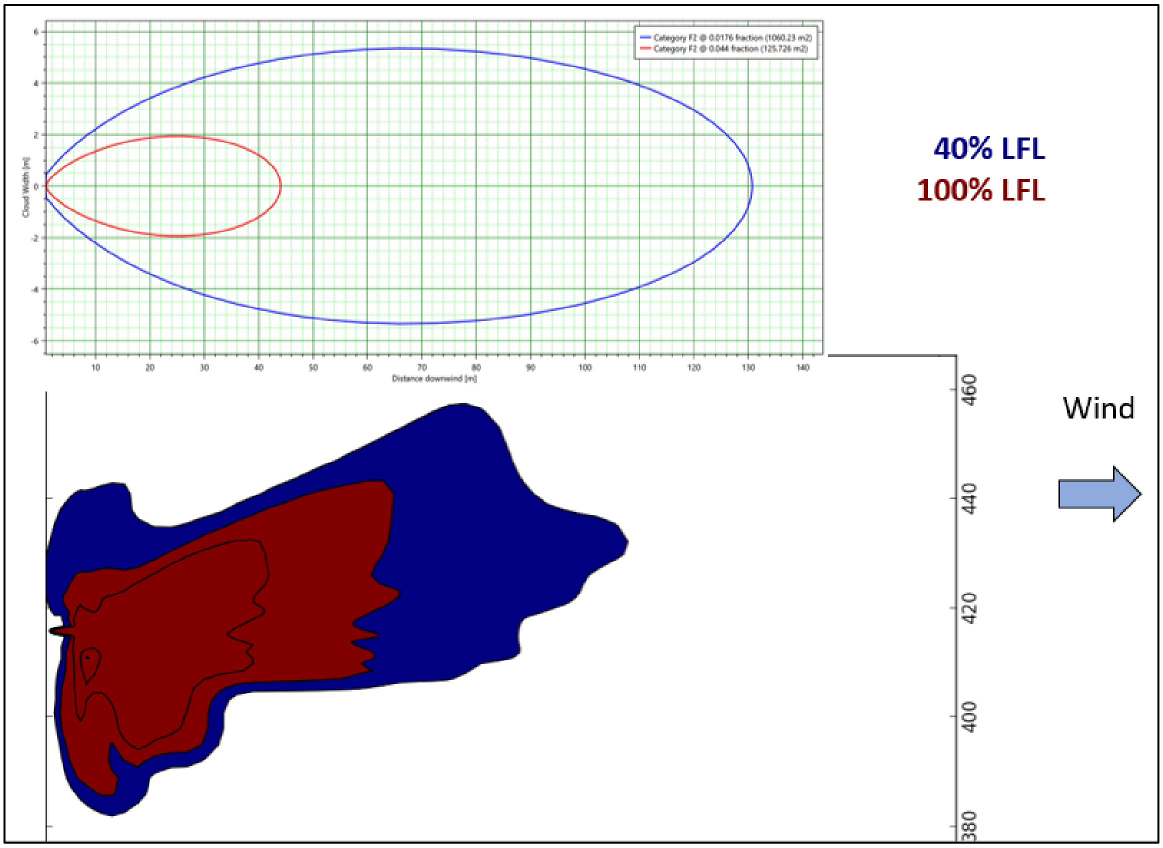

Figure 5-7: Inventory 1 – NG – Obstructed Near Source – Plan View at 0.5m.

A comparison for an LNG release from the rundown line (Inventory 5) into the liquefaction area is shown in Figure 5-8 and Figure 5-9. The side view shows the cloud at 40% LFL reaching grade at a similar downstream distance, despite the displacement associated with the modeled source in FLACS. The plan view shows a significantly wider cloud in FLACS due to the congested region; note the different scales on the vertical axis for Phast (top) and FLACS (bottom) in Figure 5-9.

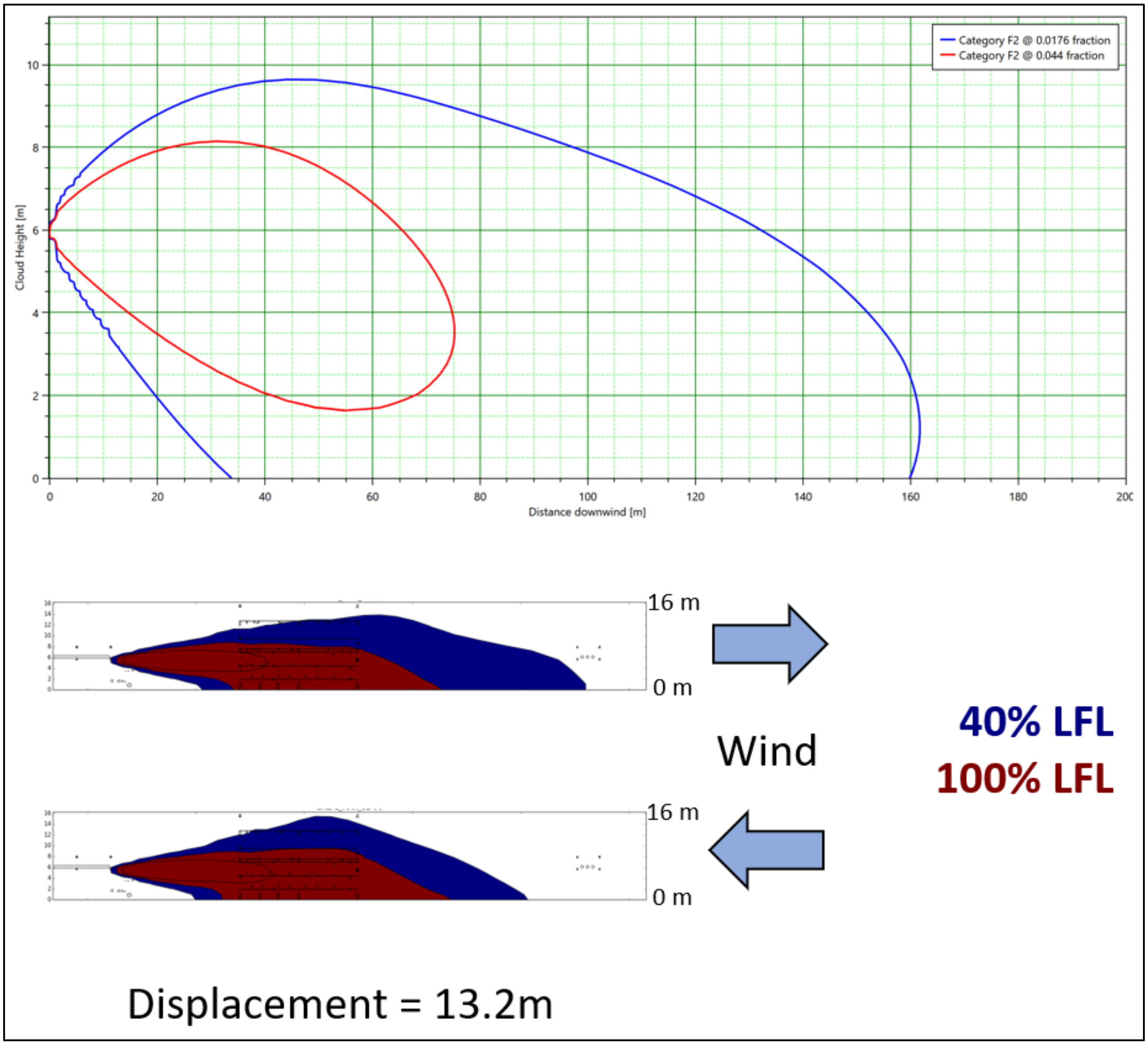

Figure 5-8: Inventory 5 – LNG – Obstructed Downstream – Side View.

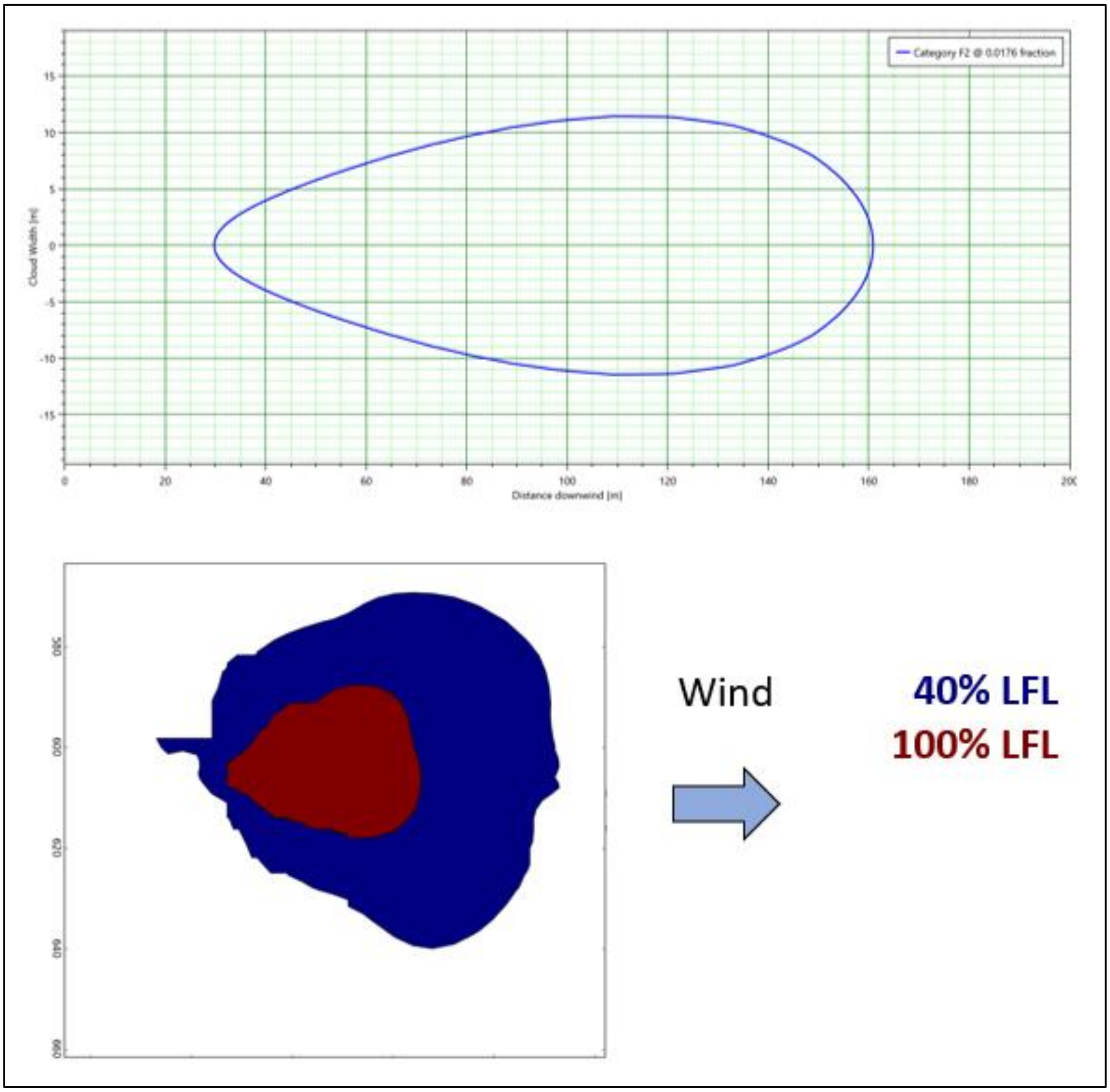

Figure 5-9: Inventory 5 – LNG – Obstructed Downstream – Plan View at 0.5m.

A comparison for a Propane release (Inventory 19) at the same location as LNG (Inventory 5) shown above is given in Figure 5-10 and Figure 5-11. The side view shows the cloud at 40% LFL reaching grade approximately 14 m farther downstream in FLACS, due to the significant displacement distance. The plan view shows how the cloud spreads at the congested area, resulting in a considerably wider cloud in FLACS; Phast reaches a similar cloud width farther downstream.

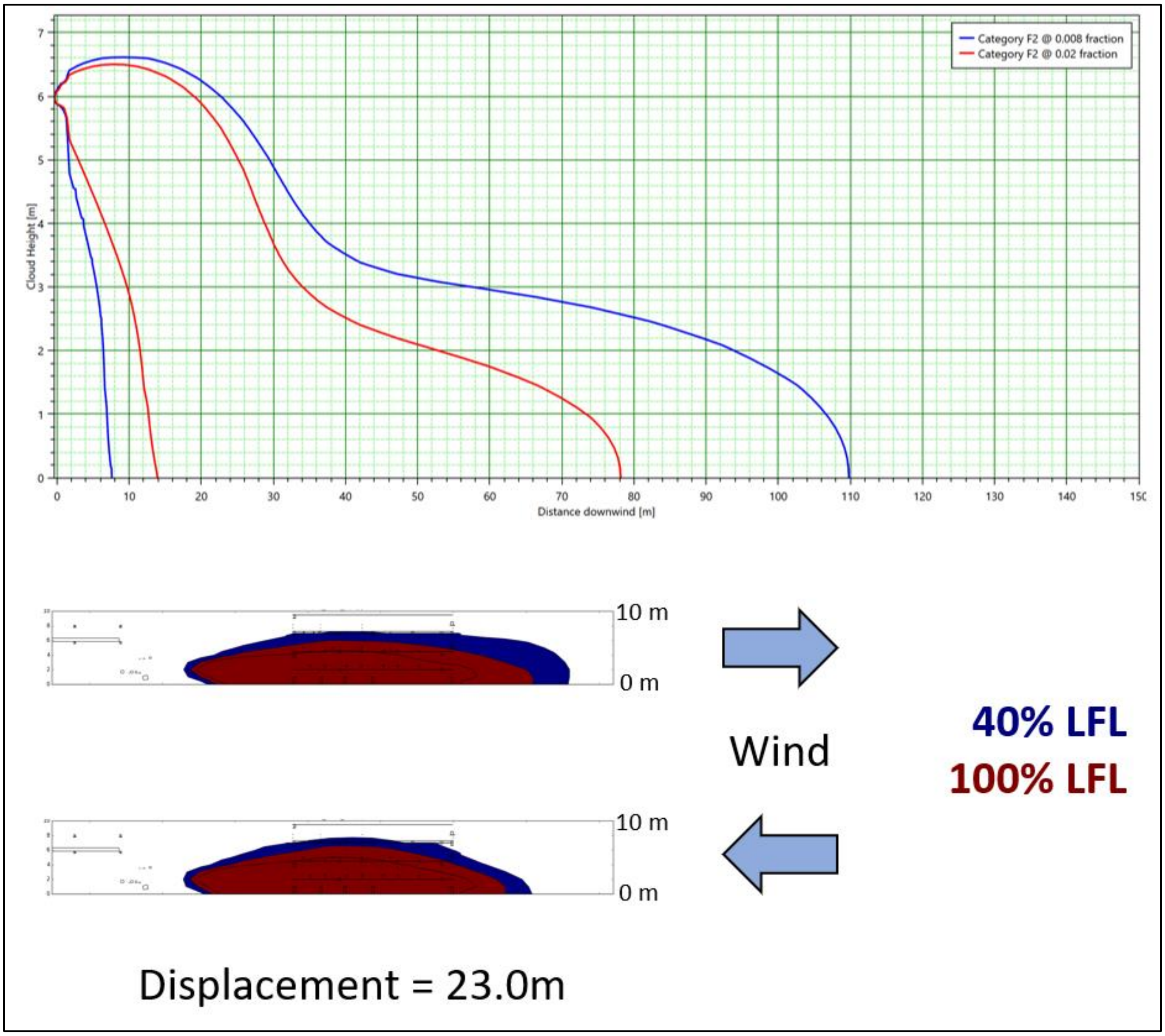

Figure 5-10: Inventory 19 – PRO – Obstructed Downstream – Side View.

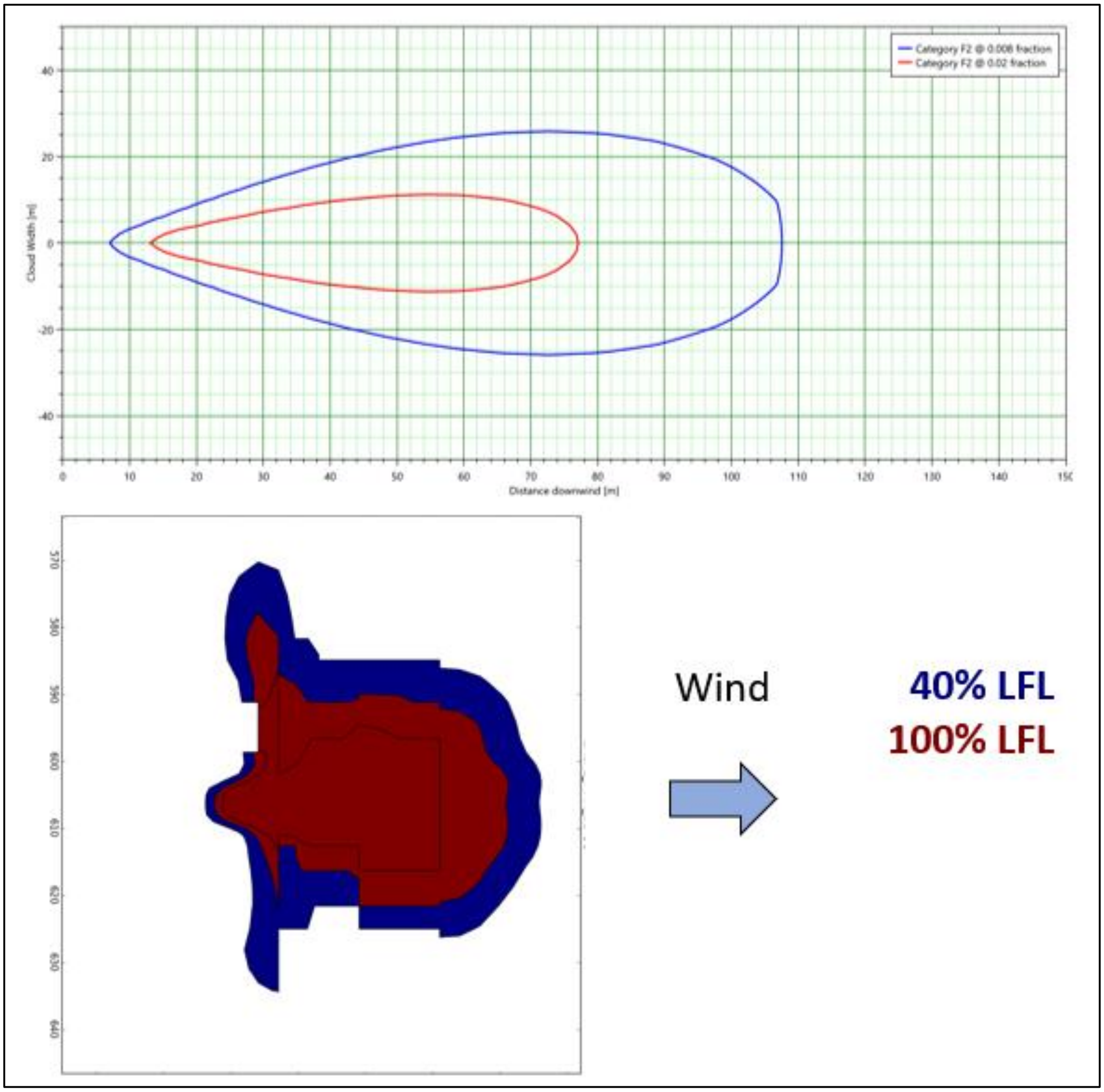

Figure 5-11: Inventory 19 – PRO – Obstructed Downstream – Plan View at 0.5m.

5.3.2 Numerical Comparison

Having established a visual representation of the flammable clouds in both Phast and FLACS, this section presents a numerical comparison of the cloud widths calculated by the two models for the same scenarios. The plots on the following pages compare the Phast cloud width with the FLACS average cloud width (based on simulations under three wind conditions: wind aligned with the release, opposite to the release, and across) as a function of downstream distance. Note that a cloud width of zero indicated the cloud was not present at 0.5 m above grade for a given downstream distance.

The results for the unobstructed releases are compiled in Figure 5-12. With the exception of cases where FLACS displacement yields a cloud width of zero, the Phast and FLACS results are similar. In general, the FLACS clouds tended to be wider than the Phast clouds; however, in the case of propane, the Phast cloud was slightly wider than the FLACS cloud at all points downstream.

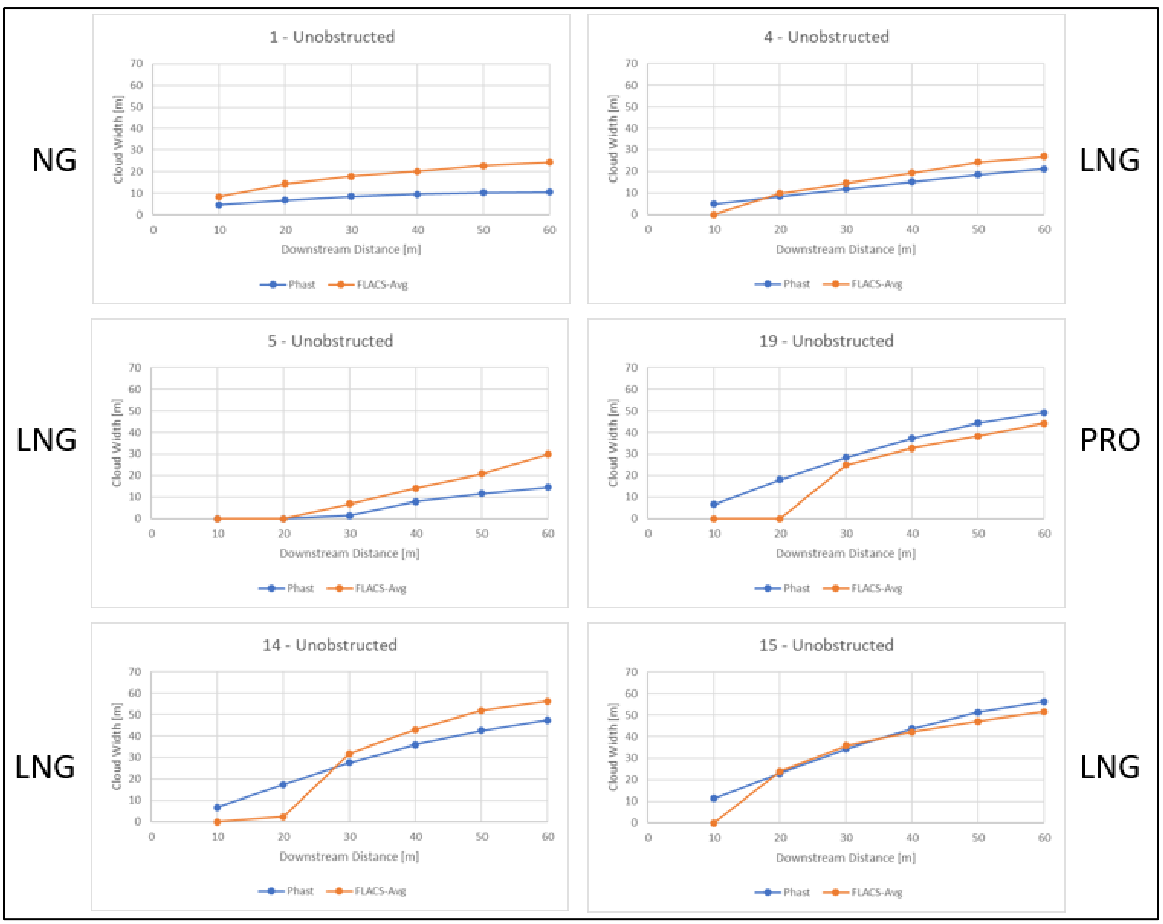

Figure 5-12: Cloud Widths at 0.5m – Unobstructed.

For releases with obstructions near the modeled source, shown in Figure 5-13, there is a significant increase in cloud width for FLACS simulations of gas releases. The mixed-refrigerant (MR) scenario grows wider than Phast as the cloud is initially held up in the congested region of the liquefaction area, while the Phast results become wider farther downstream, due to the typical teardrop shape calculated by this model. The two LNG scenarios at the bottom of the figure include about 75% rainout from the jet impinging on solid objects. Inventory 15 is the LNG truck loading scenario, where in FLACS the cloud is held up behind the obstruction, resulting in reduced cloud width downstream. The LNG sendout/vaporization scenario (Inventory 31) has a much higher flow rate that overcomes the obstacle and generates a wide cloud near the source and more narrow beyond the obstacle, resulting in an inverse trend with the unobstructed case in Phast.

