

Fire Risk Assessment of Gas Turbine Propulsion System for LNG Carriers

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Originally published in the Transactions of the WCOGI, Vol. 00, No. 00, (2007) and reprinted with the kind permission of the World Conference on Safety of Oil and Gas Industry (WCOGI)

Abstract

New and more efficient propulsion systems are being considered for LNG carriers. One of the proposed alternatives is a combination of a gas turbine with a heat recovery steam generator. This arrangement constitutes a novel approach which needs to be analyzed by a combination of engineering analysis and risk assessments to compensate for the lack of experience. Of specific concern is the high pressure fuel supply system. This paper describes the dispersion and fire analyses performed to better understand the risks involved in this arrangement and identify design improvements.

Keywords: LNG Carriers, Gas Turbine, Gas Compressors, Fire and Explosion, Risk Assessment

1. Introduction

1.1. Overview of LNG carriers

The volume of liquefied natural gas (LNG) is 600 times less than the same mass of natural gas at ambient conditions. Therefore, natural gas in the liquefied form is the most economical way for its transportation over long distances. The LNG carriers have been designed, constructed and equipped to carry cryogenic liquefied natural gas stored at a temperature of -163 °C at atmospheric pressure. If LNG leaks or spills, it may easily vaporize and create a gas/air mix within the flammable range which is approximately between 5 to 15 vol%.

Several design options for the propulsion systems and the cargo handling systems for LNG carriers have been and continue to be developed. The most important concern in the transportation of LNG is to maintain the structural integrity of the cargo containment system. Additionally, other concerns involve economic reasons to provide efficient LNG transportation. Innovations include increasing tank capacity, novel cargo handling systems such as boil-off gas (BOG) reliquefaction systems and more efficient propulsion systems such as dual fuel electric driven, diesel driven engines or gas turbine electric driven. Another important factor to consider is society's concerns regarding LNG transportation in coastal areas. The above issues stress the importance for LNG carriers to be adequately and safely designed for storing and handling their cryogenic cargo.

1.2. Gas turbine propulsion system for LNG carriers

The use of gas turbines has already been accepted by several industries as a prime mover of compressors and power generation systems. Recently, gas turbines have been considered for use in an alternative propulsion system for LNG carriers. Ship owners, manufacturers, shipbuilders and classification societies have been conducting analyses for the potential implementation of gas turbine propulsion systems in the future generation of LNG carriers.

Small and lightweight gas turbines can be located at main deck level in order to minimize space taken in the

engine room. The power station consists of one or two gas turbines and one steam turbine generator set. In order to maximize heat efficiency, the gas turbines are complemented by a heat recovery system in the exhaust. The gas turbines and steam turbine form a combined gas turbine and electric steam system (COGES) that is designed to power the ship for all sea-going operations. However, the power consumption varies during each operational mode of the LNG carrier, and the power generation system shall adjust its output accordingly. For convenience, an auxiliary smaller gas turbine and diesel generator set are installed to cope with low load demand conditions. The system incorporates a conventional gas combustion unit (GCU). The GCU provides an alternative cargo tank protection system when the boil-off gas could not successfully be consumed by the COGES. The GCU is normally designed to dispose of 100% normal boil-off gas.

The gas fuel supply system is to be equipped with two screw type compressors (each 100% duty, one in operation and one on standby) for boosting the supply gas pressure. The gas fuel supply system provides the fuel to the ship's main generators in a quantity sufficient to power the ship at maximum continuous rate (MCR) yet maintaining the cargo tank pressure within safe limits. When the boil-off gas is not enough to supply for MCR, the forcing vaporizing system will provide the required additional fuel from the LNG cargo tanks.

An emergency gas line directly connects to the GCU and the heat recovery steam generator (HRSG) burners to ensure safe disposal of gas in emergency conditions. This line does not need compression or subsequent pressure reduction valves.

Although the gas turbine propulsion system has a lot of advantages, there is no operating experience of this type of technology and it is considered a novel approach for ship propulsion. Consequently, there are not many established statutory and classification requirements and its approval for design, construction and operation requires a proactive approach using engineering analysis and risk assessment techniques, as delineated, for example, in the Guidance Notes for the Review and Approval of Novel Concepts [1].

1.3. Objectives of study

This paper describes the risk assessments performed within the context of review and approval of a novel concept. The study specifically focused on the analysis of different gas turbine propulsion designs in order to understand the risk posed by different design options and identify the most significant contributors to risk, to propose risk reducing recommendations that will improve the proposed designs.

The main objectives of the study were:

- To identify potential gas release scenarios by conducting a hazard identification (HAZID) that focused on the novel features of the gas turbine propulsion system
- Create a 3D CFD model of the design arrangement
- Perform a CFD dispersion modeling of the most credible and representative release scenarios evaluating different environmental conditions.
- Perform explosion modeling, and quantify the consequences of postulated fires using Gaussian model methods.
- Identify risk control options based on the project results, to further reduce risks.

2. Hazards of gas turbine propulsion

Hazard identification (HAZID) is a high level qualitative risk assessment technique, with the purpose of understanding the risks and qualitatively estimating them. A combined team of shipyard, class society and equipment