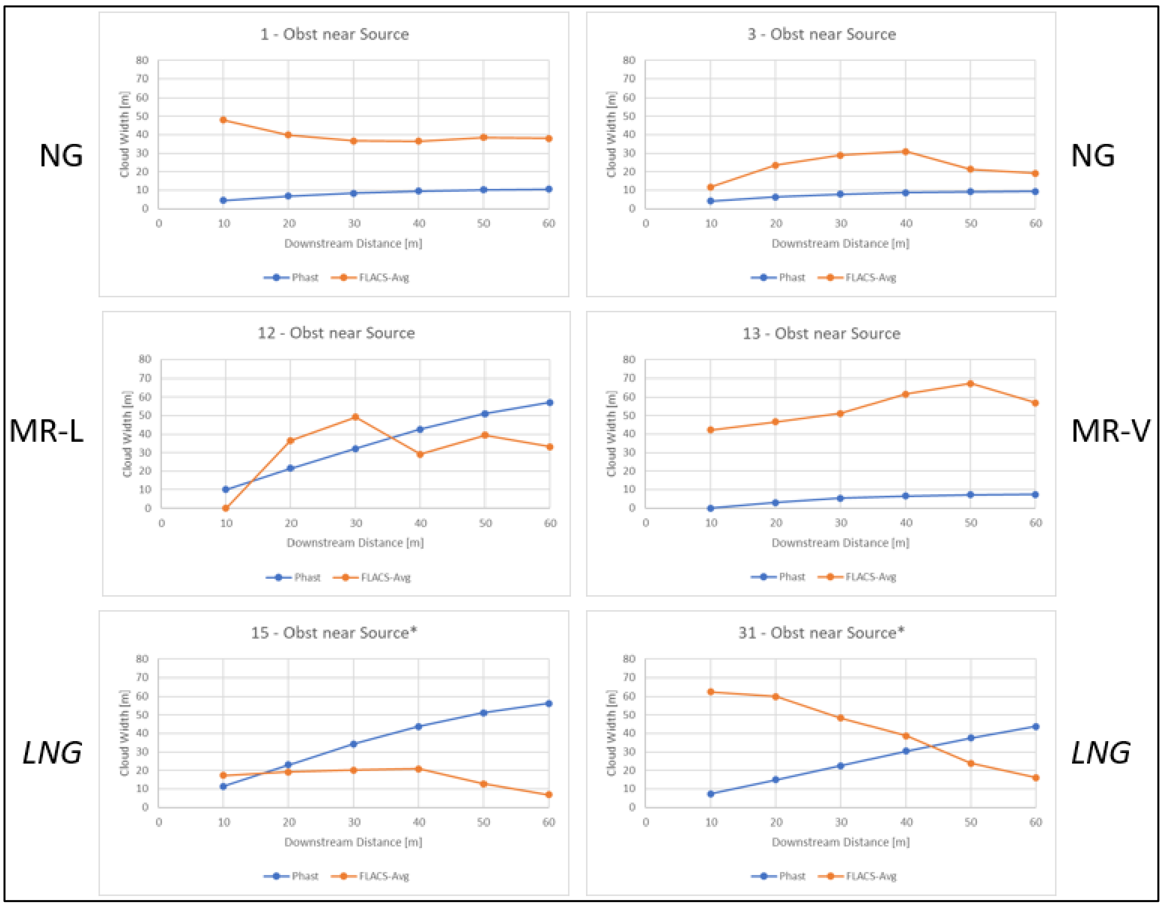

Figure 5-13: Cloud Widths at 0.5m – Obstructed near Modeled Source.

The comparisons for releases obstructed downstream of the modeled source are shown in Figure 5-14. Note that the drop in cloud width for Inventory 4 (LNG) at 30m downstream is due to a large obstruction in the geometry that artificially reduces the cloud width at this location; therefore conclusions should not be drawn regarding trends including that data point. This case highlights how complex geometries can create irregular cloud shapes.

These results show a larger impact to cloud width for methane fuels than for heavier hydrocarbons. Inventory 5 (LNG) and Inventory 19 (Propane) are releases at the same location and elevation, directed into the liquefaction area. For LNG into the congested region, the FLACS cloud width continues to grow with distance. The propane cloud spreads much wider in FLACS as it hits the congested region, but the Phast cloud width catches up farther downstream. A similar trend is seen with ethylene, though it hits a single obstruction rather than a large, congested region. For the mixed-refrigerant case, the Phast cloud width is greater than the FLACS cloud width at all downstream distances.

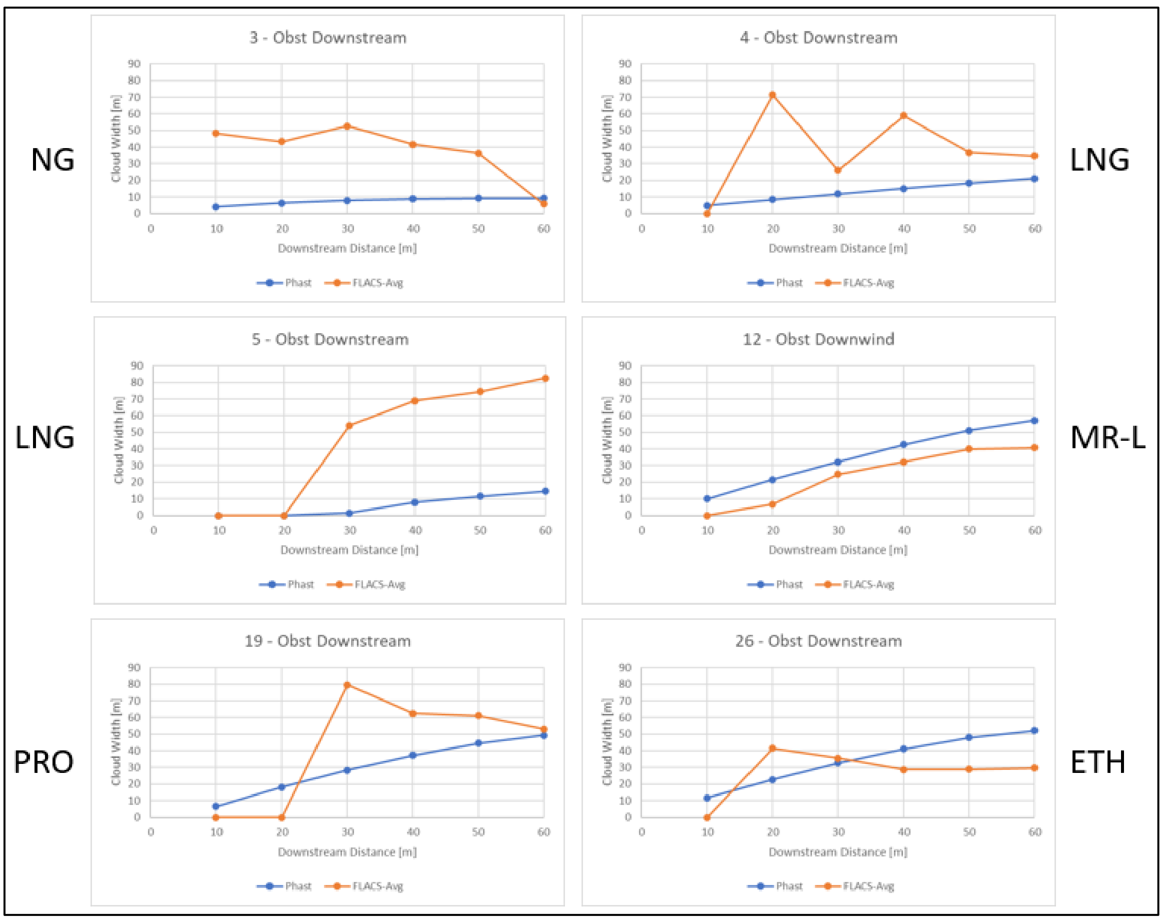

Figure 5-14: Cloud Widths at 0.5m – Obstructed Downstream.

The cloud widths from the previous plots are summarized in Table 5-2. It should be noted that locations where a model did not record a cloud width at 0.5 m above grade were not included. The results indicate that cloud widths for unobstructed releases and non-LNG liquids were similar between the two models. Obstructions downstream had a greater impact on cloud width than obstructions near the modeled source. Additionally, gas release cloud widths had a greater increase in FLACS than liquid release cloud widths.

Table 5-2: Cloud width comparisons (FLACS-Avg to Phast)

Unobstructed	Obstructed near Modeled Source	Obstructed Downstream	Gas	LNG	Non-LNG Liquids
1.5	3.9	4.6	5.3	3.5	1.1

It should be noted that these are general trends observed for this set of release scenarios and the geometry developed for the generic LNG facility; these factors should not be applied to Phast results to compensate for obstructions, nor to dispersion modeling conducted for other facilities.

5.4 Impact of Emergency Shutdown on Consequences

In addition to determining how many scenarios are successfully detected, it is important to evaluate how the modeled consequences are impacted by early detection and emergency shutdown (ESD). For example, if a release is successfully detected by two or more detectors, but the distance to the cloud front or the flammable mass available for a vapor cloud explosion are not significantly reduced, then successful detection will not lead to a meaningful risk reduction.

Consider the ESD cases summarized in Table 5-3 which assume a total release duration of 15, 20, 30 and 60 seconds for each fuel, modeled using Phast; instances resulting in a reduction of the distance to LFL or flammable mass to less than half of the 10-minute case are in bold font. Even in the case of very short release durations, the distance to the LFL cloud front and the total flammable mass of the cloud are similar to a 10-minute release when looking at gas releases (Inventories 1 and 13). The LNG release has a modest reduction, whereas the heavier hydrocarbons see significant reductions in both categories.

Table 5-3: Fixed Duration ESD Cases (Phast)

Inventory	Fuel	ESD Time [sec]	Normalized distance to LFL compared to 10-minute release	Normalized flammable Mass compared to 10-minute release
1	NG	15	0.84	1.00
1	NG	20	0.89	1.00
1	NG	30	0.95	1.00
1	NG	60	1.00	1.00
5	LNG	15	0.57	0.83
5	LNG	20	0.63	1.00
5	LNG	30	0.72	1.00
5	LNG	60	0.86	1.00
12	MR-L	15	**0.25**	**0.09**
12	MR-L	20	**0.28**	**0.11**
12	MR-L	30	**0.33**	**0.12**
12	MR-L	60	**0.46**	**0.14**
13	MR-V	15	0.88	1.00
13	MR-V	20	0.93	1.00
13	MR-V	30	0.98	1.00
13	MR-V	60	1.00	1.00
19	PRO	15	**0.33**	**0.43**
19	PRO	20	**0.36**	**0.49**
19	PRO	30	**0.42**	0.66
19	PRO	60	0.54	0.91
26	ETH	15	**0.30**	**0.08**
26	ETH	20	**0.33**	**0.10**
26	ETH	30	**0.39**	**0.12**
26	ETH	60	0.54	**0.22**

However, it should be noted that ESD times shorter than one minute may be difficult to achieve for facilities with large isolatable inventories. The total release duration in the event of successful detection is the sum of the following:

1) Time for flammable gas to reach the detector(s)
2) Detector response time
3) Signaling time
4) Time to close the ESD valve
5) Time to depressurize and de-inventory

While the time for the flammable gas to reach the detector(s) will vary for each individual scenario, the remaining items can be more easily estimated. Items 2 through 4 were evaluated during a previous PHMSA project and yielded the following results [37]:

2) Detector response = 5 seconds
3) Signaling time = 1 second
4) Valve closure = 1 second per inch diameter

Knowing the line size and total mass for each isolatable inventory, Table 5-4 updates the ESD cases from Table 5-3 to consider detector response time, signaling time, time to close the ESD valve, and de-inventory time (i.e. assuming ESD Time is equal to the time for flammable gas to reach the detectors). The results demonstrate that early detection alone is not sufficient to reduce the consequences from an accidental release below that of the standard 10-minute release; the size of each isolatable inventory may need to be significantly reduced in order to see an appreciable decrease in consequences.

Table 5-4: De-Inventory ESD Cases (Phast)

Inventory	Available Inventory	ESD Time [sec]	Normalized distance to LFL compared to 10-minute release	Normalized flammable Mass compared to 10-minute release
1	Pipeline SDV to Metering Outlet	15	0.93	1.00
1	Pipeline SDV to Metering Outlet	20	0.95	1.00
1	Pipeline SDV to Metering Outlet	30	1.00	1.00
1	Pipeline SDV to Metering Outlet	60	1.00	1.00
5	Single Train Rundown Line	15	1.00	1.00
5	Single Train Rundown Line	20	1.00	1.00
5	Single Train Rundown Line	30	1.00	1.00
5	Single Train Rundown Line	60	1.00	1.00
12	HP MR Separator to Coldbox (L)	15	1.00	0.91
12	HP MR Separator to Coldbox (L)	20	1.00	0.94
12	HP MR Separator to Coldbox (L)	30	1.00	1.00
12	HP MR Separator to Coldbox (L)	60	1.00	1.00
13	HP MR Separator to Coldbox (V)	15	1.00	1.00
13	HP MR Separator to Coldbox (V)	20	1.00	1.00
13	HP MR Separator to Coldbox (V)	30	1.00	1.00
13	HP MR Separator to Coldbox (V)	60	1.00	1.00
19	Propane Pump to Train	15	1.00	1.00
19	Propane Pump to Train	20	1.00	1.00
19	Propane Pump to Train	30	1.00	1.00
19	Propane Pump to Train	60	1.00	1.00
26	Ethylene Tank	15	1.00	1.00
26	Ethylene Tank	20	1.00	1.00
26	Ethylene Tank	30	1.00	1.00
26	Ethylene Tank	60	1.00	1.00

5.5 Consequence Modeling Conclusions

The evaluation of a gas detector layout using scenario-based coverage requires dispersion modeling. There are currently two models approved by PHMSA for dispersion analysis at LNG facilities: Phast (versions 6.6 and 6.7) which calculates unobstructed dispersion over flat terrain, and FLACS (version 9.1) which is a 3D CFD model capable of including elevation changes, obstacles (i.e., equipment and buildings) and barriers. Due to the large number of scenarios to be evaluated for an LNG facility (many isolatable inventories, each with multiple leak points, hole sizes, release directions, wind conditions, etc.), 3D modeling of every scenario will likely be impractical. Therefore, it is helpful to know which model tends to be more conservative and which scenarios tend to be impacted the most by obstructions, in order to prioritize scenarios for more detailed modeling.

Since Phast calculates unobstructed dispersion, it follows that FLACS results are similar for unobstructed releases and more detailed modeling is not warranted. This model comparison demonstrated that the cloud widths for non-LNG liquid releases (including obstructions) were generally similar between Phast and FLACS, suggesting that in many cases, more detailed modeling may not be necessary for non-LNG liquid releases to evaluate a gas detector layout. However, this could vary depending on the level of congestion and the need to more accurately determine flammable cloud sizes within congested regions.

Gas releases in the presence of obstructions had much wider clouds in FLACS than in Phast, however, these releases generally have lower consequences and may be a lower priority for detection. Higher priority releases for FLACS modeling would include LNG releases in, or directed towards, congested areas, as well as non-LNG liquids (higher reactive fuels) in large, congested areas where vapor cloud explosion hazards need to be reduced.

The displacement distance for liquid releases in FLACS (typically 40-80 ft for 2-inch holes) is also an important factor when considering more detailed modeling. For example, any gas detectors between the actual source and modeled source would not be captured in the modeling, and the cloud will reach detectors farther downstream in FLACS than in Phast for heavy fuels. Additionally, release locations near the edge of a Detection Area may result in a modeled source located outside of the Detection Area, making detection impossible unless the cloud grows large enough to reach another Detection Area. The impact of displacement would play an even larger role in small-scale LNG facilities, where the modeled source may end up outside of the process area and there are no other Detection Areas at the facility to capture the cloud.

In general, the downstream cloud dimensions calculated by Phast are similar to, or smaller than those calculated by FLACS. Therefore, a detector evaluation utilizing Phast would offer a more rigorous test of the detector layout in a shorter timeframe. Utilizing

FLACS in areas of congestion or in the presence of large obstructions could result in wider clouds within the detection area and a reduced detector count to achieve the same scenario-based coverage, however, consideration must be given to the impact of displacement and whether the clouds generated in FLACS would be too far removed from the areas where the cloud needs to be detected.

A gas detector evaluation could utilize both Phast and FLACS for dispersion modeling; it is important to note that the predicted consequences and timing associated with those consequences is specific to each model, therefore, they are not interchangeable between the two types of models (i.e., using detection times from an integral model to determine the 'mitigated' release duration to then be applied to a CFD model would be invalid). When determining which scenarios should be modeled by each tool, consideration must be given to the total number of scenarios being evaluated as it is likely that a significant number of simulations would need to be run in FLACS in order for the CFD modeling to have a notable effect on the detection rate.

Regardless of the modeling tool chosen, it should be noted that a detailed evaluation of isolatable inventories is necessary to fully evaluate the effectiveness of a gas detector layout. The analysis presented in this report demonstrates that even with detection in as little as 15 seconds, large inventories between ESD valves can result in similar consequences to 10-minute releases. Therefore, early detection and high coverage rates on their own are not sufficient to reduce consequences from an accidental release below that of the standard 10-minute release.

6 Case Study 1 – Large Scale LNG Facility

Having established a methodology for evaluating fire and gas detection systems at LNG facilities, this section demonstrates the proposed performance-based approach on a generic large scale LNG facility. Section 7 will present a case study for a small scale LNG facility using the same methodology and a different set of performance targets. These case studies are presented to show the flexibility of the proposed methodology and provide examples for different size facilities, however, the different performance targets used in these demonstratives should not be interpreted as specific to large scale and small scale facilities, respectively. Specifically, the large scale case study presented in this section will demonstrate that assigning a single detector coverage target to all inventories within a Detection Area will not focus resources on detecting higher risk scenarios, and that using a uniform detector spacing is inefficient. Based on these findings, a different approach for assigning performance targets will be followed in the small scale case study.

After the fire and gas detector layouts are complete, the 'mitigated risk' could be determined by updating the fire and explosion risk assessment with the shortened release durations and reduced probability of escalation provided by the detection system and any mitigation systems activated. It should be noted that the extent of changes in outcome from early detection would be site-specific and depend on several factors, such as the site layout, detector layout, the number and location of ESD valves, reliability of equipment installed, etc. Therefore, while determining the mitigated risk is a critical verification step in cases where intolerable risk must be reduced, it will not be demonstrated herein.

6.1 Fire and Gas Detection Philosophy

The Fire and Gas Detection Philosophy should be developed prior to assessing the facility risk or performing the hazard detector layout so that objective and unbiased performance criteria are clearly established, and all forthcoming decision-making is based on the risk tolerability of the project stakeholders. This section will describe the fire and gas detector coverage targets and voting criteria that will be used in this case study.

Flame detection will be evaluated using geographic coverage, where success is based on the fraction of a given volume that is covered. Areas with a high risk of escalation will be subject to higher coverage requirements than areas with low or no risk of escalation. It follows that areas where flame detection needs to initiate ESD or active mitigation measures will require voting by two or more detectors (2ooN) to confirm flame detection prior to taking executive action, whereas areas that just need notification for personnel to evacuate or operators to intervene will only require one detector activation (1ooN).

Gas detection will be evaluated using scenario coverage, where success is based on the ratio of detectable releases to total releases. This approach incorporates site-specific operating and weather conditions, as well as the plant layout; therefore, it optimizes the gas detector layout for the specific installation, rather than relying on a simple grid layout or expert judgment alone. Flammable gas detector coverages will be applied for 2ooN voting in all areas to initiate ESD.

While this analysis requires 2ooN voting for flame and gas detector ESD, it should be noted that this ESD logic is not currently required by PHMSA and not universally adopted across the industry. Appropriate detector voting for executive action should be based on a site-specific evaluation.

This analysis divides an LNG facility into Detection Areas and uses LSIR (or IR for brevity) contours to show which areas of the facility present the highest risk. A quantitative fire and explosion risk assessment is performed to generate the LSIR contours as outlined in Section 4. To connect the LSIR contours with appropriate levels of detection, thresholds must be established for 'intolerable' risk, where significant risk reduction is required, and 'tolerable' risk, where risk reduction is not required. Together, these provide a basis for setting detector performance targets commensurate with the level of risk in each area of the facility.

Detection Areas in the 'intolerable' risk region would require a risk reduction factor greater than 10 (i.e., one order of magnitude) and therefore a minimum of 90% detector coverage as described in ISA TR 84.00.07. In this case, an analysis must be performed to verify that the addition of the fire and gas detection system (along with any other mitigation measures) reduces the risk below the intolerable threshold. Areas of the facility in the 'tolerable' region do not require hazard detection to reduce risk, but detection may still be provided for continuous monitoring.

Risk falling between the 'intolerable' and 'tolerable' thresholds is in the in 'ALARP' region, where measures must be taken to reduce the risk to a point 'as low as reasonably practicable'. Since a risk reduction factor greater than 10 is not required in these areas, 90% detector coverage is not required; detector coverage targets are lowered according to the hazards present in each Detection Area, as outlined below.

The detector performance criteria used for this case study are summarized in the following tables. Note that detector coverage is not intended to be uniform throughout each Detection Area; detector locations should be optimized to achieve the prescribed level of coverage.

Table 6-1: Flame Detector Coverage Criteria

Risk Classification	Individual Risk of Fatality (per year)	Minimum Detector Coverage	Detection Area Notes
Intolerable & ALARP	IR > 1 x 10^{-6}	90%	Equipment coverage where cascading damage hazard is identified
		80%	Detection Areas with flammable fluid service
		60%	Detection Areas with combustible fluid service
Tolerable	IR < 1 x 10^{-6}	0%	None Required

Table 6-2: Gas Detector Coverage Criteria

Risk Classification	Individual Risk of Fatality (per year)	Minimum Detector Coverage	Detection Area Notes
Intolerable	IR > 1 x 10^{-4}	90%	Minimum 90% coverage required for risk reduction
ALARP	1 x 10^{-6} < IR < 1 x 10^{-4}	80%	Congested areas where VCE hazards are identified
		70%	Congested areas where VCE hazards are not identified, but still represent a concentration of potential leak sources
		60%	Low congestion in open areas
Tolerable	IR < 1 x 10^{-6}	0%	None Required

Table 6-3: Detector Voting Criteria

Risk Classification	Individual Risk of Fatality (per year)	Flame Detectors	Flammable Gas Detectors
Intolerable	IR > 1 x 10^{-4}	2ooN	2ooN
ALARP	1 x 10^{-6} < IR < 1 x 10^{-4}	2ooN (with cascading damage) 1ooN (without cascading damage)	2ooN

6.2 Designate Detection Areas

The generic LNG facility used in this demonstration exercise includes several hydrocarbon handling and storage areas, that have been divided into six Detection Areas based on the facility layout and hazards present as summarized in Table 6-4 and Figure 6-1. Individual Detection Area evaluations are provided in the following subsections.

Table 6-4: Summary of Detection Areas for Large Scale LNG Facility

#	Detection Area	Grouping Logic
1	Metering	Geographically isolated from similar hazards
2	Liquefaction Unit A (Liq-A)	Pretreatment area included with liquefaction area due to proximity[25]
3	Liquefaction Unit B (Liq-B)	Liquefaction units treated as separate instances
4	LNG Storage	Geographically isolated from similar hazards
5	BOG & Vaporization (BOG-V)	Low congestion areas in proximity with low-reactivity fuels
6	Trucking and Refrigerant Storage (T-RS)	Medium and high-reactivity fuels in proximity[26]

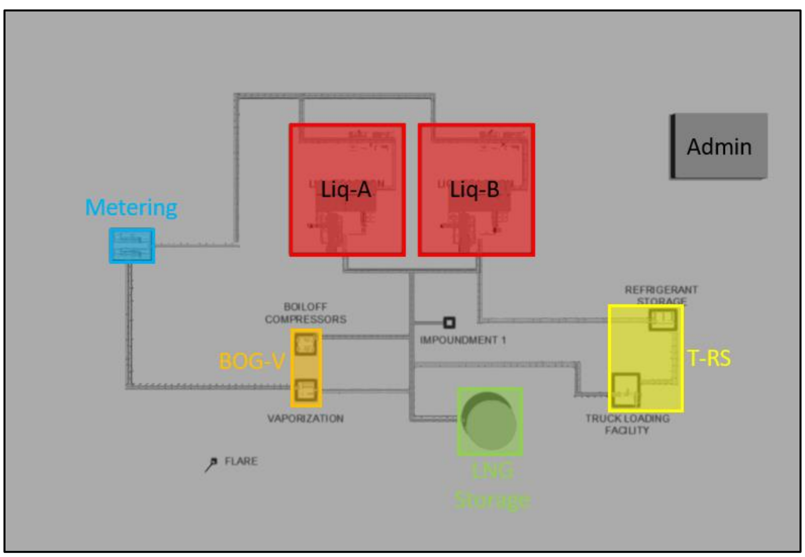

Figure 6-1: Layout showing Detection Areas for Large Scale LNG facility.

25 Facility layouts where pretreatment and liquefaction processes are separate may warrant separate Detection Areas depending on liquefaction technology (i.e. whether flammable refrigerants are utilized) and if dispersion of reactive components reaches Pretreatment.

26 Note that Trucking serves both LNG and refrigerants for this generic facility design.

Note that the piperacks between the main hydrocarbon handling and storage areas are not included in the Detection Areas; since long piping runs at LNG facilities are welded and have a very low leak frequency compared to other components, it is best to focus fire and gas detection resources in other areas. Given that piperacks often have large isolatable inventories, even very early detection and isolation is unlikely to result in significant hazard mitigation due to the time to de-inventory the isolated section. Additionally, many detection layouts (including the one evaluated in this analysis) include open-path gas detectors around the perimeter of each Detection Area which would detect piperack releases that were migrating into a hydrocarbon handling or storage area and prompt operator intervention.

Fire and gas detection for the LNG impoundment is not evaluated in this exercise. Impoundments at LNG facilities are typically provided low temperature, flame and gas detection over the area of the impoundment; since the hazard is isolated to a well-defined area, no further optimization is warranted. Further, since the impoundment is remote of the LNG storage tank in this layout, it is not included in the LNG Storage Detection Area.

6.2.1 Metering

The Metering area serves both inlet gas from the pipeline and sendout from vaporization. Feed gas from the pipeline is approximately 95% methane, therefore feed gas and sendout gas are evaluated as pure methane, consistent with current PHMSA procedures for hazard modeling. This area is geographically isolated from the rest of the facility and has low congestion. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Metering area is provided in Table 7-3.

Table 6-5: Metering Evaluation

Flammable Streams	Natural Gas (methane)
Potential Leak Scenarios	These lines operate at high pressure, therefore a leak would result in a high velocity flammable gas release.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	No (gaseous inventories only)
Cascading Damage	None

6.2.2 Liquefaction Unit A/B

Depending on the size and configuration of the facility, the pretreatment area may be in the same section of the plant as the liquefaction area or standalone. In the layout considered for this analysis, pretreatment is within the area identified as the "Liquefaction Unit". The pretreatment process removes acid gas and moisture from the feed gas in preparation for liquefaction. It should be noted that while toxic gases are outside the scope of the current project, an evaluation of toxic gas detection could be performed in a similar methodology as presented for flammable gas detection, with the establishment of separate toxic gas hazard thresholds.

This analysis considers an LNG facility with a mixed-refrigerant liquefaction process, which introduces hazards from additional flammables such as ethylene, propane, and butane[27]. These refrigerants are more reactive than methane and present increased hazard potential from VCEs. Since dispersion from the refrigerant lines in the liquefaction unit could reach the pretreatment area, these have been grouped into one Detection Area.

Though ethylene is considered a 'high' fuel reactivity, it makes up less than half of the mixed refrigerant streams, therefore the highest fuel reactivity for the Liquefaction Unit is considered 'medium'. Additionally, the Liquefaction Unit is the most congested area of this facility. The Detection Area Evaluation is summarized in Table 6-6.

Table 6-6: Liquefaction Evaluation

Flammable Streams	Natural Gas and LNG (methane) Refrigerants (Ethylene, Propane, Butane, and mixtures)
Potential Leak Scenarios	Flammable gas releases from 'clean gas' lines from the pretreatment area or mixed-refrigerant vapor lines. Flashing and jetting releases of LNG or liquid mixed-refrigerant. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	Yes (medium reactivity fuel; medium congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	None

[27] Pentane is also commonly used at LNG facilities

6.2.3 LNG Storage

The generic LNG facility includes a full containment storage tank and is geographically isolated from areas of similar hazards. Piping in this area includes LNG rundown lines from the liquefaction area, LNG sendout lines to the vaporization or truck transfer areas, and boil off gas (BOG) lines, all of which are typically welded lines. The facility design includes in-tank pumps, therefore, fire and gas detection are provided at the top connections to the LNG storage tank. The Detection Area Evaluation is summarized in Table 7-6.

Table 6-7: LNG Storage Evaluation

Flammable Streams	LNG and BOG (methane)
Potential Leak Scenarios	Flashing and jetting releases of LNG from rundown or sendout lines. Liquid spills from large-bore LNG line ruptures that would be directed into the facility trenches and impoundment. Flammable vapor releases from boil off gas lines.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	No[28] (remote impoundment)
Cascading Damage	No[29] (remote impoundment)

[28] While PHMSA siting would require evaluation of a tank top fire, this design case is not applied to the hazard detection layout as any equipment on top of the tank would have failed with the tank roof.

[29] While BLEVE hazards are not a concern for the full containment tank, flame detection will be provided on the tank top for piping connections and PRVs.

6.2.4 BOG & Vaporization

The BOG and Vaporization areas are located in proximity to one another with dispersion distances that overlap; although the operating pressure varies and the Vaporization area contains LNG, both areas are low congestion and only contain methane fuels. Therefore, these two areas have been grouped together. A summary of the hazards presented by a loss of containment of flammable fluid streams in the BOG and Vaporization areas are provided in Table 7-7.

Table 6-8: BOG and Vaporization Evaluation

Flammable Streams	Natural Gas, LNG (methane)
Potential Leak Scenarios	Flammable gas releases from gaseous inventories. Flashing and jetting releases of LNG. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes[30] (Vaporization only)
Cascading Damage	None

[30] While pool fire hazards only apply to Vaporization, jet fire hazards apply to both and flame detection will be provided for both.

6.2.5 Trucking & Refrigerant Storage

The truck loading/unloading area for the generic LNG facility serves both LNG and refrigerants. Given the similar hazards present and proximity (ability for flammable clouds to migrate to the other area quickly), these areas have been grouped together. The Detection Area Evaluation is provided below in Table 6-9.

Table 6-9: Trucking and Refrigerant Storage Evaluation

Flammable Streams	LNG and BOG (methane – Trucking only) Refrigerants (Ethylene, Propane, Butane)
Potential Leak Scenarios	Flashing and jetting releases from liquid piping or transfer hose. Liquid spill from large-bore piping or hose ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	Yes (medium/high reactivity fuels; low/medium congestion)
Jet Fire	Yes
Pool Fire	Yes
Cascading Damage	BLEVE of pressurized storage vessels or trailers

6.3 Identify Hazard Scenarios

Having established the Detection Areas, the next step is to determine the unmitigated risk which will be used to assign the detector performance targets; the results are shown below in Figure 6-2. Recall that the hole size sensitivity from Section 4.4 revealed that releases 2-in and larger were driving the risk for this generic facility design, therefore the hazard detection layout for this facility should be evaluated against hole sizes 2-in and larger.

Due to the prevalence of potential leak points and reactive fuels, the risk contours are centered on the liquefaction units. The tolerable risk contour extends beyond the facility fenceline as can be seen by the green line on the right-hand side of Figure 6-2 (note that the contour extends around the facility beyond the top, bottom, and left sides, outside the boundaries of this image). The liquefaction units are in the 'intolerable' region and all other Detection Areas are in the 'ALARP' region. Note that this demonstrative is based on a generic facility design and that conservative estimates were used for parts counts when developing the LSIR contours; it should not be assumed that these LSIR contours would apply to other LNG facilities.

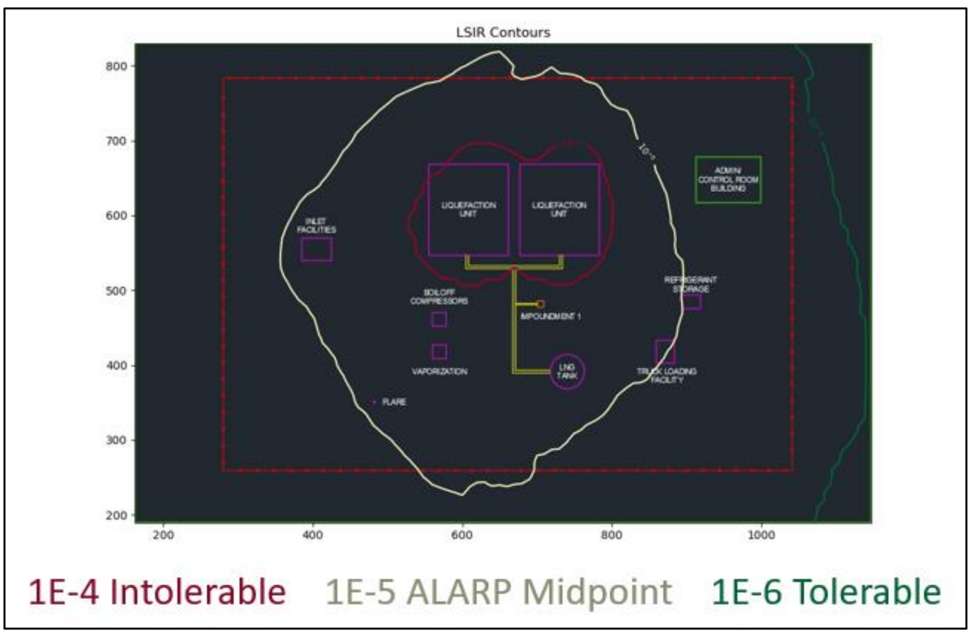

Figure 6-2: Unmitigated risk for the Large Scale LNG facility.

6.4 Assign Performance Targets

Each Detection Area is assigned performance targets according to the unmitigated risk contours presented in the previous section and the criteria outlined in Section 6.1; this is summarized below in Table 6-10. Recall that equipment identified for cascading damage requires 90% flame coverage with 2ooN detectors as this will initiate ESD and/or fire protection systems, therefore, the minimum flame coverage below applies to the remaining portions of each Detection Area with 1ooN voting for operator notification and intervention. In all cases, 2ooN voting is applied to gas detectors in this exercise as quick detection and isolation is necessary to achieve reduced consequences. Note that single detector activation rates will be higher and they will still prompt operator intervention, but will unlikely result in isolation fast enough to reduce consequences below those from the standard 10-minute release used for PHMSA siting studies[31].

Table 6-10: Detection Area Coverage Targets

#	Detection Area	Risk Category	Min Flame Coverage[32]	Min Gas Coverage
1	Metering	ALARP	80% (flammables)	60% (low congestion/open)
2	Liquefaction Unit A	Intolerable	80% (flammables)	90% (Intolerable)
3	Liquefaction Unit B	Intolerable	80% (flammables)	90% (Intolerable)
4	LNG Storage	ALARP	80% (flammables)	60% (low congestion/open)
5	BOG & Vaporization	ALARP	80% (flammables)	60% (low congestion/open)
6	Trucking and Refrigerant Storage	ALARP	80% (flammables)	80% (VCE hazards)

[31] This was demonstrated in Section 5.4

[32] Equipment identified for cascading damage in Detector Area Evaluations require 90% coverage

6.5 Flame Detector Evaluation

Given the well-defined field-of-view of flame detectors, evaluating a layout by geographic coverage does not require hazard modeling. Additionally, the release scenarios used for evaluating gas detector layouts vary between Detection Areas (e.g flammable fluids present, operating conditions, release points, etc), whereas flame detection only depends on the layout/geometry. Therefore, one Detection Area was chosen for demonstrating the flame detector evaluation rather than repeating the same process for every Detection Area. The Refrigerant Storage Area was chosen since cascading damage hazards were identified, which requires 90% coverage by two or more detectors under the performance targets outlined in Section 6.1.

Flame detector layouts are often developed on a 2D plot plan of the facility showing the cone of vision for each detector based on the sensitivity setting. However, flame detectors are line-of-sight detectors, therefore the effective coverage area is impacted by obstructions that may cause blind spots. A simple example of an obstructed field of view is shown below in Figure 6-3; the top view shown on the left is similar to the cone of vision that would be evaluated in a 2D layout, however, the view on the right visualizes the blind spot caused by the obstructions.

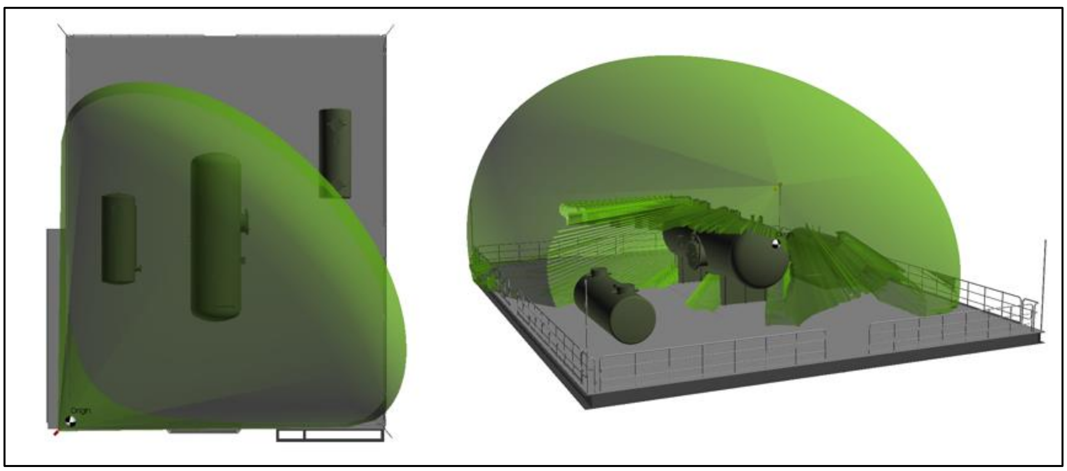

Figure 6-3: Flame detector field of view shown in green; unobstructed top view shown on left and obstructed field of view shown on right (image generated from Detect3D).

A qualitative assessment of flame detector coverage can be made in low congestion areas by evaluating flame detector locations and orientations relative to large obstructions to identify critical blind spots. As such, there are many cases where a 2D flame detector layout is sufficient; for example, generally open areas with only large obstructions, such as a cold box or bullet tanks, can be reasonably accounted for in a 2D layout. However, it is often difficult to quantify detector coverage accurately in this manner and blockages become harder to evaluate in more congested areas. Further, it can be increasingly difficult to quantify areas of coverage by two or more detectors.

6.5.1 3D Flame Detector Mapping using the Acceptable Shadow Approach

To detail the impact of obstructions, flame detector layouts can be performed using software capable of 3D ray tracing, which visualizes the field of view in the presence of equipment and other obstructions. Example flame detector mapping will be shown in this report using the 3D software Detect3D by Insight Numerics. Detect3D allows the detector coverage to be quantified by two methods as shown in Figure 6-4: a Point Cloud Method that establishes a 3D grid of points and determines how many can be seen by each detector, and a Fire Area Method that defines a fire size and how much of the fire needs to be seen for a detector to activate, which is then translated throughout the zone of interest.

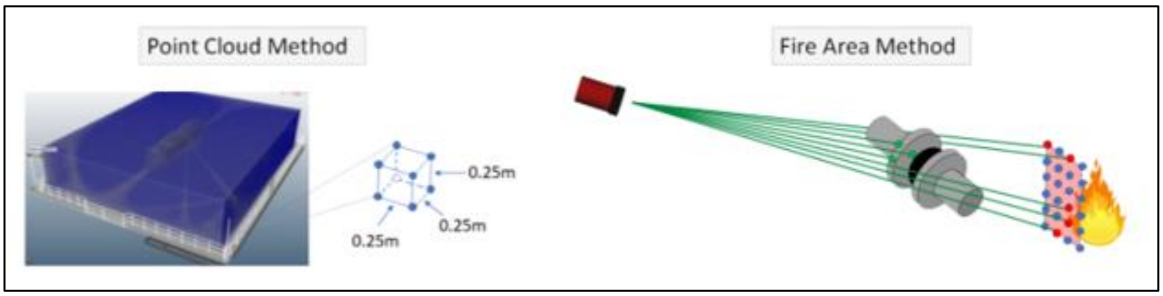

Figure 6-4: Diagrams for Point Cloud Method and Fire Area Method from Detect3D User Manual.

The Point Cloud Method is a strenuous test on flame detector coverage as even small obstructions can block the view of individual points in space, even though these blockages may only result in small shadows that would not negatively impact the performance of the flame detection system. Therefore, the Fire Area Method is more commonly used. Since there is a large range of possible fire scenarios (e.g. jet flames of different sizes and orientations, pool fires of different sizes), rather than calculating how much of a given fire size the detector can see, it is proposed to calculate how much of a given fire size the detector cannot see (i.e. define the size of an 'acceptable shadow'). This can be achieved by defining a fire area with the same dimensions as the acceptable shadow and setting a very low activation threshold (i.e. only 1% of the surface area must be seen by the detector).

Requiring a flame detector layout to cover 100% of a given volume is impractical as well as unnecessary, since very small fires do not have the capability of causing escalation of events and therefore can be detected by slower means. Such an approach has been captured in the NORSOK-S001 standard for the offshore industry that specifies the following minimum requirements for flame detection [38]:

- A flame size of 0.5 meter in diameter and length of 1 meter shall be detected by at least one detector
- A flame size of 1 meter in diameter and length of 3 meters shall be detected by at least two detectors

In effect, the NORSOK criteria require any shadows caused by obstructions to be small enough that a cylinder 0.5 m in diameter and 1 m long cannot be hidden from any flame detector. While pool and jet fire flames at LNG facilities are likely to be larger than the NORSOK criteria listed above, multiple obstructions could exist between a flame detector and the fire event, causing multiple shadows (i.e. unseen portions of the flame). Therefore, a conservatively small acceptable shadow size is necessary to evaluate geographic coverage. Considering all possible orientations of the smaller NORSOK cylinder essentially creates a 1 meter (3.3 foot) diameter sphere, which can be approximated as a 1 meter cube for the purposes of flame detector mapping. By defining an acceptable shadow as a 1 meter cube, this will filter out small blind spots when evaluating flame detector coverage.

6.5.2 Refrigerant Storage Area Example

A sample refrigerant storage area geometry is shown in Figure 6-5, where the red box denotes the protected volume where flame detector coverage is desired. The protected volume should include areas surrounding the targets subject to cascading damage hazards and sources of thermal radiation (i.e. pool and jet fires) that could initiate said hazards. While hazard modeling is not required to evaluate geographic coverage, it can be useful in defining the protected volume. In the case shown below, the protected volume does not include the piperack as any jet fire hazard from this area would have to extend into the protected volume to impact the storage vessels. In the geographic approach, detector coverage will be evaluated as the percent of the protected volume that meets the performance targets. The Detection Area Evaluation for the Refrigerant Storage Area in Section 6.2.5 identified cascading damage hazards, therefore the performance target for the flame detectors is 90% coverage by two or more detectors.

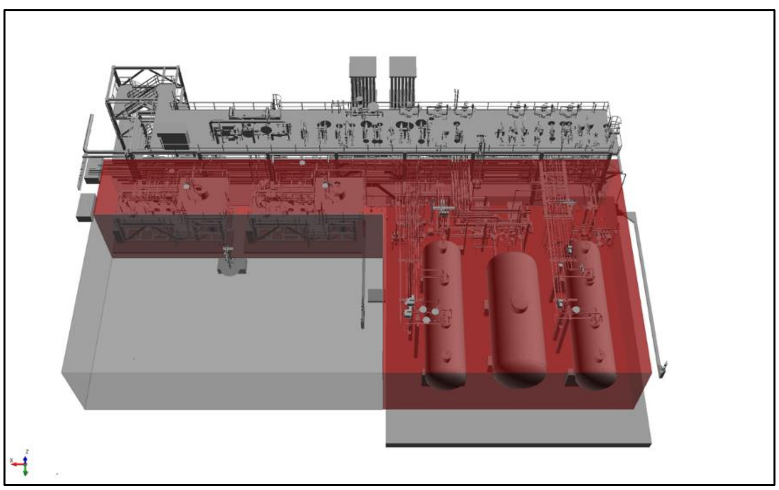

Figure 6-5: Sample refrigerant storage geometry with protected volume shown in red.

In contrast to the simple obstructed field of view given in Figure 6-3, the field of view for a detector in a more congested area such as this is shown in Figure 6-6. While some obstructions are small and would not negatively impact detector performance, this figure demonstrates the combined effect of several small obstructions to generate larger blind spots further out in the field of view.

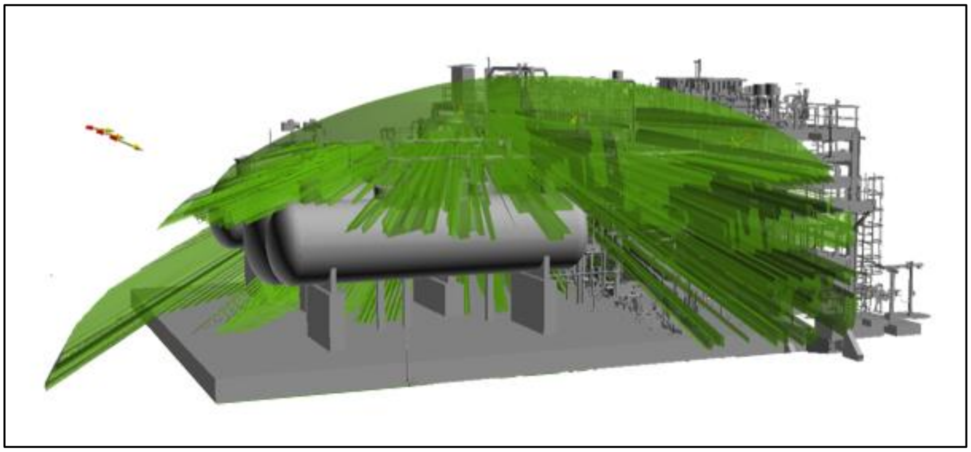

Figure 6-6: Obstructed field of view in congested area.

The Detect3D software was utilized to determine flame detector locations and orientations to achieve 90% coverage by 2ooN detectors with an acceptable maximum shadow area of 1 m^2. One possible solution is shown below using six flame detectors and a maximum range of 125 ft for the detection of a 32-inch propane plume (actual coverage 93.3% for 1ooN and 90.1% for 2ooN). Note that all detectors were angled down to prevent concerns with nuisance alarms from distant sources of radiation. Additionally, it should be noted that the detection range for different fuels needs to be confirmed with product listings and coordinated with the manufacturer for fuels not included in the listing.

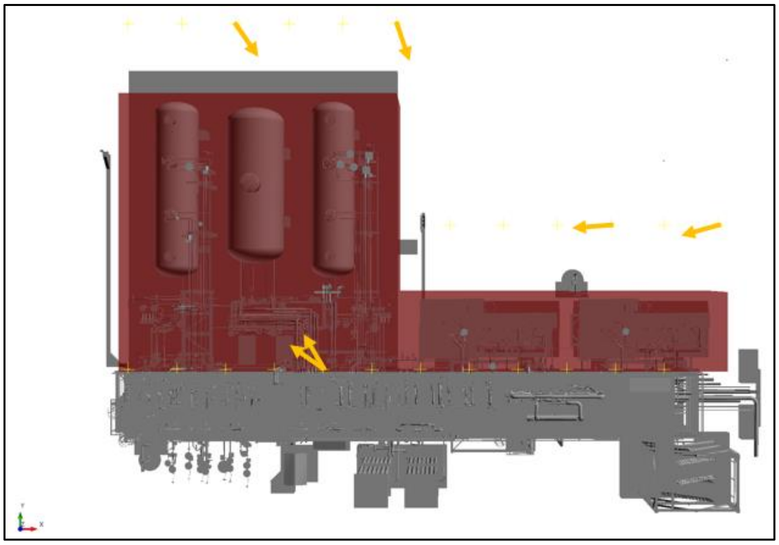

Figure 6-7: Flame detectors for 90% coverage by 2ooN detectors; detector locations and orientations indicated by orange arrows.

With the minimum detector coverage criteria satisfied, blind spots should still be evaluated. Figure 6-8 shows the volume not seen by any flame detectors in black (concentrated in the lower-right corner). Since there are no jet fire sources in this area, grading could be utilized under the vessels to prevent accumulation of liquids and the presence of a pool fire in the blind spot, in which case the blind spot may be deemed acceptable. Alternatively, a single flame detector could be added to provide 1ooN coverage and operator notification, or two detectors would be required to achieve automatic ESD for a fire event in this blind spot.

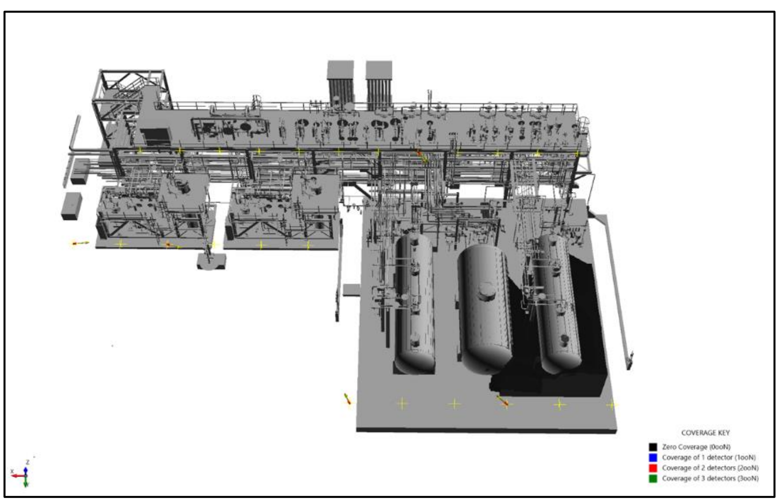

Figure 6-8: Flame detector blind spots shown in black for 6 detector configuration above (i.e. 0ooN coverage).

The above example demonstrates that 90% coverage by 2ooN targets can be achieved with an appropriate number of flame detectors using the acceptable shadow approach. In addition to quantifying flame detector coverage, this methodology also provides a means to optimize the location and orientation of flame detectors in the presence of obstructions.

6.6 Gas Detector Evaluation

Each subsection that follows will demonstrate how dispersion modeling can be used to evaluate gas detector layouts. The example modeling is performed using the integral model Phast (version 8.22) however, the same methodology could be followed using other integral models as well as CFD tools. In the absence of detailed design documents, conservative estimates were made regarding the number of potential release locations and release directions. Therefore, these results should be regarded as a demonstrative and not as gas detector placement that can be applied to other facilities or Detection Areas with a similar layout.

The cloud envelope (width and height) for each time step of each release scenario is tested against the gas detector layout for each Detection Area to determine if the scenario will result in 'ESD' (2ooN) or 'Detection' (1ooN) and the time at which the governing condition occurs (i.e., if the scenario results in ESD, the time to Detection is less critical). Based on the total number of release scenarios for each Detection Area, the percentage of scenarios resulting in ESD and Detection can be calculated (i.e. scenario-based coverage). Note that the 'Detection' percentage will also include the 'ESD' scenarios.

The cloud footprint will obviously differ between integral and CFD models in the presence of obstructions, as demonstrated in Section 5. Generally speaking, the narrower clouds associated with Phast are likely to present a more rigorous test of the detector layout as these clouds will be harder to detect. However, this is not the case with open-path gas detectors. Since the Phast cloud is allowed to extend freely downwind in the unobstructed field, the effectiveness of open-path gas detectors could be over-predicted. Therefore, open-path gas detectors will be included in this analysis, however, a gas cloud intersecting open-path gas detectors is allowed to account for a maximum of one of the two votes required for ESD (i.e., if the cloud extends far enough to trigger more than one open-path-detector, only the first one is counted). Since CFD modeling can account for obstructions to cloud development, this restriction on open-path gas detector voting would not apply.

The gas detector layout for each Detection Area will begin as a 10 m grid of point gas detectors, with perimeter detection provided by open-path gas detectors; detectors will be added or removed as appropriate to meet the performance targets assigned in Section 6.4. The grid pattern was selected to yield a simple demonstrative, however, detectors could be placed using any logic desired – including placement in sensitive locations, such as a building air intake – and then evaluated using this methodology. The demonstration case will only report ESD and Detection cases that occur in less than 30 seconds, since Phast predicts near steady-state cloud dimensions to be reached around that time, as well as the average time to ESD (which is typically less than 10 seconds).

In the following examples, point gas detectors are located at 0.5 m above grade, unless otherwise noted. The open-path gas detectors are typically elevated to reduce traffic interference with the beam, so they are located at 3.0 m elevation in this case study.

As noted, the Phast calculations reach steady-state quickly, therefore, it could be argued that the detection times reported herein are not conservative. However, it must also be noted that timing is relative and though the Phast analysis reports quick ESD times, maximum consequences are also reached quickly, therefore tempering the risk reduction associated with early detection. Further, as discussed previously, the quick detection times are also coupled with narrow clouds that are more difficult to detect (i.e. typically require more detectors). If a CFD model were to be used, the times to detection may be expected to be longer, but the cloud development (before and after detection) would also be slower. The main outcome is that the two types of models cannot be combined for the same scenario (i.e., using detection times from an integral model to determine the 'mitigated' release duration to then be applied to a CFD model would be invalid).

The goal of this analysis is to quantify detector performance with respect to detector coverage. There will always be uncertainties associated with the analysis, but the use of an integral model and 2ooN voting scheme described above is believed to apply a test of appropriate rigor to the detector layout.

6.6.1 Metering

The Metering area was assigned a scenario-based coverage target of 60% by 2ooN gas detectors. Beginning with a 10 m grid resulted in an array of 20 point gas detectors, accompanied by perimeter open-path detection (baseline detector layout). Since most piping and other potential leak sources are low in this area the detector elevation was not adjusted; though natural gas is buoyant and will rise under ambient conditions, the high-pressure releases in this area will form an expanding jet and will not rise until the momentum of the release is sufficiently reduced downstream of the release point.

Figure 6-9 compares how many hits each point gas detector received (i.e., scenarios where the cloud reached the detector location at or above 40% LFL resulting in a Detection or ESD case) for the baseline detector layout. This plot shows which gas detectors were most utilized (left) and which gas detectors were least utilized (right). The baseline detector layout resulted in scenario-based coverage of 81% detection and 64% ESD. Since the baseline detector layout exceeded the scenario coverage target, the lowest performing point gas detectors were progressively removed and the layout was re-evaluated to optimize to the prescribed detection rate as summarized in Table 6-11 (scenario coverage above target is indicated by orange, below target by red, and on target by green). Recall that conservative estimates were made regarding the number of potential release locations and release directions. Therefore, these results should be regarded as a demonstrative and not as gas detector placement that can be applied to other facilities or Detection Areas with a similar layout.

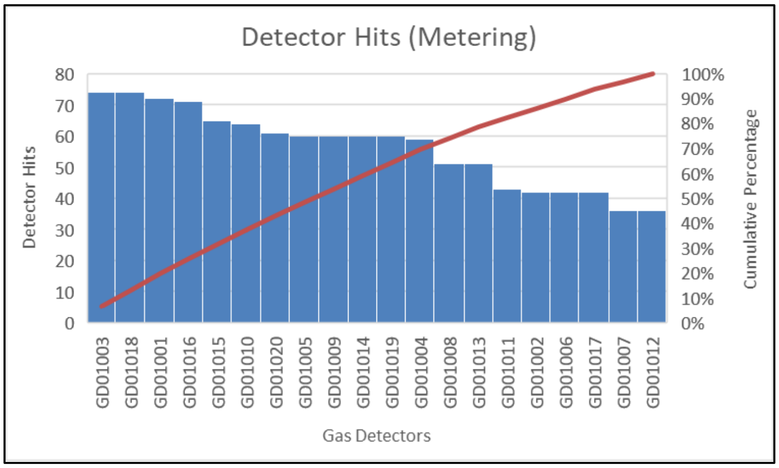

Figure 6-9: Detector hits for baseline layout - Metering.

Table 6-11: Metering Detector Results

Point Detectors	20	18	16	14
1ooN	81%	81%	79%	73%
2ooN	64%	64%	60%	50%
ESD Avg [s]	1.6	1.6	1.7	--

The ‘Before’ and ‘After’ gas detector layouts are shown in Figure 6-10, overlaid upon the 3D model of the generic LNG facility; the location of the point and open-path gas detectors are given by the blue dots and the blue box, respectively. The boundary of the Detection Area was relatively tight around the equipment in this case, therefore only a few detectors could be removed to maintain the required detection rate for the narrow, pressurized gas jets. While this layout satisfies the detection performance targets, it should be noted that it is just a demonstration and other layouts could also achieve the required detector coverage.

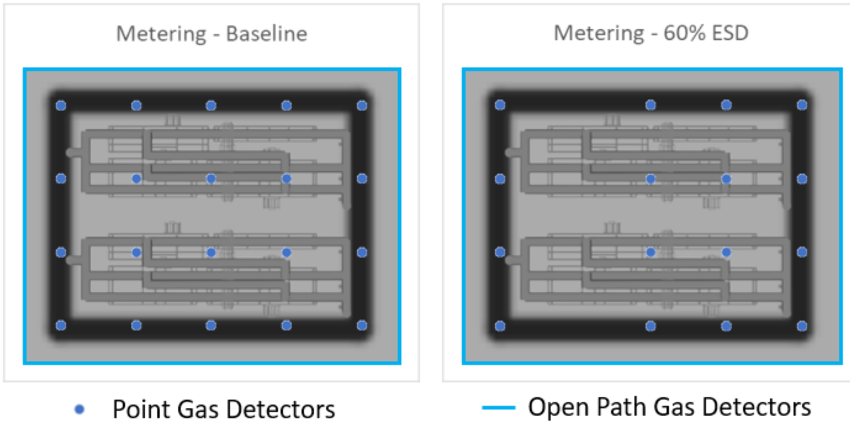

Figure 6-10: Point Gas Detectors for Metering (baseline – left and 60% ESD - right).

6.6.2 Liquefaction Unit A/B

The Liquefaction Units were assigned a scenario-based coverage target of 90% by 2ooN gas detectors due to intolerable risk. Beginning with a 10 m grid (point gas detectors at 0.5 m throughout for the presence of heavy gases, and at 3.0 m within the liquefaction train) resulted in a total of 348 point gas detectors (174 for each train). This Detection Area had perimeter detection around both units A and B, as well as open-path detectors around the liquefaction train and the pretreatment area located in the top-right corner (see Figure 6-12); note that the 10 m grid was based on the overall Detection Area so the perimeter detection around the liquefaction train is not evenly spaced with respect to the point gas detectors.

This baseline detector layout resulted in 95% Detection and 86% ESD. Individual point gas detector hits are shown in Figure 6-11 showing a much larger spread between the most utilized detector and the least utilized detector when compared to the Metering case shown in Figure 6-9. Had the risk classification been ALARP for this Detection Area (i.e. 80% ESD coverage requirement), the detector count could have been reduced to 145 point gas detectors (total including both trains); however, the intolerable risk classification requires a minimum 90% coverage, which means that additional detectors are required. The detector spacing was therefore adjusted to 5 m within the liquefaction train and pretreatment area, which significantly increased the detector count to 666; eliminating the lowest performing detectors, a total of 461 sensors were sufficient to achieve 90% ESD (total both trains) as shown in Figure 6-13.

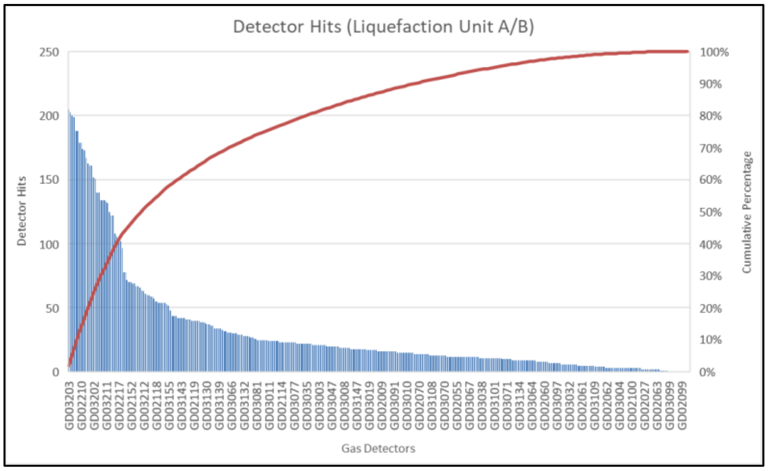

Figure 6-11: Detector hits baseline – Liquefaction Unit A.

The results of the different detector counts are summarized below in Table 6-12. The locations of the point and open-path gas detectors are represented by the blue dots and red boxes, respectively, in the 'Before' and 'After' plots below in Figure 6-12 and Figure 6-13. As the scenario-based coverage target increases, not only is the detector layout taxed with detecting more total releases, but it must also detect a higher percentage of smaller releases. This is largely driven by the number of natural gas and other vapor release scenarios which generate narrow clouds that are difficult to detect. In this case, the added cost of the significant increase in detector counts is disproportional to the benefit of detecting these gas/vapor clouds which have comparatively low consequences compared to the liquid inventories.

Table 6-12: Liquefaction Detector Results

Point Detectors	348	145	666	461
1ooN	95%	91%	97%	96%
2ooN	86%	80%	91%	90%
ESD Avg [s]	2.4	4.5	1.8	2.0

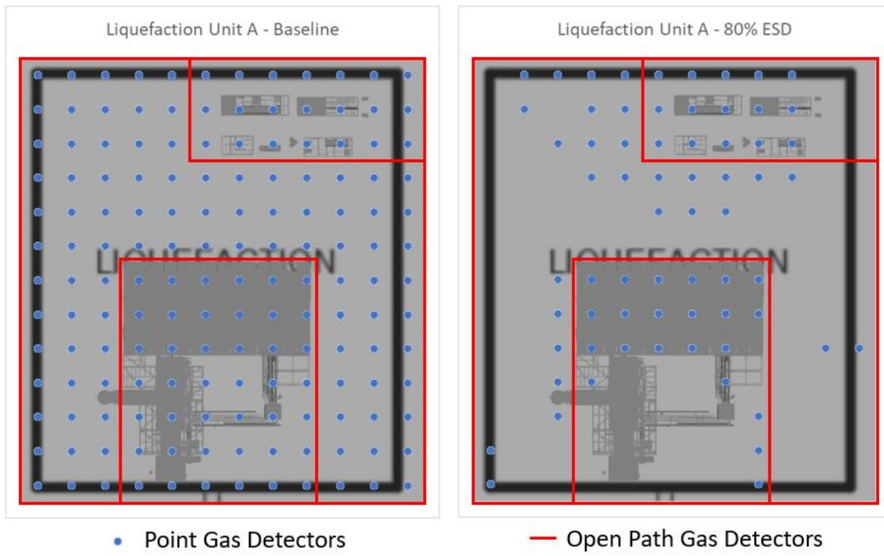

Figure 6-12: Point Gas Detectors for Liquefaction Unit A (baseline – left and 80% ESD - right).

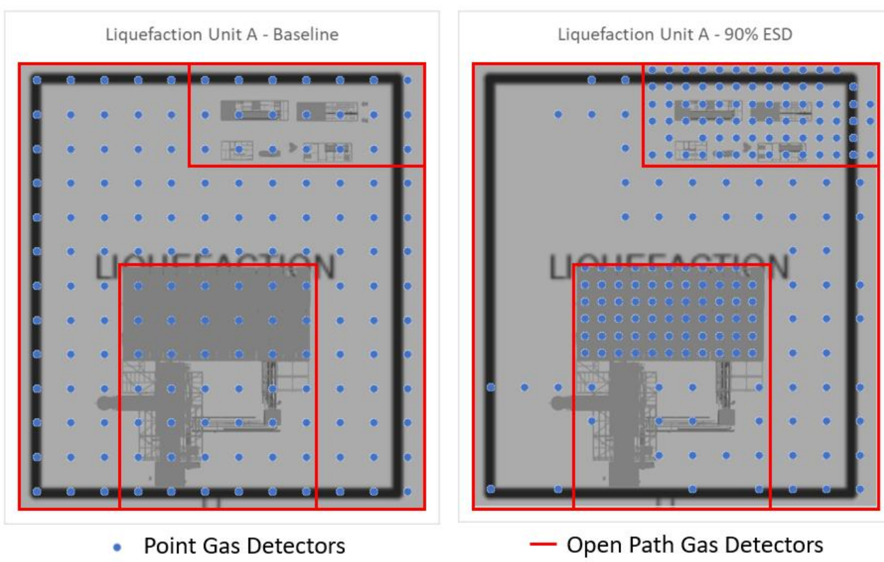

Figure 6-13: Point Gas Detectors for Liquefaction Unit A (baseline – left and 90% ESD - right).

6.6.3 LNG Storage

The LNG Storage area was assigned a scenario-based coverage target of 60% by 2ooN gas detectors. Typical gas detection layouts for full containment LNG storage tanks include a point gas detector for each major line on top of the tank. In this section, the scenario-based detection rate of this approach will be compared to a ring of point gas detectors around the perimeter of the tank. These two layouts can be seen in the baseline configuration of Figure 6-14: the three orange dots represent the release locations, the three green dots represent gas detectors next to each location, and the blue dots represent gas detectors around the perimeter of the tank top. No open-path detection was included in this comparison exercise.

The perimeter case resulted in 67% ESD, which exceeded the performance target. Therefore, the lowest performing point gas detectors were progressively removed and the layout was re-evaluated to optimize to the prescribed detection rate as summarized in Table 6-13 resulting in 22 point gas detectors to achieve at least 60% ESD. The case with just three detectors adjacent to the rundown and sendout pipes only achieved 8% ESD, as limited release angles are capable of triggering two detectors. It should be noted that this assessment does not conclude that detectors must be provided around the perimeter of LNG tanks; rather, it simply compares the scenario-based coverage of these two arrangements.

Table 6-13: LNG Storage Detector Results

Point Detectors	30	22	20	3
1ooN	67%	63%	58%	42%
2ooN	67%	63%	58%	8%
ESD Avg [s]	3.0	3.5	--	--

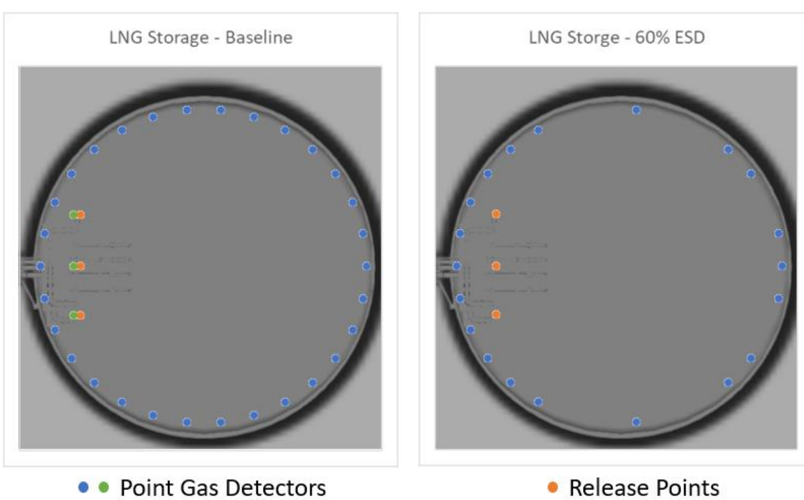

Figure 6-14: Point Gas Detectors for LNG Storage (baseline – left and 60% ESD – right).

6.6.4 BOG & Vaporization

The BOG and Vaporization area was assigned a scenario-based coverage target of 60% by 2ooN gas detectors. Perimeter detection was provided separately for the BOG and Vaporization area; in this case, the base 10 m grid of point gas detectors extended outside the open-path detectors as shown in the baseline detector layout in Figure 6-15. The baseline detector layout included 60 point gas detectors and resulted in 87% Detection and 79% ESD. The lowest performing point gas detectors were progressively removed and the layout was re-evaluated to optimize to the prescribed detection rate as summarized in Table 6-14. The 'Before' and 'After' gas detector layouts are shown in Figure 6-15 where the blue dots represent point gas detectors and the orange lines represent open path gas detectors.

Table 6-14: BOG & Vaporization Detector Results

Point Detectors	60	35	20	17
1ooN	87%	82%	74%	71%
2ooN	79%	70%	60%	55%
ESD Avg [s]	3.6	6.9	9.4	--

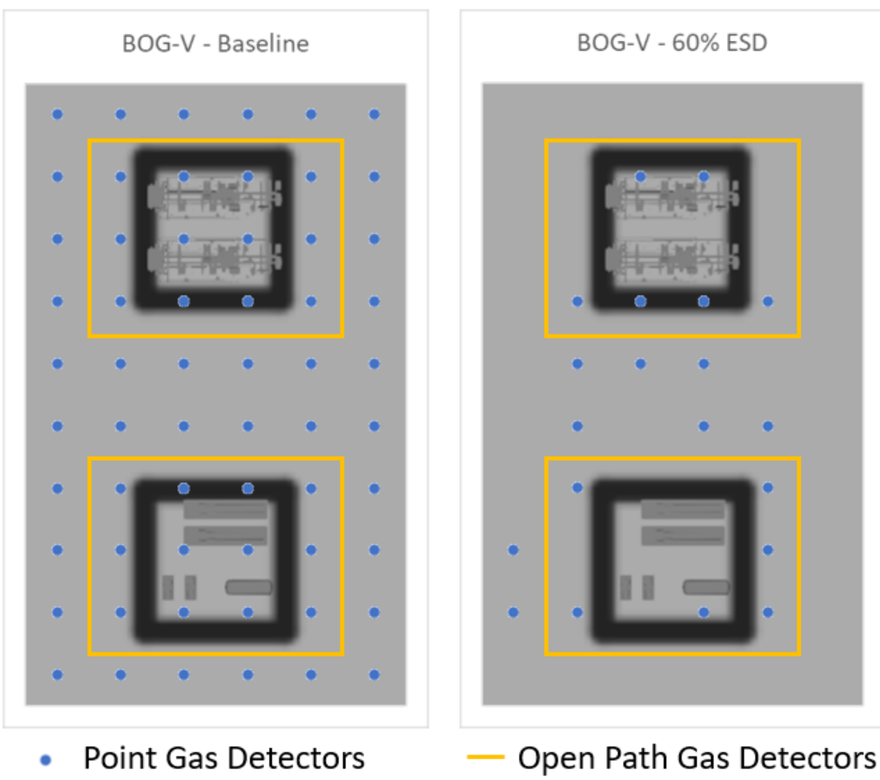

Figure 6-15: Point Gas Detectors for BOG-V (baseline – left and 60% ESD – right).

6.6.5 Trucking & Refrigerant Storage

The Trucking and Refrigerant Storage area was assigned a scenario-based coverage target of 80% by 2ooN gas detectors. The baseline point gas detector layout followed a 10 m spacing guide, but was adjusted for driving lanes in the Trucking area and to be between vessels in the refrigerant storage area as shown below in Figure 6-16; perimeter detection was provided separately for the Trucking and Refrigerant Storage area. The baseline detector layout resulted in 62% Detection and 55% ESD, which was below the performance target for this Detection Area. Therefore, a ring of point gas detectors was added outside the open-path gas detectors for a total of 58 point gas detectors, which resulted in 88% Detection and 85% ESD, which increased performance above the assigned coverage. The lowest performing point gas detectors were progressively removed and the layout was re-evaluated to optimize to the prescribed detection rate as summarized in Table 6-15. The 'Before' and 'After' gas detector layouts are shown in Figure 6-16 where the blue dots represent point gas detectors and the yellow lines represent open path gas detectors.

Table 6-15: Trucking & Refrigerant Storage Detector Results

Point Detectors	24	58	42	38
1ooN	62%	88%	84%	82%
2ooN	55%	85%	80%	78%
ESD Avg [s]		4.8	6.1	--

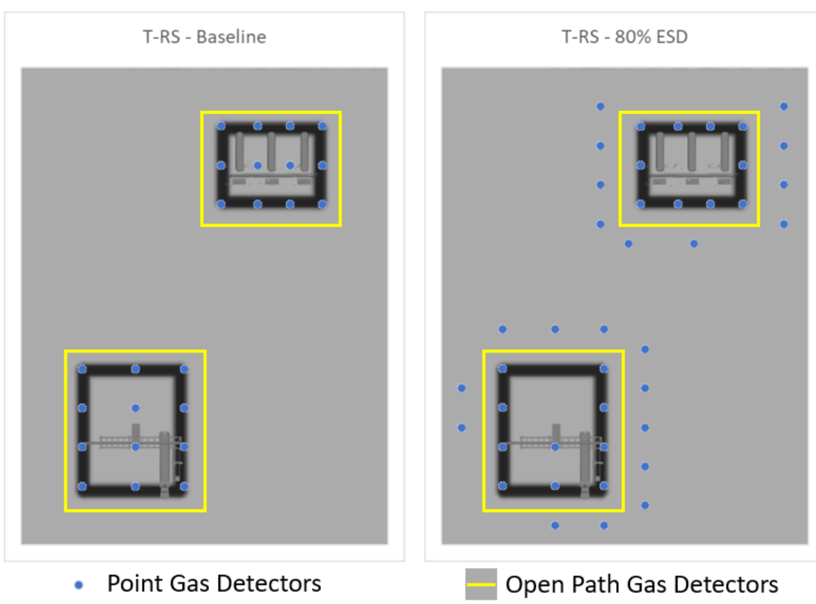

Figure 6-16: Point Gas Detectors for T-RS (baseline – left and 80% ESD - right).

6.7 Large Scale Case Study Conclusions

The preceding sections demonstrated how dispersion modeling can be used to evaluate and optimize a gas detector layout using scenario-based coverage. The baseline gas detector layout could be based on a simple grid distribution as shown above, or specific locations determined by other means. Either way, the layout can be evaluated against a set of hazard scenarios to determine the scenario-based coverage.

The detector layouts included in these examples are not intended to be replicated at another LNG facility – all detector layout evaluations are site specific. In the absence of detailed design documents, conservative estimates were made regarding the number of potential release locations and release directions. Therefore, these results should be regarded as a demonstrative and not as gas detector placement that can be applied to other facilities or Detection Areas with a similar layout. Further, these examples are not intended to predict the exact detectors and activation times that would follow an accidental release. This methodology provides for an objective evaluation of a gas detector layout based on the areas where flammable clouds will be present in the event of an accidental release, rather than release locations alone.

This demonstration was carried out using an integral model, however, the same approach could be used with CFD models, to take into account the interaction of the releases with obstacles and obstructions within the facility. It is important to note that the predicted consequences and timing associated with those consequences is specific to each model, therefore, they are not interchangeable between the two types of models.

The detector activation level for the dispersion modeling was set to 40% LFL, as commonly used for second alarm in LNG facilities. In all scenarios modeled for this exercise, which was limited to releases of 2-in diameter or larger, the average ESD time was less than 10 seconds; this is reasonable considering the detector spacing and the initial velocity of clouds from a pressurized jet release. Therefore, initiating executive action at a lower concentration threshold (e.g., 20% LFL) would not have a significant effect on reducing the overall release duration for the ESD case, which also includes detector response time, signaling time, valve closure, and de-inventory.

Modeling results indicate that as scenario-based coverage targets approach 90%, the number of point gas detectors required increases significantly. This was demonstrated in the Liquefaction Unit where 145 point gas detectors were required between the two trains in order to achieve 80% coverage, compared to 461 point gas detectors required for 90% coverage. Generally, as detector coverage increases, the detector layout is picking up the larger clouds in the scenario set and smaller clouds make up the majority of the undetected scenarios. Therefore, increasing gas detector coverage targets requires not only detecting more clouds, but also smaller clouds, which leads to a higher number of detectors. Further, this case study demonstrated the difficulty (or significant number of detector resources required) in order to detect pressurized releases in relatively open areas. As a result, potential release points and directions must be carefully considered in a detector evaluation and will be further refined in the second case study.

The results of the gas detector evaluation also demonstrate that applying a single detector coverage target to an entire Detection Area may be inappropriate. For example, applying a uniform detector coverage target to the Liquefaction Unit applies the same criteria to natural gas streams (which generate narrow plumes that are difficult to detect) as it does to mixed refrigerant liquid streams (which generate larger clouds and are more reactive). As a result, additional detection resources are required for generally low-risk release scenarios. Therefore, more refined performance targets are recommended that focus on different flammable streams.

This analysis evaluated gas detector coverage targets at 2ooN voting to initiate ESD; accordingly, a higher percentage of scenarios were detected (covered by 1ooN detectors) than achieved shut down. Therefore, even though executive action would not be taken for scenarios only achieving 1ooN, quick notification is still provided to operators in the event of an accidental release. It should be noted that some facilities may want to limit the executive actions taken by the gas detection system. In this case, the facility would need to demonstrate that the delay and overall change in reliability of intervention associated with operator intervention would still satisfy criteria for intolerable risk or ALARP.

In summary, this case study demonstrates:

- a uniform detector coverage target for the entire Detection Area does not focus resources on higher risk scenarios; therefore, detector coverage targets should be inventory specific.
- a detector layout based on uniform spacing is inefficient.
- the significant increase in point gas detectors required to achieve 90% scenario-based detection compared to 80% within the liquefaction unit.

It should be noted that this case study was developed to illustrate the above points and does not suggest the given detector counts or layouts to be practical for an LNG facility.

7 Case Study 2 – Small Scale LNG Facility

A second case study was performed to demonstrate application of the proposed methodology on a smaller facility, as well as to evaluate a different set of performance targets. The previous case study assigned the same detector coverage targets to all inventories within a Detection Area based on the risk classification (e.g. intolerable or ALARP). However, this broad grouping was found to require a disproportionate number of gas detectors in some cases. For example, applying a uniform detector coverage target to the Liquefaction Unit applies the same criteria to natural gas streams (which generate narrow plumes that are difficult to detect) as it does to mixed refrigerant liquid streams (which generate larger clouds and are more reactive).

This case study will assign detector coverage targets to each flammable fluid in a given Detection Area based on the corresponding hazards. This allows for the detector resources to be focused on the scenarios that present the greatest risk, without placing overly burdensome requirements on low-risk scenarios in the same Detection Area.

The small scale case study will focus on flammable gas detection using the scenario-based coverage approach. An example of flame detector mapping was provided in the previous case study using geographic-based coverage; since this approach is not dependent on the size of the facility or flammable fluids present[33], flame detector coverage is not included in the current analysis.

7.1 Fire and Gas Detection Philosophy

Gas detector coverage targets in this case study will be more generally defined based on the three risk classifications listed in Table 7-1, which are adapted from the ISA TR 84.00.07 to LNG facilities designed and built to current PHMSA regulations. Similar to the previous study, one detector activation (1ooN) will initiate operator notification and intervention while two detectors are required to activate (2ooN) to confirm the hazard before automated action is taken. Therefore, when evaluating detector coverage, a scenario that presents a high risk and/or warrants immediate emergency shutdown will require coverage by 2ooN detectors, whereas coverage by 1ooN (which requires less detectors to satisfy) is sufficient for a scenario that does not warrant immediate emergency shutdown (i.e. the delay and reduced reliability associated with operator intervention is acceptable). Note that the voting criteria used to evaluate the detector layout represent minimum thresholds and do not limit the functionality of the gas detection system. For example, the minimum detection coverage target may be specified at 1ooN, however, 2ooN detector activation can still initiate emergency shutdown.

[33] Flame detector listings for field of view are fuel specific, however, the geographic-based coverage approach is only based on geometry and is not impacted by different hazard scenarios present at different types of facilities.

Table 7-1: Detector Coverage Basis

Risk Classification	Minimum Detector Coverage
High	90%
Normal	80%
Low	60%

LNG facilities under PHMSA jurisdiction are already designed to limit the likelihood of an accidental release, prevent unacceptable offsite impacts, and protect building occupants. However, if a project relies on hazard detection to satisfy PHMSA siting requirements (i.e., uses a release duration less than 10 minutes for calculating dispersion hazards), unsuccessful detection could lead to severe consequences. Therefore, a minimum detector coverage of 90% is assigned to scenarios using a reduced release duration based on detection and isolation[34]. Conversely, releases in open areas with well-controlled ignition sources or low-reactivity gas releases pose comparatively smaller risk to the facility; given the difficulty to detect such releases, the same detection target would require a disproportionate share of detection resources. Therefore, these releases are considered low risk and assigned a detection target of 60%. For the purposes of this demonstrative, 2ooN voting is assigned uniformly to result in automatic emergency shutdown for all loss of containment scenarios.

Table 7-2: Flammable Gas Detector Coverage Criteria

Risk Classification	Scenario Description	Minimum Detector Coverage
High	Releases where duration less than 10 minutes is assumed based on detection	90% by 2ooN
Normal	All remaining scenarios	80% by 2ooN
Low	Releases in open areas with well-controlled ignition sources and all low reactivity gas releases	60% by 2ooN

It should be noted that this methodology can be adapted to use different detector coverage criteria than what is given above. For example, a project may desire to evaluate detector coverage based on 1ooN voting for low-risk scenarios rather than 2ooN, to reduce detector counts. However, such a decision would require careful consideration of the reliability of the detection system components and operator intervention.

[34] Total release duration must consider the time for the gas to reach the detector (considering potential leak points and detector locations), detector activation time, signaling time, valve closure time, and depressurization/de-inventory of the isolated section.

7.2 Designate Detection Areas

The layout for the LNG peakshaver facility used in this demonstrative has been adapted from previous PHMSA research projects and is shown in Figure 7-1 along with highlighted Detection Areas. The liquefaction system is nitrogen-based, therefore no flammable refrigerants are present. As a result, overpressure hazards are not a concern and the Pretreatment Area (PreT) has been separated from the Liquefaction Area (Liq) for this analysis. LNG is stored in horizontal bullet tanks, which are grouped with the neighboring LNG pumps in the LNG Storage Area. The Vaporization Area (Vap) is located between the Pretreatment Area and the LNG Storage Area. The Truck Loading Area (TL) is located in the southeast corner of the facility.

The boil-off-gas compressors are located within an enclosure in the facility design, therefore, this area was not included in the current analysis. Individual Detection Area evaluations are provided in the following subsections.

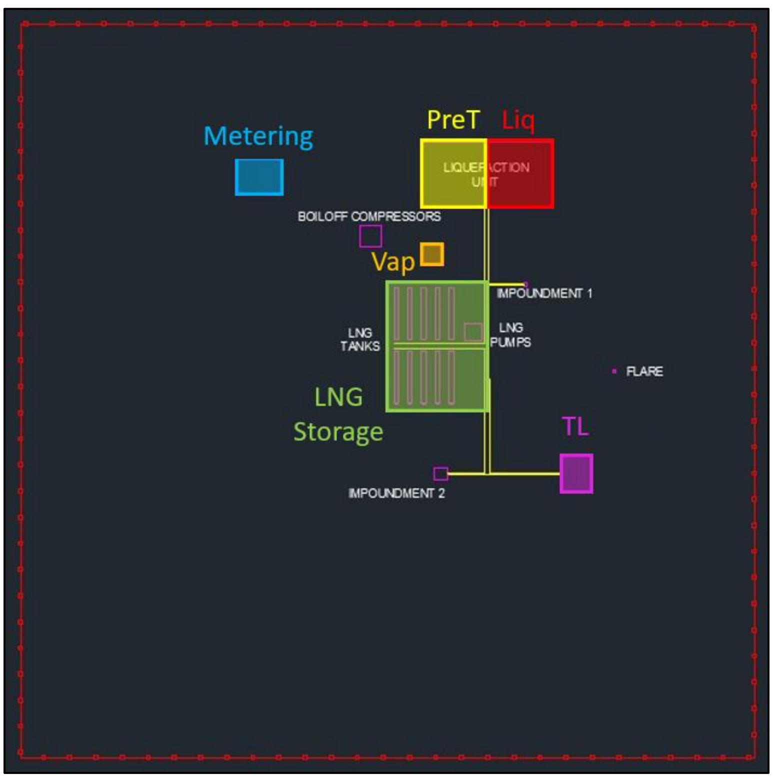

Figure 7-1: Detection Areas for the Small Scale LNG facility.

7.2.1 Metering

The Metering Area serves both inlet gas from the pipeline and sendout from vaporization. Feed gas from the pipeline is approximately 95% methane, therefore feed gas and sendout gas are evaluated as pure methane, consistent with current PHMSA procedures for hazard modeling. This area is geographically isolated from the rest of the facility and has low congestion. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Metering Area is provided in Table 7-3.

Table 7-3: Metering Area Evaluation

Flammable Streams	Natural Gas (methane)
Potential Leak Scenarios	These lines operate at high pressure, therefore a leak would result in a high velocity flammable gas release.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	No (gaseous inventories only)
Cascading Damage	None

7.2.2 Pretreatment Area

The pretreatment process removes acid gas and moisture from the feed gas in preparation for liquefaction. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Pretreatment Area is summarized in Table 7-4.

Table 7-4: Pretreatment Area Evaluation

Flammable Streams	Natural Gas (methane)
Potential Leak Scenarios	These lines operate at high pressure, therefore a leak would result in a high velocity flammable gas release.
Flash Fire	Yes
VCE	No (low reactivity fuel; low-medium congestion)
Jet Fire	Yes
Pool Fire	No (gaseous inventories only)
Cascading Damage	None

7.2.3 Liquefaction Area

This analysis considers an LNG facility with a nitrogen-based liquefaction process, therefore, there are no flammable refrigerants onsite. Small scale LNG facilities, such as peakshavers, typically have low to medium levels of congestion, which combined with low-reactivity fuels, do not present significant overpressure hazards[35]. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Liquefaction Area is summarized in Table 7-5.

Table 7-5: Liquefaction Area Evaluation

Flammable Streams	LNG (methane)
Potential Leak Scenarios	Flashing and jetting releases of LNG. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	No (low reactivity fuel; low-medium congestion)
Jet Fire	Yes
Pool Fire	Yes (remote impoundment)
Cascading Damage	None

[35] Detailed in Section 3.5

7.2.4 LNG Storage Area

The LNG peakshaver layout has been revised from previous PHMSA research projects to include ten horizontal storage vessels rather than a single containment tank of equal capacity. The LNG Storage Area also includes the LNG truck loading and sendout pumps. A summary of the hazards presented by a loss of containment of flammable fluid streams in the LNG Storage Area is summarized in Table 7-6.

Table 7-6: LNG Storage Area Evaluation

Flammable Streams	LNG
Potential Leak Scenarios	Flashing and jetting releases of LNG from rundown or sendout lines. Liquid spills from large-bore LNG line ruptures that would be directed into the facility trenches and impoundment.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes (remote impoundment)
Cascading Damage	BLEVE of pressurized vessels

7.2.5 Vaporization Area

The Vaporization Area includes high pressure LNG and natural gas sendout lines. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Vaporization Area is summarized in Table 7-7.

Table 7-7: Vaporization Area Evaluation

Flammable Streams	Natural Gas, LNG (methane)
Potential Leak Scenarios	Flammable gas releases from gaseous inventories. Flashing and jetting releases of LNG. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes (remote impoundment)
Cascading Damage	None

7.2.6 Truck Loading Area

The Truck Loading Area is located away from the process and storage areas, therefore releases are generally into open areas with well-controlled ignition sources. Additionally, truck loading operations are typically manned providing opportunity for swift operator response. A summary of the hazards presented by a loss of containment of flammable fluid streams in the Truck Loading Area is summarized in Table 7-7.

Table 7-8: Truck Loading Area Evaluation

Flammable Streams	LNG (methane)
Potential Leak Scenarios	Flashing and jetting releases of LNG. Liquid spills from large-bore LNG line ruptures flowing into the facility trenches and impoundment.
Flash Fire	Yes
VCE	No (low reactivity fuel; low congestion)
Jet Fire	Yes
Pool Fire	Yes (remote impoundment)
Cascading Damage	BLEVE of LNG trailer

7.3 Identify Hazard Scenarios

With potential leak scenarios established for each Detection Area, the next step is to determine which scenarios will be used to evaluate the detector layout. The following figures compare the location specific individual risk (LSIR) contours for the baseline case (which includes all hole size categories) with the risk contours including only subsets of releases. For this case study, this process is only used to determine which scenarios to include in the evaluation and not to assign performance targets, therefore, it is only necessary to compare the relative risk of each subset to the baseline case and specific values are not given for each contour.

Figure 7-2 includes releases 6 inches and larger in the comparison subset while Figure 7-3 includes releases 2 inches and larger in the comparison subset.

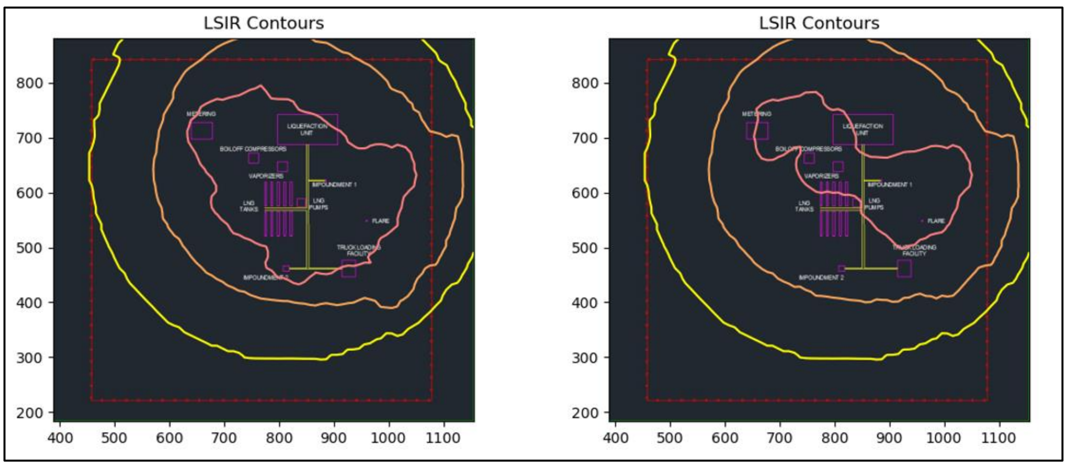

Figure 7-2: LSIR contours for baseline case (left) and releases 6 inches & larger (right).

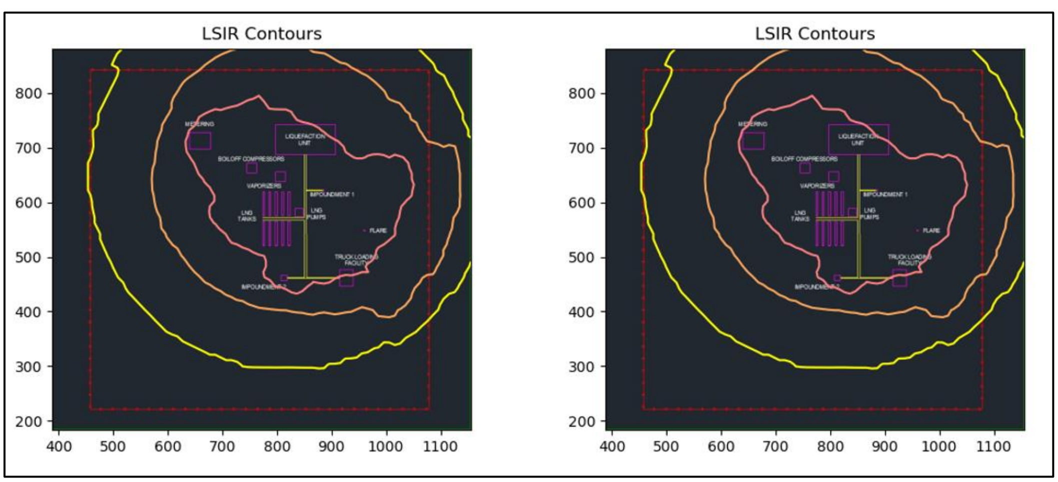

Figure 7-3: LSIR contours for baseline case (left) and releases 2 inches and larger (right).

The comparisons show that, for this specific case, releases smaller than 2 inches diameter do not contribute appreciably to the individual risk at the specified tolerability thresholds. Therefore, the performance-based evaluation of the gas detector layout for this case study was limited to releases 2 inches and larger.

It is important to note that the results of the sensitivity study are case-specific and depend on the risk tolerability criteria used; they should not be considered generally applicable to other facilities. For each facility, a hole size sensitivity should be performed to determine the minimum hole size to be considered in the detector evaluation.

7.4 Assign Performance Targets

Having detailed the hazards present in each Detection Area and established which scenarios should be used to evaluate the gas detector layout, coverage targets can be applied according to the criteria given in Section 7.1.

The detector performance targets for this analysis are summarized below in Table 7-9. All low reactivity fuel releases are assigned minimum 60% coverage. LNG releases from the Truck Loading Area disperse into open areas with well controlled ignition sources, and truck loading operations are constantly manned, therefore these releases are considered low risk and 60% coverage is assigned to these scenarios as well. For this demonstrative, it is assumed that a shortened release duration is desired for LNG releases in the Liquefaction Area, therefore a coverage target of 90% is set. All remaining LNG releases are assigned 80% coverage. For the purposes of this demonstrative, 2ooN voting is assigned uniformly to result in automatic emergency shutdown for all loss of containment scenarios.

Table 7-9: Flammable Gas Detector Coverage Criteria

#	Detection Area	Flammable Inventory	Minimum Detector Coverage
1	Metering	Natural Gas	60% by 2ooN
2	Pretreatment	Natural Gas	60% by 2ooN
3	Liquefaction	LNG	90% by 2ooN
4	LNG Storage	LNG	80% by 2ooN
5	Vaporization	LNG Natural Gas	80% by 2ooN 60% by 2ooN
6	Truck Loading	LNG	60% by 2ooN

7.5 Gas Detector Evaluation

The example modeling in this analysis is performed using the integral model Phast (version 8.22), however, the same methodology could be applied using other integral models as well as CFD tools. The cloud envelope for each release scenario is tested against the gas detector layout to determine if the scenario will result in successful detection (2ooN at 40% LFL or higher) and the time at which this occurs. Based on the total number of release scenarios for each inventory type in the Detection Area, the percentage of successful detection can be calculated (i.e., scenario-based coverage). This demonstration will only report successful detection cases that occur before steady-state conditions are reached (approximately 30 seconds according to Phast).

The cloud footprint will obviously differ between integral and CFD models in the presence of obstructions. Generally speaking, the narrower clouds associated with Phast are likely to present a more rigorous test of the detector layout as these clouds will be harder to detect. However, this is not the case with open-path gas detectors. Since the Phast cloud is allowed to extend freely downwind in the unobstructed field, the effectiveness of open-path gas detectors could be over-predicted. Therefore, open-path gas detectors were included in this analysis as perimeter detection for each Detection Area, however, a maximum of one open-path gas detector was counted towards ESD voting.

Similar to the previous case study, releases from piperacks between Detection Areas were not included; since long piping runs at LNG facilities are welded and have a very low leak frequency compared to other components, it is best to focus fire and gas detection resources in other areas. Given that piperacks often have large isolatable inventories, even very early detection and isolation is unlikely to result in significant hazard mitigation due to the time to deinventory the isolated section. Additionally, the detection layout used in this analysis includes open-path gas detectors around the perimeter of each Detection Area which would detect piperack releases that were migrating into a hydrocarbon handling or storage area and prompt operator intervention.

Gas detection for the LNG impoundment is not evaluated in this exercise. Impoundments at LNG facilities are typically provided low temperature, flame and gas detection over the area of the impoundment; since the hazard is isolated to a well-defined area, no further optimization is warranted.

7.5.1 Release Points and Directions

In addition to hole sizes, calculating scenario-based coverage for gas detectors will depend on the release points and directions considered. Fire and explosion risk assessments typically assume releases are equally likely to occur in all directions, such as the four cardinal directions (i.e., every 90 degrees) or more discrete steps including 8 or 16 release directions. However, when evaluating gas detector layouts by scenario-based coverage, using too many release directions may be overly burdensome. Additionally, the plant layout may justify excluding certain release directions for the various release points.

As an example, consider the LNG Storage Area shown below in Figure 7-4 where release points are indicated by the color-coded dots. For each storage tank, a release point is considered at the tank connection and at the piperack connection (i.e., the middle dot along the piperack represents two leak points, one for the tank to the north and one for the tank to the south). For the inner tanks (blue dots), most release directions would hit obstructions from the large bullet tanks and their supports, therefore, detectors will be placed in this area to detect an accumulation of flammable gas and modeling was limited to releases in the east and west directions. For the tanks on the east and west sides, additional angled releases were considered (as indicated by the red and green dots with corresponding arrows). Given equipment and piping considerations for the LNG pumps, releases were evaluated in 8 directions (i.e., 45-degree increments).

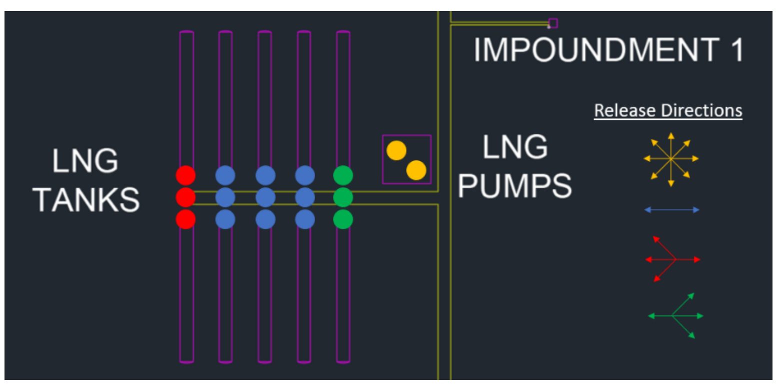

Figure 7-4: Release locations and directions for the LNG Storage Area.

It should be noted that a detailed design was not developed for this example peakshaver facility and these release points and directions are based on assumptions for this demonstrative. Application of this approach elsewhere would depend on site-specific layouts and conditions.

7.5.2 Example Gas Detector Layout

Based on the detector coverage targets provided in section 7.4, flammable cloud dispersion data was used to develop the gas detector layout shown below in Figure 7-5; the detector coverage targets and achieved scenario-based coverage are summarized in Table 7-10. All point and open-path gas detectors are located at 1 m above grade. A total of 35 point gas detectors, along with perimeter detection for each Detection Area provided by four open-path gas detectors, were utilized to meet the detector performance targets. For comparison, a geographic approach using a 10 m grid of point gas detectors within each Detection Area would result in 179 detectors.

Table 7-10: Scenario-Based Flammable Gas Detector Coverage (2ooN)

#	Detection Area	Flammable Inventory	Target	Achieved
1	Metering	Natural Gas	60%	66%
2	Pretreatment	Natural Gas	60%	64%
3	Liquefaction	LNG	90%	90%
4	LNG Storage	LNG	80%	85%
5	Vaporization	LNG Natural Gas	80% 60%	83% 88%
6	Truck Loading	LNG	60%	60%

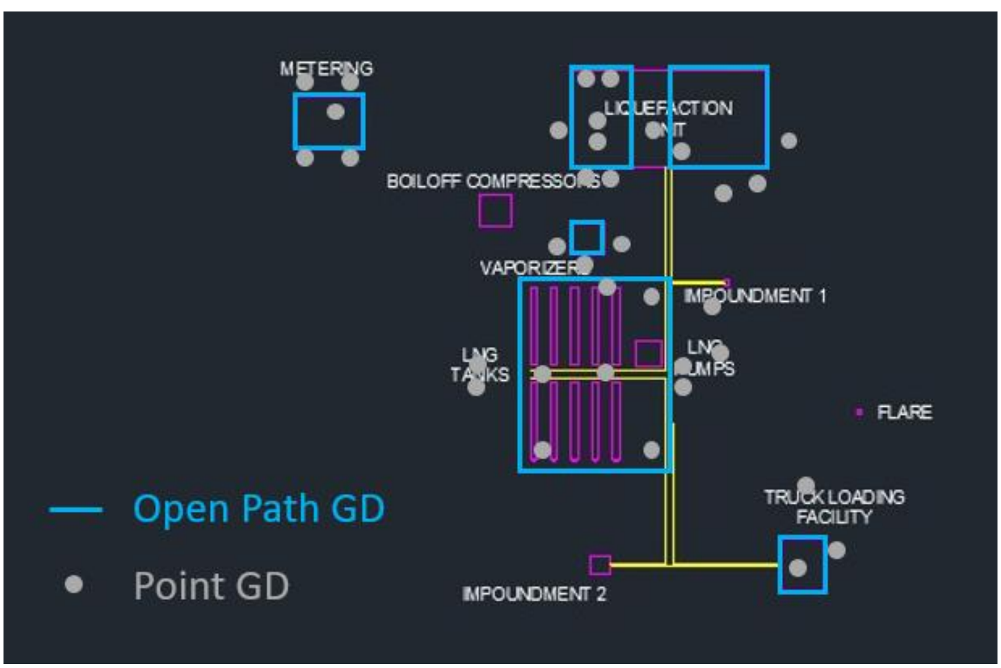

Figure 7-5: Example flammable gas detector layout showing open path perimeter detection for each Detection Area by blue lines and point gas detectors by gray dots.

In the example detector layout, there are several instances of point gas detectors being located outside of the Detection Areas. Since pressurized releases have very small cross-sectional area near the leak point, placing detectors further away allows for a single detector to serve multiple release scenarios. This strategy must be balanced with large obstructions in the Detection Area and the additional time required for the cloud to travel to these detector locations.

While this example only considered open-path gas detectors for perimeter detection, they can also be utilized for leak detection within Detection Areas. This strategy would be particularly helpful in areas with pressurized gas releases which result in very narrow clouds that are difficult to detect with point gas detectors. However, point gas detectors should still be included for their ability to track gas cloud concentration, accumulation around large obstructions, and protect ignition sources such as fired-equipment.

7.6 Small Scale Case Study Conclusions

The small scale case study demonstrated the flexibility of the proposed methodology for evaluating flammable gas detector layouts at LNG facilities by changing the detector coverage targets. In the previous case study, the same detector coverage targets, assigned by the risk classification pertaining to each Detection Area (i.e. intolerable or ALARP), were applied to all scenarios within a Detection Area. In the current study, detector coverage targets were assigned to each flammable fluid within a Detection Area, which allows for the detector resources to be focused on the scenarios that present the greatest risk, without placing overly burdensome requirements on low-risk scenarios in the same Detection Area. Isolatable inventories can then easily be grouped into low, normal and high risk categories with detector coverage rates assigned accordingly.

While CFD models will offer the best representation of cloud development in the presence of obstructions, the size and shape of flammable clouds in unobstructed terrain are similar between integral and CFD models. Since LNG peakshaver facilities typically have low levels of congestion, the benefit of a more detailed analysis using CFD models may be limited in the absence of vapor barriers or other large obstructions to cloud development.

The number of detectors required to satisfy scenario-based coverage targets depends on the release locations and directions included in the analysis. Assumptions regarding large obstructions in the vicinity of the release can be used to reduce the number of release directions that need to be evaluated; depending on the configuration, it may be reasonable to place point gas detectors in areas where flammable clouds from obstructed releases are likely to accumulate and focus on unobstructed releases for hazard modeling. This sensitivity to release points and directions further amplifies the importance of a site-specific analysis for gas detector layouts.

The example gas detector layout presented in this case study is a generic example and is not intended to be replicated at another LNG facility – all detector layout evaluations are site specific. Further, this example is not intended to predict the exact detectors and activation times that would follow an accidental release. This methodology provides for an objective evaluation of a gas detector layout based on the areas where flammable clouds will be present in the event of an accidental release, rather than release locations alone.

8 Project Summary

This research project established a performance-based methodology for developing and evaluating hazard detection layouts at LNG facilities. The methodology brings consistency to how detector coverage is evaluated and which hazard scenarios should be included in the evaluation, while allowing for a site-specific analysis where parameters such as risk tolerance and voting criteria can be established by the user. While risk tolerance, harm criteria, and performance targets must be chosen for the purposes of the demonstratives included in this report, these targets should not be interpreted as requirements of DOT-PHMSA nor as acceptable to them.

8.1 Main Hazard Detection Concepts

The performance-based methodology is based on the following hazard detection concepts:

- Flame detector coverage is best evaluated using geographic coverage and does not require hazard modeling.
    - Flame detector coverage can be determined qualitatively by evaluating detector locations and orientations relative to large obstructions to minimize critical blind spots. In many cases, a 2D evaluation of the flame detector field of view is sufficient. However, this can become difficult in congested areas where the cumulative effect of smaller objects, such as pipes, can create larger obstructions to the detector field of view.
    - Flame detector coverage can be determined quantitatively by using 3D models capable of ray tracing and utilizing the Acceptable Shadow Approach which filters out small blind spots that would not negatively impact the performance of the flame detection system.
    - 3D modeling not only provides means to quantify coverage (e.g., percent volume covered by 2ooN) but optimizes the location and orientation of flame detectors in the presence of obstructions.

- Gas detector coverage is best evaluated using scenario coverage and placing detectors where flammable clouds are most likely to develop rather than near potential leak sources.
    - Gas detector coverage can be determined qualitatively by considering the most likely release locations (e.g., flanges, piping connections and instrumentation, etc.), potential release directions (considering nearby obstructions to pressurized jets), and the physics of flammable cloud formation (e.g., pressure, temperature and density of the released material, topography, large obstructions, etc.) to understand where flammable clouds are most likely to develop.

- Gas detector performance targets need to be inventory specific; assigning uniform performance targets across an entire Detection Area or facility does not focus detection resources on higher-risk scenarios.
- A detector layout based on uniform spacing is inefficient for detecting pressurized release scenarios typical to LNG facilities.
- A site-specific hole size sensitivity study needs to be performed, if justification is sought to define a minimum hole size for the detector evaluation.
- Potential release points and directions must be carefully considered in a gas detector evaluation.
- As the scenario-based coverage target increases, not only is the detector layout taxed with detecting more total releases, but it must also detect a higher percentage of smaller releases, which leads to a significant increase in detector resources.
- A gas detection strategy should include point and open path gas detectors to benefit from both technologies.

- Both integral models and CFD models have benefits and limitations with respect to dispersion modeling for gas detection.
  - Integral models require less expertise and have short computing times, but cannot account for obstacles and by extension may over-estimate the effectiveness of open path gas detectors.
  - CFD models are more accurate, but require more expertise and computing time. Additionally, for flashing and jetting releases, the displacement of the vapor source may move the modeled leak outside of the Detection Area and make it difficult to evaluate the detector layout.
  - Higher priority releases for CFD modeling would include LNG releases in, or directed towards, congested areas, as well as non-LNG liquids (higher reactive fuels) in large, congested areas where vapor cloud explosion hazards need to be reduced.
  - A single facility can employ both integral and CFD models in a detector evaluation, however, individual scenarios cannot be intermingled between the two models. Consideration must also be given to the total number of scenarios and how many would need to be run using CFD to have an appreciable impact on the overall detection rate.

- Successful detection must be coupled with the appropriate action and consider the time to the end of the release, not just the time to detection.
  - Early detection and high coverage rates on their own are not sufficient to reduce consequences from an accidental release below that of the standard 10-minute release for PHMSA siting studies; isolatable inventories must be sized appropriately.

8.2 A Performance-Based Methodology

Application of the performance-based methodology was demonstrated through two case studies, including a large scale LNG facility (Section 6) and a small scale LNG facility (Section 7). While the same methodology was utilized in both cases, different approaches for establishing detector performance targets were taken for each case study to demonstrate the impact of applying uniform detection rates across a Detection Area (shown in the large scale case study) versus inventory specific detection rates within a Detection Area (shown in the small scale case study). The results of this research project demonstrate that uniform detection rates across a Detection Area is not appropriate and that detection rates should be inventory specific.

The performance-based methodology for evaluating hazard detection layouts at LNG facilities is summarized in Figure 8-1. Example detector coverage criteria is shown in Table 8-1 and Table 8-2.

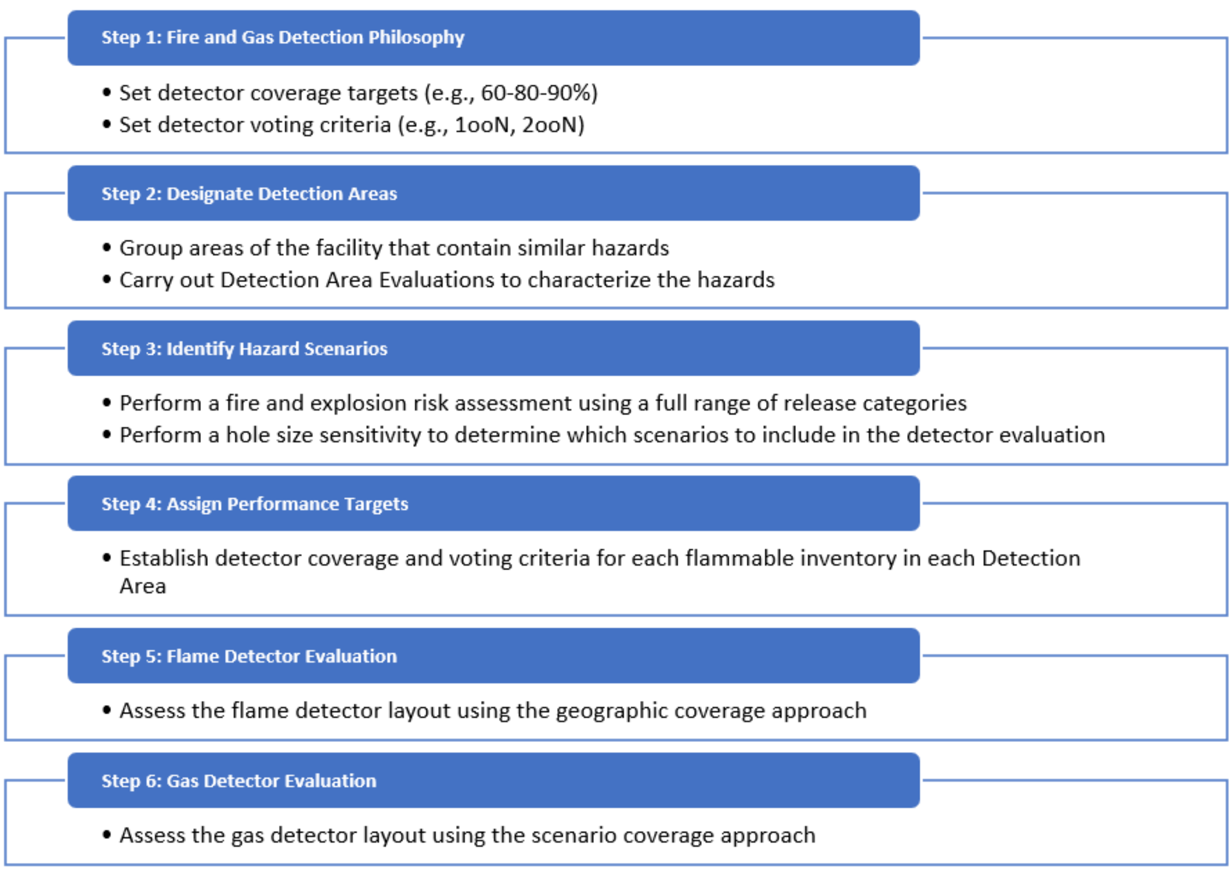

Figure 8-1: Performance-based methodology for evaluating hazard detection layouts at LNG facilities

Table 8-1: Example Flame Detector Coverage Criteria

Risk Classification	Scenario Description	Minimum Detector Coverage
High	Equipment coverage where cascading damage hazard due to fire is identified	90% by 2ooN
Normal	Detection Areas with flammable fluid service	80% by 1ooN
Low	Detection Areas with combustible fluid service only	60% by 1ooN

Table 8-2: Example Flammable Gas Detector Coverage Criteria

Risk Classification	Scenario Description	Minimum Detector Coverage
High	Releases where duration less than 10 minutes is assumed based on detection	90% by 2ooN
Normal	All remaining scenarios	80% by 2ooN
Low	Releases in open areas with well-controlled ignition sources and all low reactivity gas releases	60% by 2ooN

9 Impact of Research Results

This research project was initiated because the LNG industry lacks a consistent approach to developing hazard detection layouts and there is no systematic method for authorities to evaluate these designs. The key impacts of this research project on the LNG industry are summarized in the following subsections.

9.1 PHMSA and other AHJs

Current codes and regulations require hazard detection systems for LNG facilities, but in the absence of prescriptive codes or generally accepted performance targets, consistent criteria for submitted studies or hazard detection layout reviews cannot be specified. This research project provides a basis for PHMSA and other AHJs to understand:

- The level of detail required to quantify fire and gas detector performance (i.e., the extent of the analysis requested of a petitioner and the extent of analysis required for review)
- The parameters that must be considered and/or prescribed when requiring this type of analysis
- The limitations in prescribing a single detector coverage target for an entire facility, or even a single region within a facility
- The burden on owners and operators (i.e., significant number of detectors) to achieve high performance targets, such as 90% scenario-based gas detection

This report presented two case studies to demonstrate the flexibility of the proposed methodology. This provides PHMSA and other AHJs with the information needed to evaluate this methodology and consider adopting it or using it as a basis to develop their own, to set detector study submission requirements, and to perform reviews of hazard detection layouts.

Specifically for PHMSA, the proposed methodology and expanded discussion of hazard detection concepts specific to LNG facilities detailed in this report serve as valuable references to inform future rulemaking for 49 CFR Part 193.

9.2 NFPA 59A

Fire and gas detection systems are required to be installed at LNG facilities by NFPA 59A, however, no requirements or guidance for the location of hazard detection devices is provided. Hazard detection layouts will always require a site-specific analysis, but there is a need for guidance and consistency for this topic in the LNG industry. As the leading code developing body for the LNG industry, the NFPA 59A Technical Committee can consider the performance-based methodology discussed in this report, along with other important hazard detection concepts, to update the code requirements and/or provide annex information related to fire and gas detection systems.

9.3 ISA TR 84.00.07

The methodology proposed in this report closely follows the performance-based design process outlined in ISA TR 84.00.07 which is maintained by ISA 84 Working Group 7. Many determinations had to be made as part of developing the proposed methodology for onshore LNG facilities, which may help inform future versions of this important guidance document.

ISA TR 84.00.07 provides example flammable gas detection philosophies for onshore process plants and offshore facilities separately, but only provides one set of example design basis gas hazards. The example gas hazards span hole sizes of 1-25 mm (i.e., up to 1 inch) which generate small clouds that may require a significant number of detectors for an onshore process plant. Additionally, gas detector coverage is heavily dependent on release orientations, which also lacks guidance and consistency across the industry. Working Group 7 may consider adopting the scenario selection approach utilized in this methodology or using it as a basis to develop their own.

The ISA guidance calls for "detectors located in proximity to leak sources" which as described previously, is often interpreted as locating detectors right next to potential leak sources. Working Group 7 may consider revised terminology to encourage the placement of detectors where flammable clouds are likely to develop, which will improve detector coverage and highlight this important gas detection concept.

It would also be helpful to differentiate the application of 5-10 m spherical clouds as a design basis for gas detectors between onshore and offshore applications. As discussed in this report, this concept does not translate well to the onshore industry for several reasons: flammable clouds do not grow as a sphere, large isolatable inventories may allow the cloud to grow notably after detection, congestion levels are comparatively lower, most personnel are remote of process areas, and explosion hazards may not be driving facility risk.

Finally, the discussion of flame detector coverage in ISA TR 84.00.07 may benefit from considering the Acceptable Shadow Approach developed as part of this research project. By focusing on minimizing critical blind spots, flame detector coverage can be optimized without requiring detailed scenario selection or hazard modeling.

9.4 Safety Consultants and Operators

In addition to proposing a performance-based methodology that can be used for developing hazard detection layouts, this report discusses several important hazard detection concepts that can be used in developing effective detector layouts. Adopting this methodology, or incorporating elements into existing procedures, will bring a level of consistency to fire and gas detection layouts in the LNG industry and increase plant safety.

9.5 New Technologies

Determining flame detector coverage is fairly straight-forward using the geographic coverage approach since these detectors have a well-defined field of view. While a scenario-based approach is more appropriate for gas detection, it requires a much more detailed analysis and is based on critical assumptions such as release locations and directions. Developing technologies such as Gas Cloud Imaging (GCI) could allow gas detector coverage to be evaluated using the simpler geographic coverage approach. Additionally, GCI could be used in addition to point and open path gas detection to reduce the number of gas detectors required.

10 Final Financial Section

The contract for this research project was fixed-price with 80% funded by DOT-PHMSA and the remaining 20% funded by industry cost share. Cash contributions were provided by Distrigas of Massachusetts, a division of Exelon Generation, and Southern Company Gas.

This project was completed on schedule and on budget with no discrepancies or variances in contributions.

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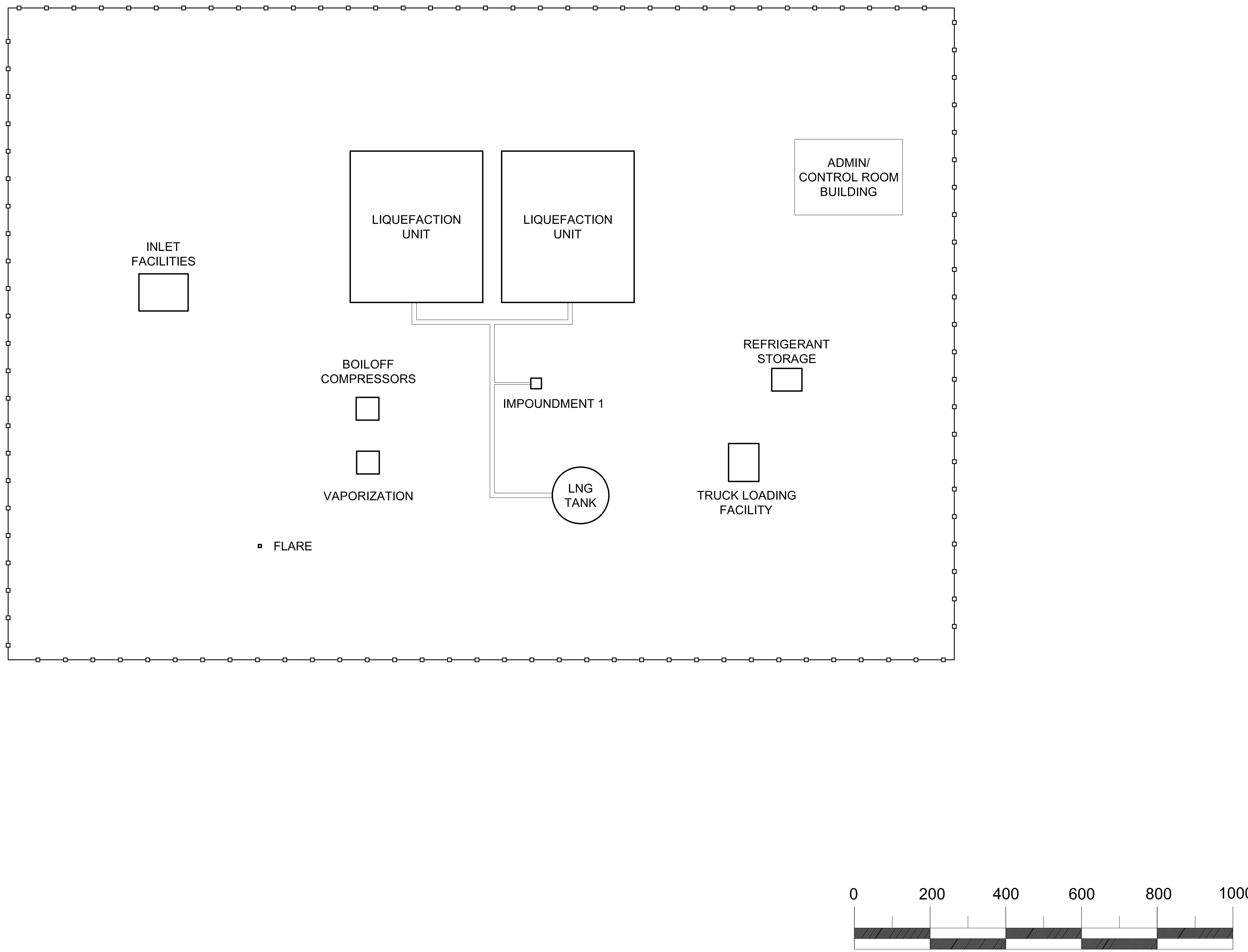
Appendix A – Plot Plans



NOTES

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PLOT PLAN
LARGE SCALE FACILITY

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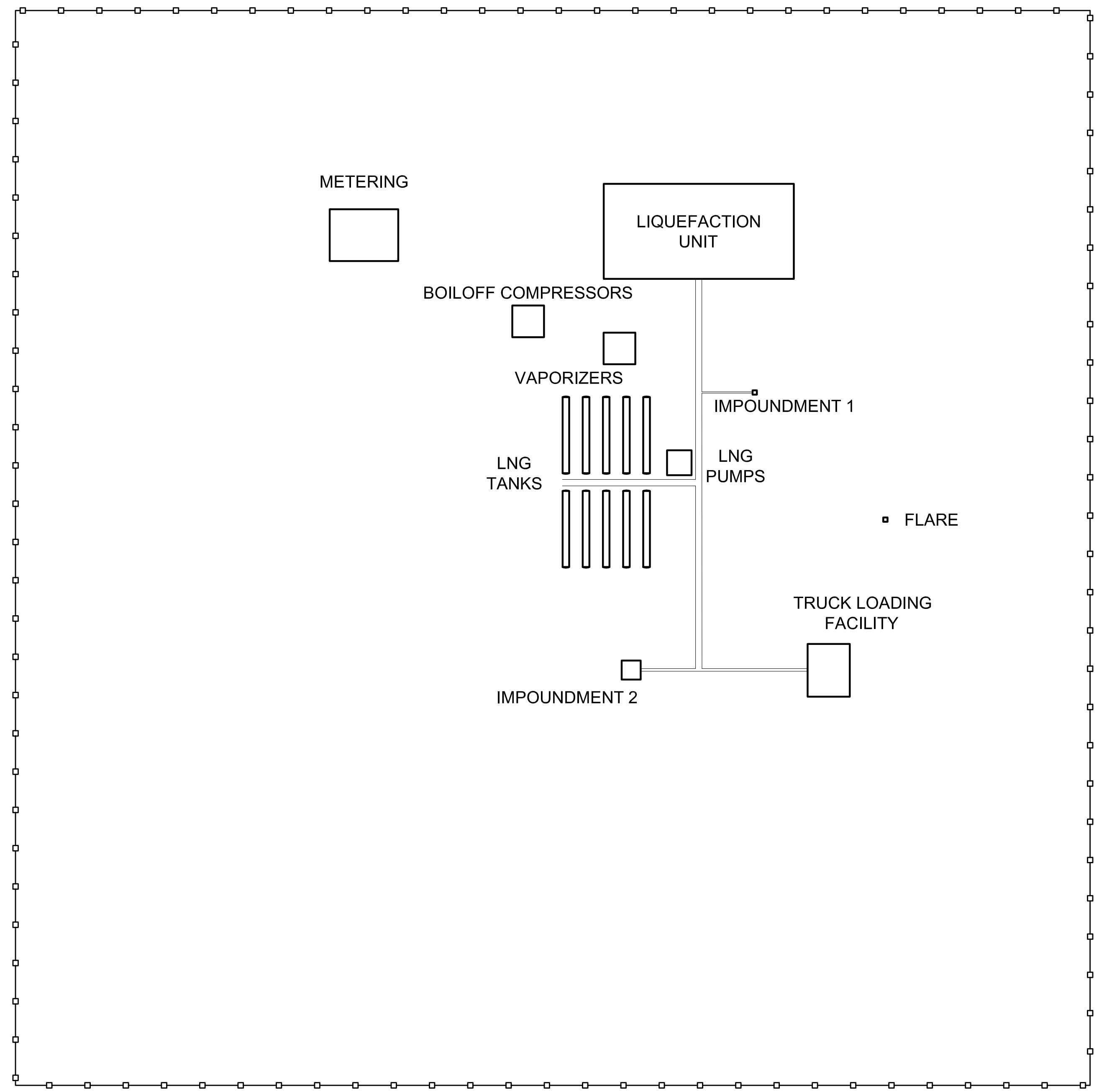

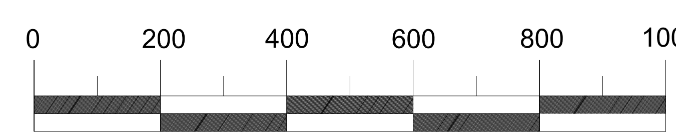

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SMALL SCALE FACILITY

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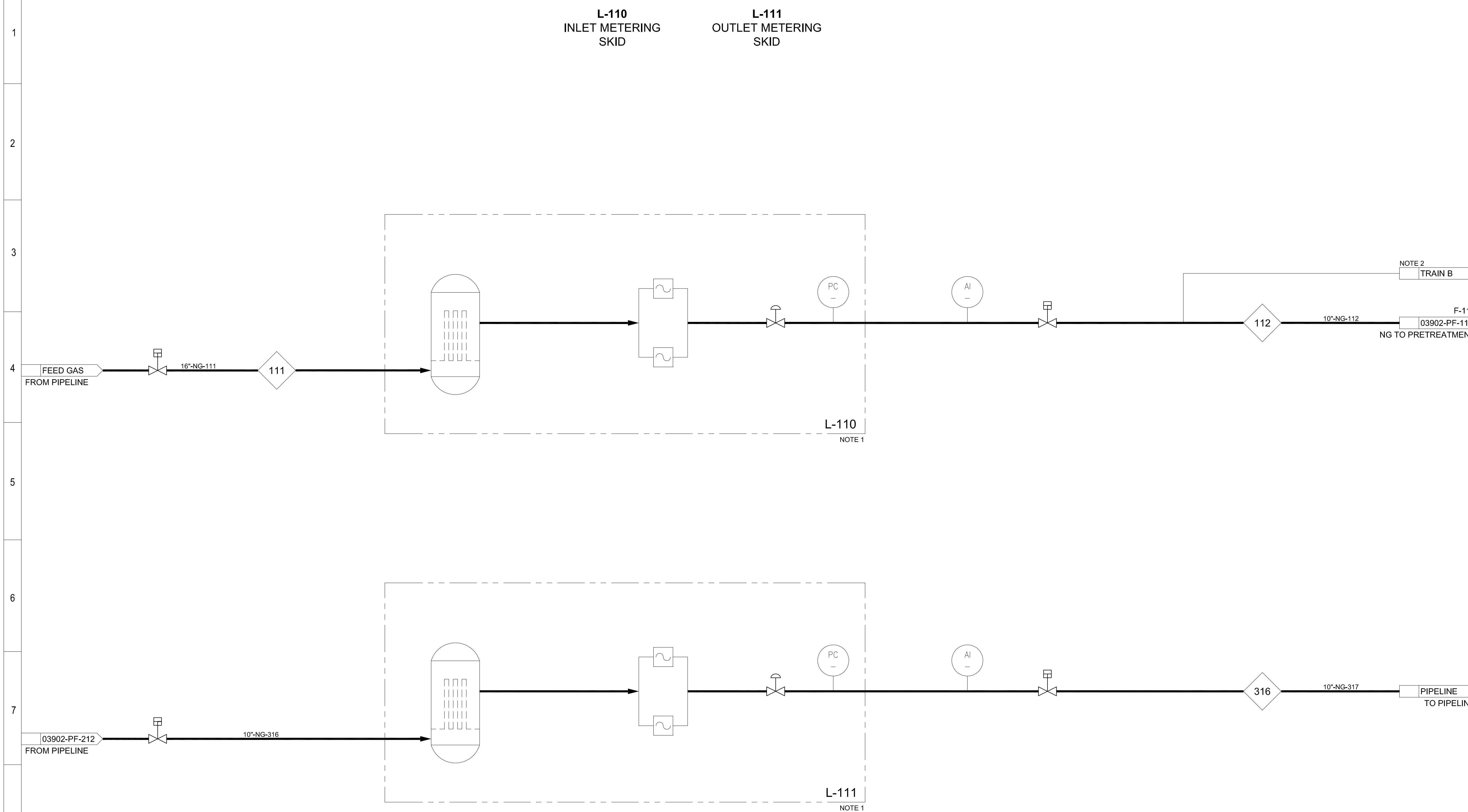
Appendix B – Process Flow Diagrams



NOTES

1. METERING SKID CONSISTS OF FILTER COALESCERS, FLOW METERS, AND CONTROL VALVES TO FEED THE FACILITY.
2. TRAIN B IS IDENTICAL TO TRAIN A AND IS NOT SHOWN IN THIS DESIGN.

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PROCESS FLOW DIAGRAM
LARGE SCALE FACILITY
INLET GAS

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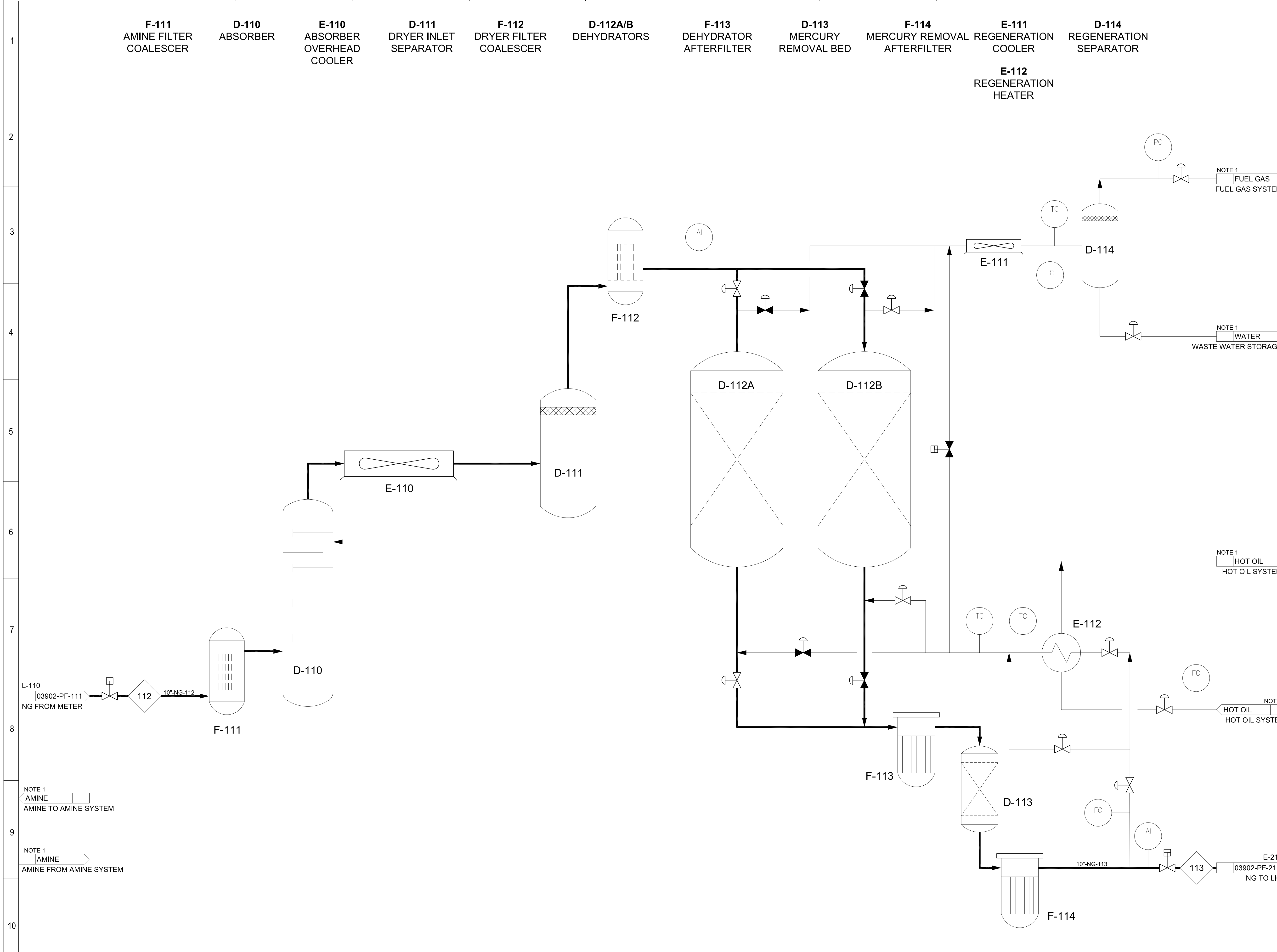

NOTES
1. FUEL GAS, WASTE WATER, HOT OIL, AND AMINE SYSTEMS TO BE DEVELOPED IN FEED.

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PROCESS FLOW DIAGRAM
LARGE SCALE FACILITY
PRETREATMENT

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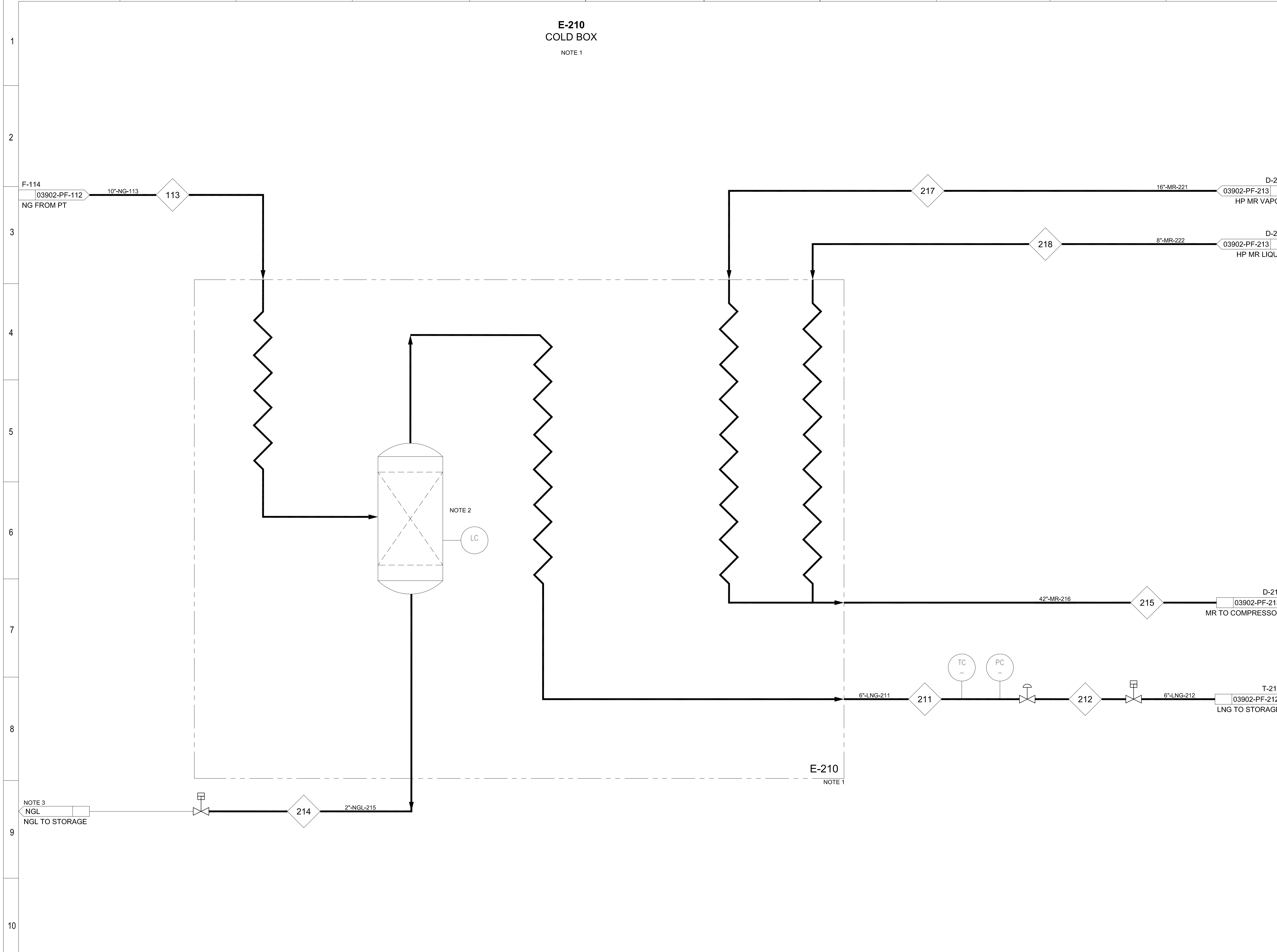
NOTES
1. COLD BOX TO CONSIST OF SEVERAL EXCHANGERS AND KNOCK OUT DRUMS. THESE ARE NOT SHOWN IN THIS DESIGN.
2. KNOCKOUT DRUM(S) WILL BE PRESENT INSIDE OF THE COLD BOX TO REMOVE NGL FROM THE NATURAL GAS STREAM.
3. NGL PROCESSING AND STORAGE SYSTEMS NOT INCLUDED IN THE DESIGN.



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LIQUEFACTION

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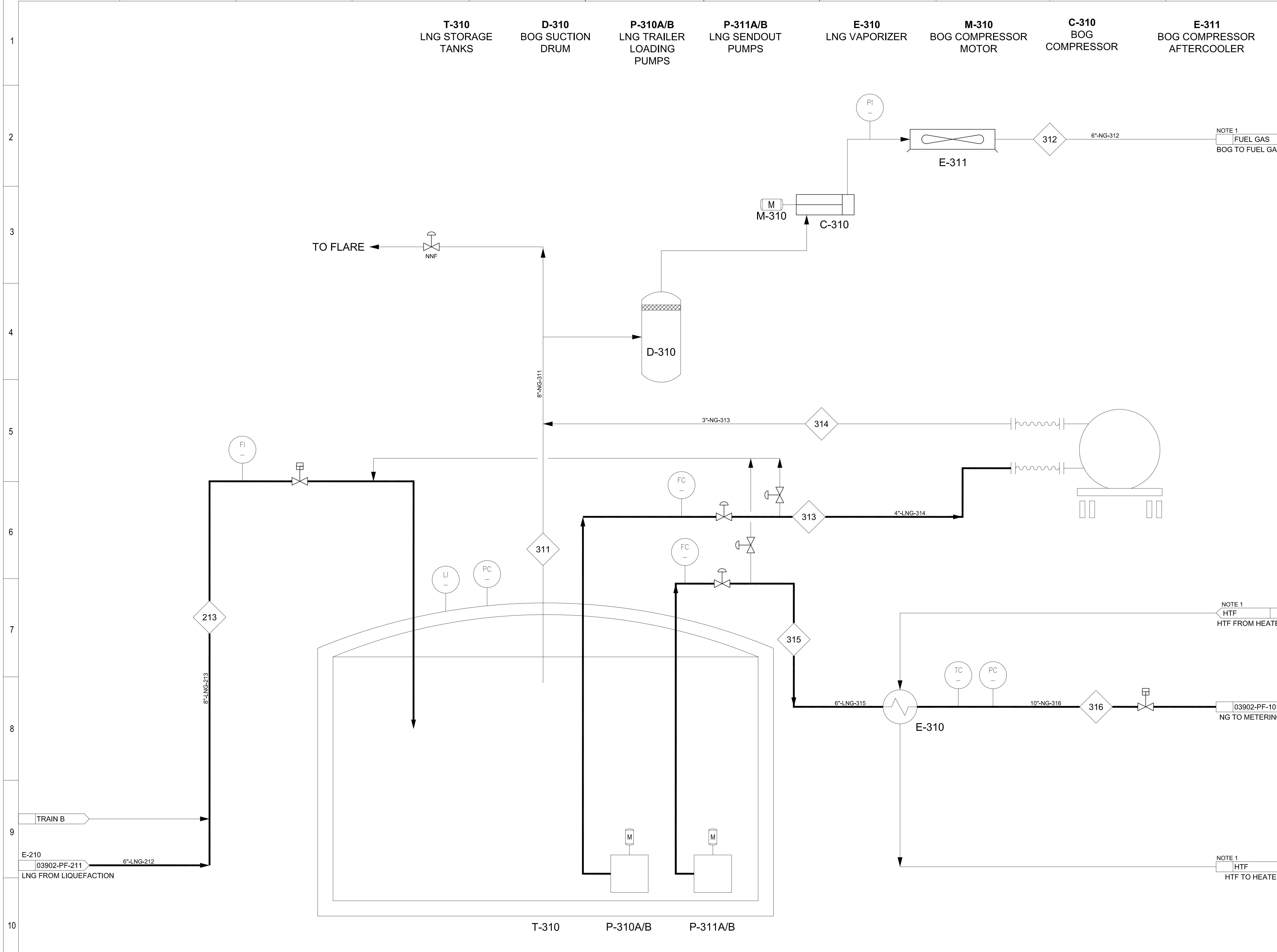

NOTES
1. HEAT TRANSFER FLUID AND FUEL GAS SYSTEM NOT INCLUDED IN THE DESIGN.

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BALANCE OF PLANT

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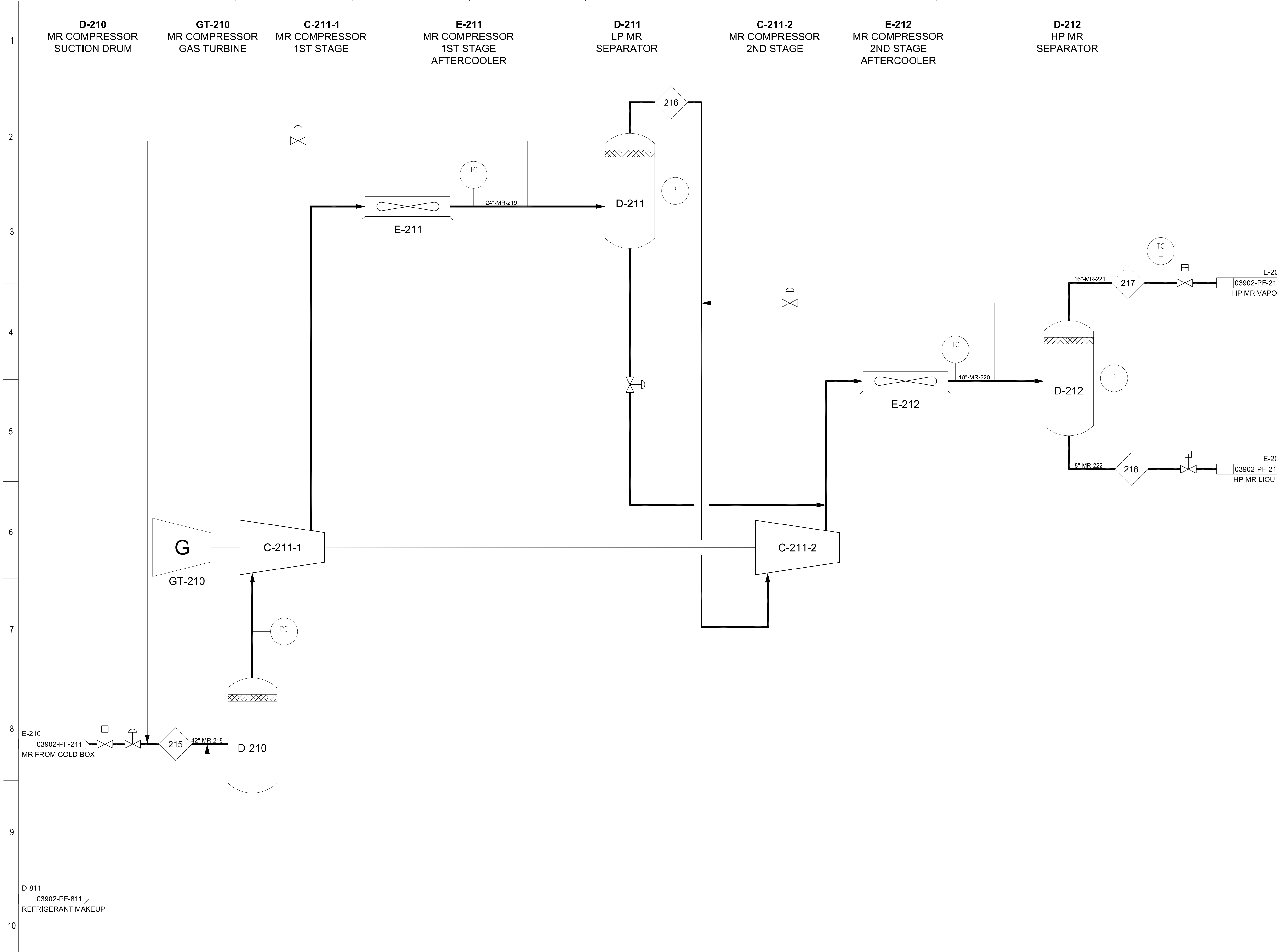


NOTES

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/16/21	ISSUED AS FINAL	JP	FG	BH	-

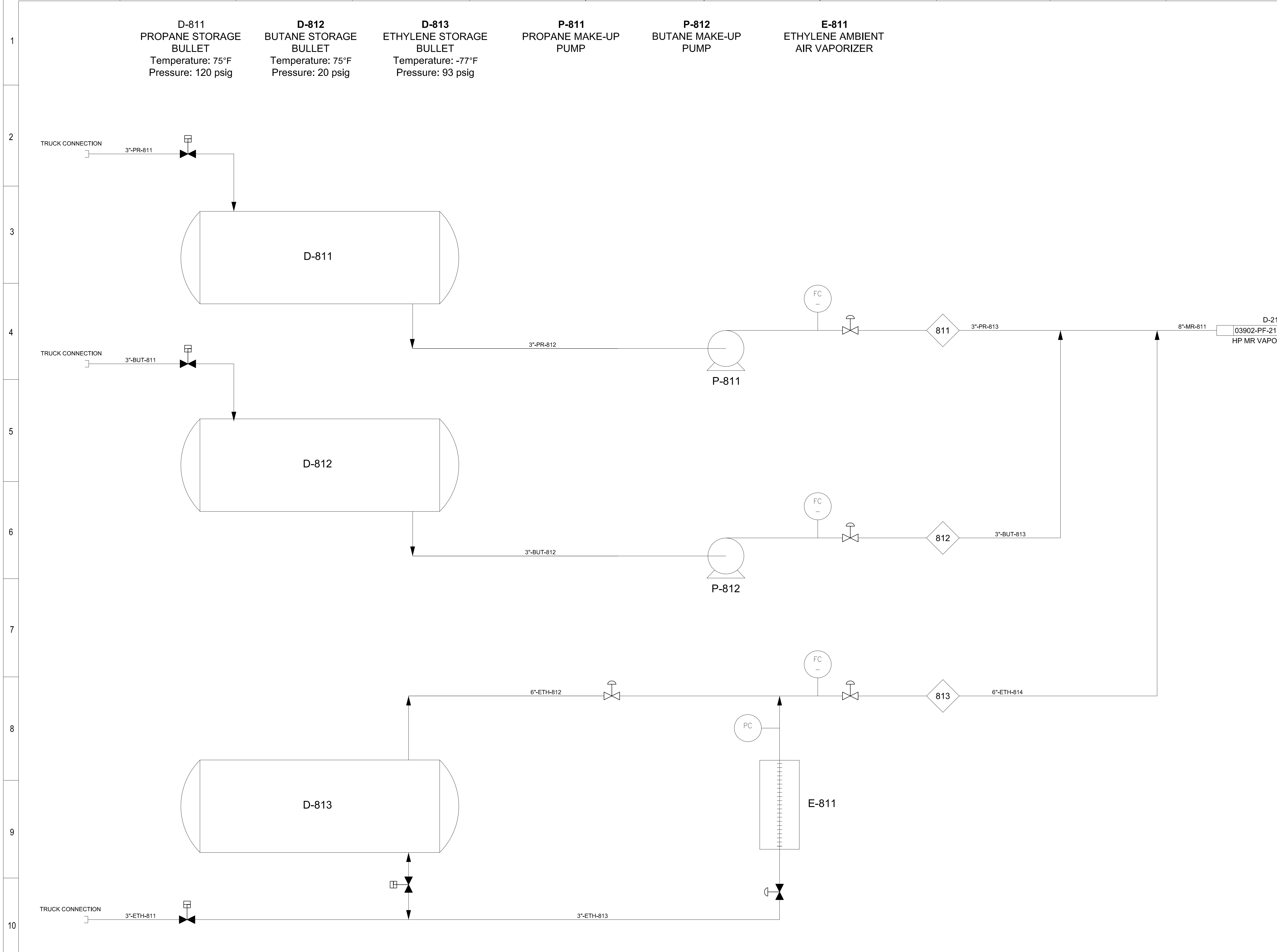
DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

BLUE®

PROCESS FLOW DIAGRAM
LARGE SCALE FACILITY
MIXED REFRIGERANT

BLUE

DOCUMENT NO.	SHEET	REV
03902-PF-213	1 OF 1	0



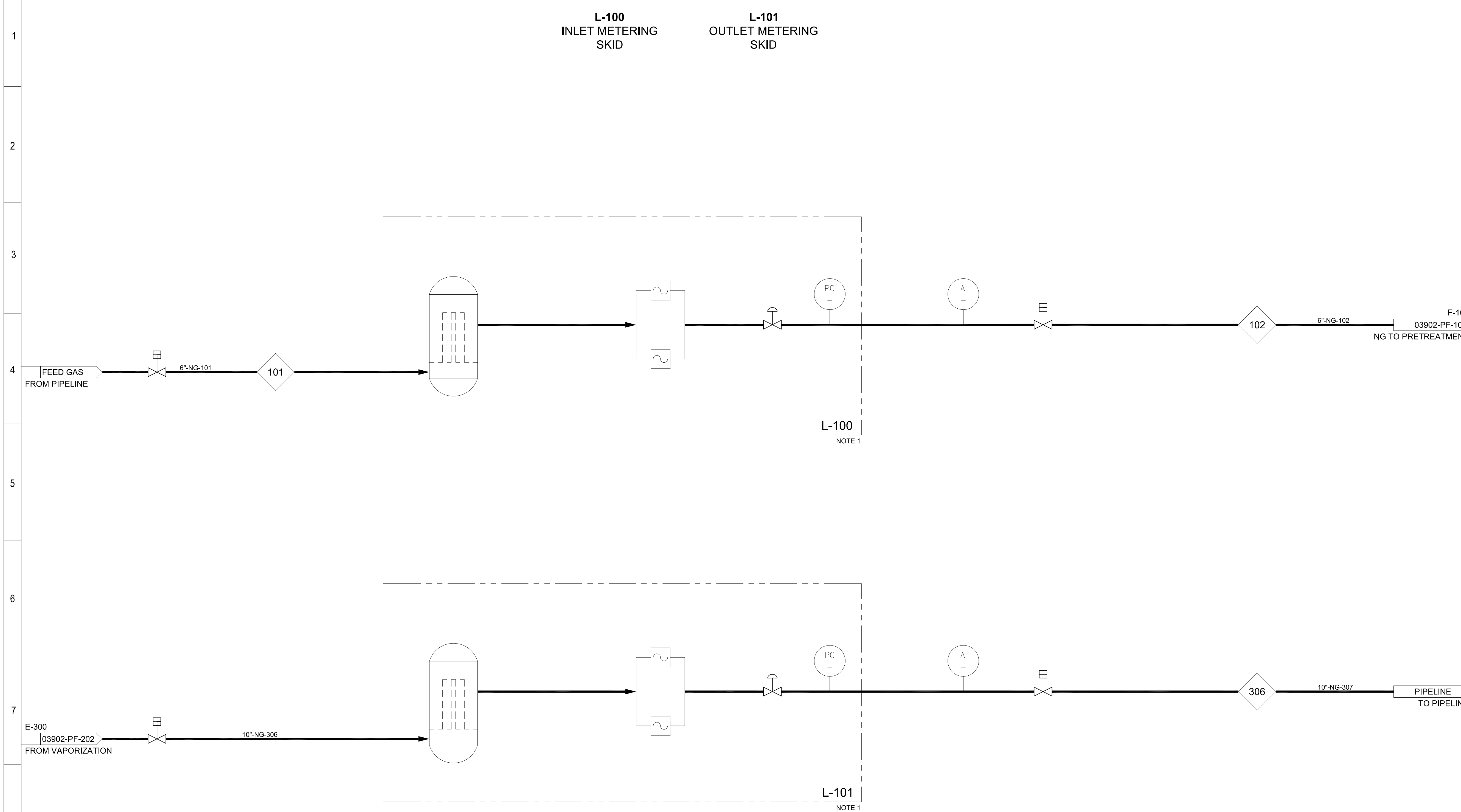
NOTES

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/16/21	ISSUED AS FINAL	JP	FG	BH	-

BLUE®

PROCESS FLOW DIAGRAM
LARGE SCALE FACILITY
REFRIGERANT STORAGE

DOCUMENT NO.	SHEET	REV
03902-PF-811	1 OF 1	0



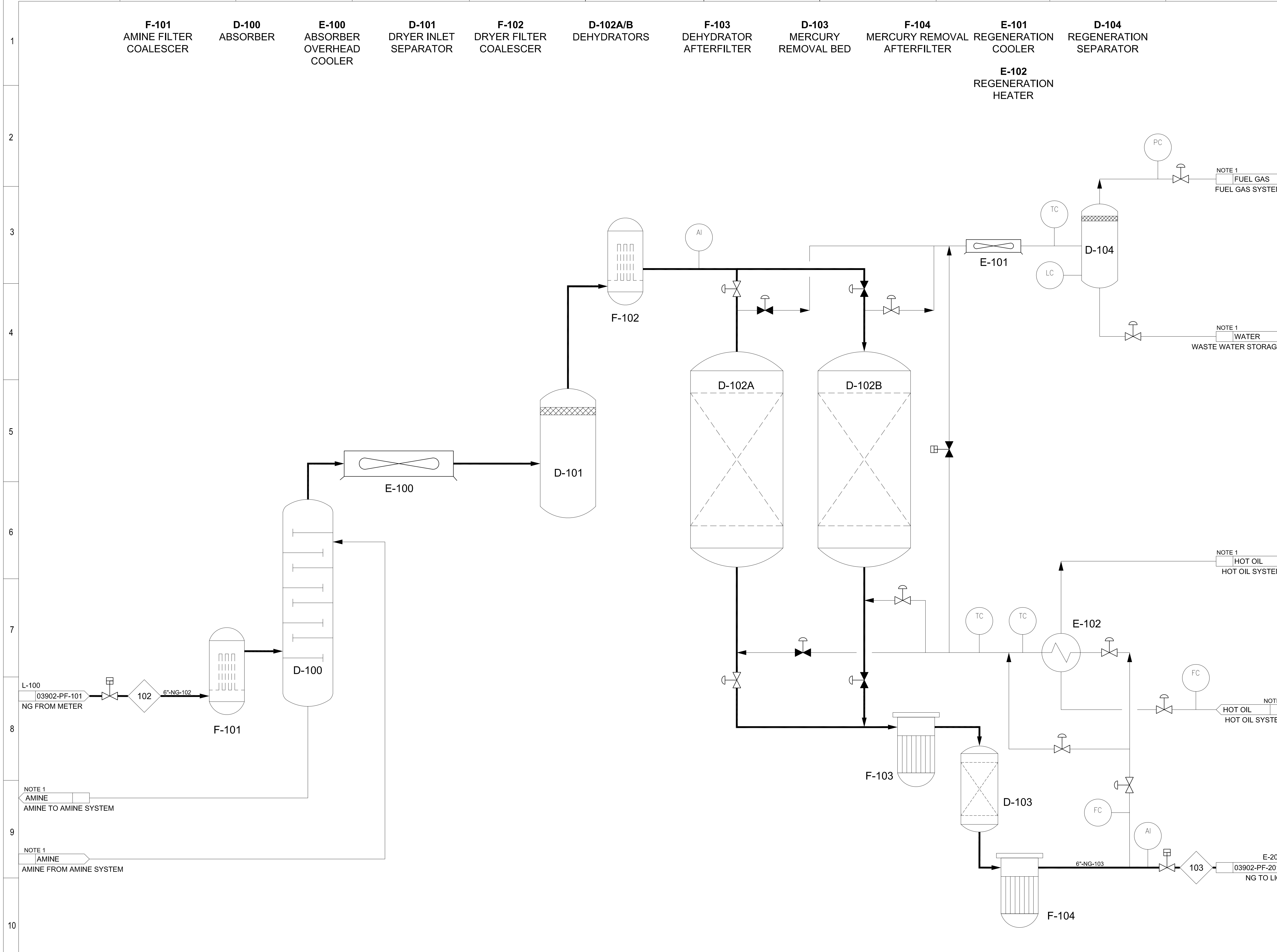
NOTES
1. METERING SKID CONSISTS OF FILTER COALESCERS, FLOW METERS, AND CONTROL VALVES TO FEED THE FACILITY.
2. TRAIN B IS IDENTICAL TO TRAIN A AND IS NOT SHOWN IN THIS DESIGN.

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/21/21	ISSUED AS FINAL	JP	FG	BH	-

BLUE®

PROCESS FLOW DIAGRAM
SMALL SCALE FACILITY
INLET GAS

DOCUMENT NO.	SHEET	REV
03902-PF-101	1 OF 1	0



NOTES
1. FUEL GAS, WASTE WATER, HOT OIL, AND AMINE SYSTEMS TO BE DEVELOPED IN FEED.

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/21/21	ISSUED AS FINAL	JP	FG	BH	-

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

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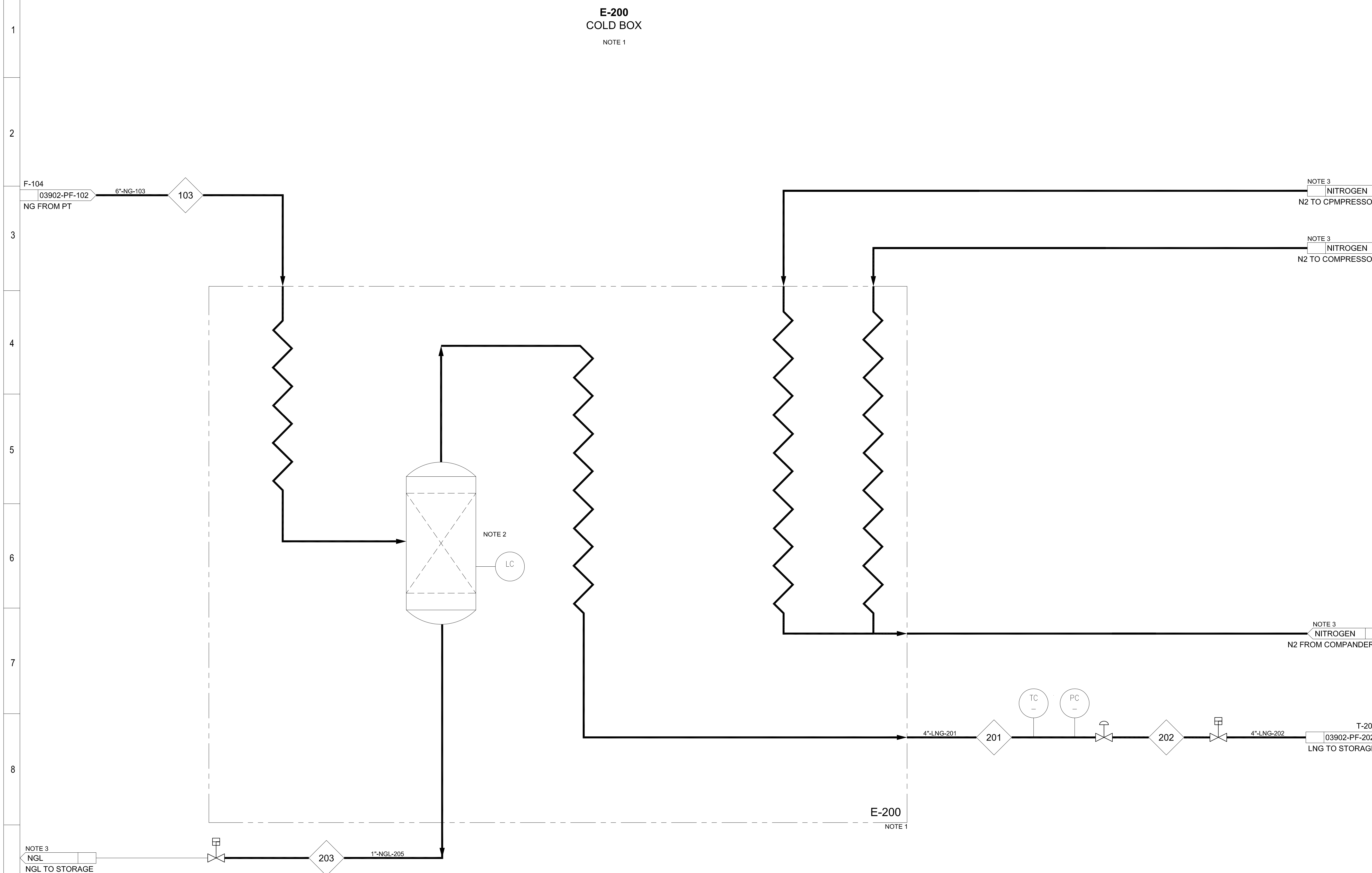
PROCESS FLOW DIAGRAM
SMALL SCALE FACILITY
PRETREATMENT

BLUE

DOCUMENT NO.	SHEET	REV
03902-PF-102	1 OF 1	0



NOTES

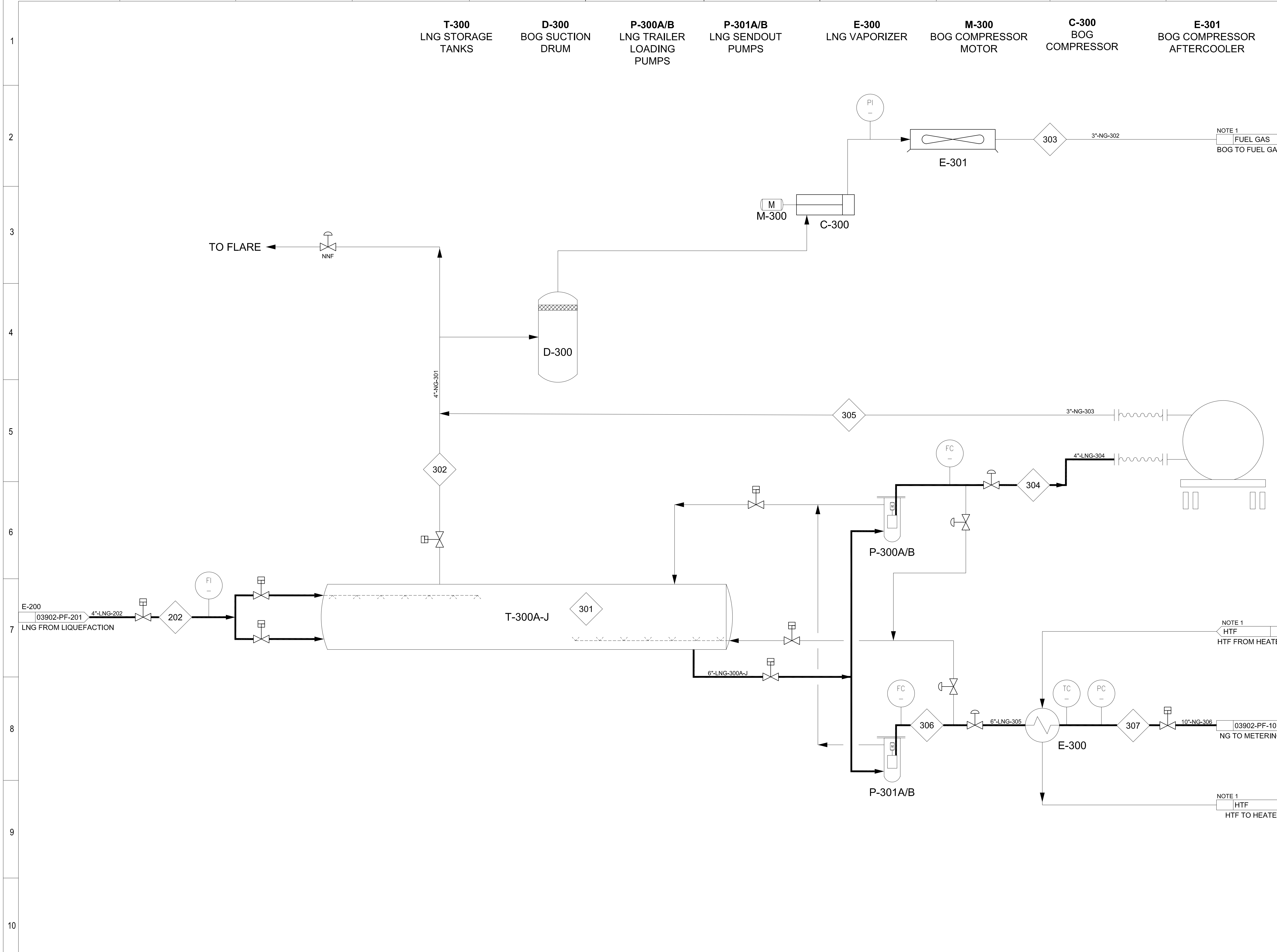
1. COLD BOX TO CONSIST OF SEVERAL EXCHANGERS AND KNOCK OUT DRUMS. THESE ARE NOT SHOWN IN THIS DESIGN.
2. KNOCKOUT DRUM(S) WILL BE PRESENT INSIDE OF THE COLD BOX TO REMOVE NGL FROM THE NATURAL GAS STREAM.
3. REFRIGERANT NITROGEN AND NGL PROCESSING AND STORAGE SYSTEMS NOT INCLUDED IN THE DESIGN.

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/21/21	ISSUED AS FINAL	JP	FG	BH	-

BLUE®

PROCESS FLOW DIAGRAM
SMALL SCALE FACILITY
LIQUEFACTION

BLUE		
03902-PF-201	1 OF 1	0
DOCUMENT NO.	SHEET	REV



NOTES
1. HEAT TRANSFER FLUID AND FUEL GAS SYSTEM NOT INCLUDED IN THE DESIGN.

REV	DATE	REVISION DESCRIPTION	BY	CHK	APP	CLIENT
0	7/21/21	ISSUED AS FINAL	JP	FG	BH	-

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

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PROCESS FLOW DIAGRAM
SMALL SCALE FACILITY
BALANCE OF PLANT

DOCUMENT NO.	SHEET	REV
03902-PF-202	1 OF 1	0

Appendix C – Heat and Material Balance Sheets

Revision:	B	Document No:	03902-PF-001
Date:	6/4/2020	Client:	DOT PHMSA
By:	JP	Project:	Gas Detector
Checked:	FG	HMB Case:	Large Scale
Approved:	BH		

BLUE

Heat and Material Balance

Public

Stream Number		111	112	113	211	212	213	214	215	216	217
Stream Name		Inlet Gas from Pipeline	Feed Gas to Pretreatment (Train A)	Clean Gas to Liquefaction (Train A)	LNG to J-T Valve (Train A)	Rundown to Header (Train A)	Rundown Header to Storage	Heavies to Storage (Train A)	MR to Compressor (1st Stage)	MR to Compressor (2nd Stage)	MR Vapor to Cold Box
Phase		V	V	V	L	L	L	L	V	V	V
Vapor Fraction		1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0
Total Mass Flow	lb/hr	318,000	159,000	131,970	131,178	131,178	261,565	792	802,700	802,700	637,249
Total Molar Flow	lbmol/hr	18,710	9,350	8,000	7,950	7,950	15,850	50	31,466	31,466	24,406
Temperature	°F	90	90	85	-255	-260	-260	-126.5	50	95	95
Pressure	psig	1,000	950	850	600	160	100	450	65	300	810
Molecular Weight	lb/lbmol	17.0	17.0	16.5	16.5	16.5	16.5	20.1	25.5	25.5	26.1
Specific Enthalpy	Btu/lb	-2,000	-2,000	-1,900	-2,300	-2,300	-2,300	-900	-1,300	-1,300	-1,400
Vapor											
Mass Flow	lb/hr	318,000	159,000	131,970	--	--	--	--	802,700	802,700	637,249
Molar Flow	lbmol/hr	18,710	9,350	8,000	--	--	--	--	31,466	31,466	24,406
Standard Gas Flow	MTPA	1.15	0.58	0.5	--	--	--	--	--	--	--
Actual Gas Flow	ft^3/hr	90,695	45,350	39,450	--	--	--	--	1,589,791	347,600	98,462
Molecular Weight	lb/lbmol	17.0	17.0	16.9	--	--	--	--	25.51	25.51	26.1
Mass Density	lb/ft^3	2.0	2.0	2.0	--	--	--	--	0.5	2.3	6.5
Mass Heat Capacity	Btu/lb-°F	0.6	0.6	0.6	--	--	--	--	0.4	0.5	0.75
Viscosity	cP	0.01	0.01	0.01	--	--	--	--	0.01	0.01	0.01
Thermal Conductivity	Btu/hr-ft-°F	0.02	0.02	0.02	--	--	--	--	0.02	0.02	0.01
Specific Enthalpy	Btu/lb	-2,000	-2,000	-1,900	--	--	--	--	-1,300	-1,300	-1,400
Liquid											
Mass Flow	lb/hr	--	--	--	131,178	131,178	261,565	792	--	--	--
Molar Flow	lbmol/hr	--	--	--	7,950	7,950	15,850	50	--	--	--
Actual Volume Flow	gal/day	--	--	--	691,632	691,632	2,074,896	7,072	--	--	--
Molecular Weight	lb/lbmol	--	--	--	16.5	16.5	16.5	18.2	--	--	--
Mass Density	lb/ft^3	--	--	--	26.6	27.2	27.2	20.1	--	--	--
Mass Heat Capacity	Btu/lb-°F	--	--	--	0.82	0.82	0.82	0.71	--	--	--
Viscosity	cP	--	--	--	0.11	0.11	0.11	0.08	--	--	--
Thermal Conductivity	Btu/hr-ft-°F	--	--	--	0.11	0.11	0.11	0.07	--	--	--
Specific Enthalpy	Btu/lb	--	--	--	-2,300	-2,300	-2,300	-900	--	--	--
Composition											
Methane	mol%	94.3	94.3	96.6	96.6	96.6	96.6	80.1	40.0	40.0	35.0
Ethane	mol%	4.0	4.0	2.7	2.7	2.7	2.7	13.2	0.0	0.0	0.0
Ethylene	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.0	35.0	40.0
Propane	mol%	0.5	0.5	0.3	0.3	0.3	0.3	1.8	5.0	5.0	5.0
Butane	mol%	0.1	0.1	0.0	0.0	0.0	0.0	4.2	5.0	5.0	5.0
Pentane	mol%	0.02	0.02	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Hexane	mol%	0.01	0.01	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Heptane+	mol%	0.01	0.01	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Benzene	mol%	0.001	0.001	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0
Toluene	mol%	0.001	0.001	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0
Xylene	mol%	0.001	0.001	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0
Hydrogen Sulfide	mol%	0.001	0.001	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0
Mercapton	mol%	0.001	0.001	0.0	0.0	0.0	0.0	0.01	0.0	0.0	0.0
Water	mol%	0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	mol%	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrogen	mol%	0.4	0.4	0.4	0.4	0.4	0.4	0.4	15.0	15.0	15.0
Total	mol%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Stream Number		218	311	312	313	314	315	316	811	812	813
Stream Name		MR Liquid to Cold Box	BOG to Compressor	BOG to Fuel Gas	LNG Truck Loading	Truck Vapor Return	LNG to Vaporizer	Natural Gas to Pipeline	Propane Makeup	Butane Makeup	Ethylene Makeup
Phase		L	V	V	L	V	L	V	L	L	V
Vapor Fraction		0.0	1.0	1.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0
Total Mass Flow	lb/hr	165,451	50,000	50,000	64,100	943	249,480	249,480	5,740	6,400	4,900
Total Molar Flow	lbmol/hr	3,934	3,050	3,050	3,880	60	15,120	15,120	130	110	174
Temperature	°F	95	-255	100	-260	-150	-260	60	75	75	-77
Pressure	psig	810	1.0	500	60	7	300	250	120	95	92
Molecular Weight	lb/lbmol	42.1	16.4	16.4	16.5	16.5	16.5	16.5	44.1	58.1	28.1
Specific Enthalpy	Btu/lb	-1,500	-1,700	-1,700	-2300	-1,700	-2300	-1,700	-2,000	-2,100	-1,800
Vapor											
Mass Flow	lb/hr	--	50,000	50,000	--	943	--	249,480	--	--	4,900
Molar Flow	lbmol/hr	--	3,050	3,050	--	60	--	15,120	--	--	174
Standard Gas Flow	MTPA	--	--	--	--	0.5	--	0.95	--	--	--
Actual Gas Flow	ft^3/hr	--	500,000	500,000	--	550	--	1,050	--	--	49,000
Molecular Weight	lb/lbmol	--	16.4	16.4	--	16.4	--	16.4	--	--	28.1
Mass Density	lb/ft^3	--	0.1	0.1	--	0.4	--	0.4	--	--	0.1
Mass Heat Capacity	Btu/lb-°F	--	0.5	0.5	--	0.5	--	0.5	--	--	0.4
Viscosity	cP	--	0.008	0.005	--	0.008	--	0.008	--	--	0.01
Thermal Conductivity	Btu/hr-ft-°F	--	0.01	0.01	--	0.01	--	0.01	--	--	0.01
Specific Enthalpy	Btu/lb	--	-1,700	-1,700	--	-1,700	--	-1,700	--	--	-1,800
Liquid											
Mass Flow	lb/hr	165,451	--	--	64,100	--	249,480	--	5,740	6,400	--
Molar Flow	lbmol/hr	3,934	--	--	3,880	--	15,120	--	130	110	--
Actual Volume Flow	gal/day	986,103	--	--	432,000	--	1,667,000	--	33,133	31,826	--
Molecular Weight	lb/lbmol	30.6	--	--	16.5	--	16.5	--	44.1	58.1	--
Mass Density	lb/ft^3	25.0	--	--	27.2	--	27.2	--	31.1	36.1	--
Mass Heat Capacity	Btu/lb-°F	0.75	--	--	0.82	--	0.82	--	0.4	0.6	--
Viscosity	cP	0.06	--	--	0.11	--	0.11	--	0.05	0.07	--
Thermal Conductivity	Btu/hr-ft-°F	0.05	--	--	0.11	--	0.11	--	0.05	0.05	--
Specific Enthalpy	Btu/lb	-1,500	--	--	-2,300	--	-2,300	--	-2000	-2100	--
Composition											
Methane	mol%	15.0	89.0	89.0	96.8	96.8	96.8	96.8	0.0	0.0	0.0
Ethane	mol%	0.0	0.0	0.0	2.8	2.8	2.8	2.8	0.0	0.0	0.0
Ethylene	mol%	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Propane	mol%	5.0	0.0	0.0	0.2	0.2	0.2	0.2	100.0	0.0	0.0
Butane	mol%	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Pentane	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hexane	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heptane+	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Benzene	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Toluene	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Xylene	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen Sulfide	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mercapton	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrogen	mol%	0.0	11.0	11.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0
Total	mol%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Revision:	A	Document No:	03902-PF-002
Date:	10/29/2020	Client:	DOT PHMSA
By:	JP	Project:	Gas Detector
Checked:	FG	HMB Case:	Small Scale
Approved:	BH		

Heat and Material Balance

Public

Stream Number		101	102	103	201	202	203	301	302	303	304	305	306	307
Stream Name		Inlet Gas from Pipeline	Feed Gas to Pretreatment	Clean Gas to Liquefaction	LNG to J-T Valve	Rundown to Storage	Heavies to Storage	LNG Storage Tank	BOG to Compressor	BOG to Fuel Gas	LNG Truck Loading	Truck Vapor Return	LNG to Vaporizer	Natural Gas to Pipeline
Phase		V	V	V	L	L	L	L	V	V	L	V	L	V
Vapor Fraction		1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0
Total Mass Flow	lb/hr	53,600	53,600	44,488	44,221	44,221	267	N/A	3,142	3,142	64,100	924	249,480	249,480
Total Molar Flow	lbmol/hr	3,150	3,150	2,700	2,680	2,680	20	N/A	190	190	3,880	60	15,120	15,120
Temperature	°F	90	90	85	-255	-260	-126.5	-256	-255	100	-260	-150	-260	60
Pressure	psig	400	370	350	325	160	250	60.0	20.0	500	60	7	400	350
Molecular Weight	lb/lbmol	17.0	17.0	16.5	16.5	16.5	20.1	16.5	16.4	16.4	16.5	16.5	16.5	16.5
Specific Enthalpy	Btu/lb	-2,000	-2,000	-1,900	-2,300	-2,300	-900	-2,300	-1,700	-1,700	-2300	-1,700	-2300	-1,700
Vapor														
Mass Flow	lb/hr	53,600	53,600	44,488	--	--	--	--	3,142	3,142	--	924	--	249,480
Molar Flow	lbmol/hr	3,150	3,150	2,700	--	--	--	--	190	190	--	60	--	15,120
Standard Gas Flow	MMSCFD	29	29	24	--	--	--	--	1.7	1.7	--	0.5	--	135
Actual Gas Flow	ft^3/hr	90,695	90,700	75,280	--	--	--	--	31,416	31,416	--	550	--	149,480
Molecular Weight	lb/lbmol	17.0	17.0	16.9	--	--	--	--	16.4	16.4	--	16.4	--	16.4
Mass Density	lb/ft^3	2.0	2.0	2.0	--	--	--	--	0.1	0.1	--	0.4	--	0.4
Mass Heat Capacity	Btu/lb-°F	0.6	0.6	0.6	--	--	--	--	0.5	0.5	--	0.5	--	0.5
Viscosity	cP	0.01	0.01	0.01	--	--	--	--	0.008	0.005	--	0.008	--	0.008
Thermal Conductivity	Btu/hr-ft-°F	0.02	0.02	0.02	--	--	--	--	0.01	0.01	--	0.01	--	0.01
Specific Enthalpy	Btu/lb	-2,000	-2,000	-1,900	--	--	--	--	-1,700	-1,700	--	-1,700	--	-1,700
Liquid														
Mass Flow	lb/hr	--	--	--	44,221	44,221	267	N/A	--	--	64,100	--	249,480	--
Molar Flow	lbmol/hr	--	--	--	2,680	2,680	20	N/A	--	--	3,880	--	15,120	--
Actual Volume Flow	gal/day	--	--	--	298,791	298,791	2,384	N/A	--	--	432,000	--	1,685,676	--
Molecular Weight	lb/lbmol	--	--	--	16.5	16.5	18.2	16.5	--	--	16.5	--	16.5	--
Mass Density	lb/ft^3	--	--	--	26.6	27.2	20.1	27.2	--	--	27.2	--	27.2	--
Mass Heat Capacity	Btu/lb-°F	--	--	--	0.82	0.82	0.71	0.82	--	--	0.82	--	0.82	--
Viscosity	cP	--	--	--	0.11	0.11	0.08	0.11	--	--	0.11	--	0.11	--
Thermal Conductivity	Btu/hr-ft-°F	--	--	--	0.11	0.11	0.07	0.11	--	--	0.11	--	0.11	--
Specific Enthalpy	Btu/lb	--	--	--	-2,300	-2,300	-900	-2,300	--	--	-2,300	--	-2,300	--
Composition														
Methane	mol%	94.3	94.3	96.6	96.6	96.6	80.1	96.6	89.0	89.0	96.8	96.8	96.8	96.8
Ethane	mol%	4.0	4.0	2.7	2.7	2.7	13.2	2.7	0.0	0.0	2.8	2.8	2.8	2.8
Ethylene	mol%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propane	mol%	0.5	0.5	0.3	0.3	0.3	1.8	0.3	0.0	0.0	0.2	0.2	0.2	0.2
Butane	mol%	0.1	0.1	0.0	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pentane	mol%	0.02	0.02	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hexane	mol%	0.01	0.01	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heptane+	mol%	0.01	0.01	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Benzene	mol%	0.001	0.001	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Toluene	mol%	0.001	0.001	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Xylene	mol%	0.001	0.001	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen Sulfide	mol%	0.001	0.001	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mercapton	mol%	0.001	0.001	0.0	0.0	0.0	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	mol%	0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	mol%	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrogen	mol%	0.4	0.4	0.4	0.4	0.4	0.4	0.4	11.0	11.0	0.2	0.2	0.2	0.2
Total	mol%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0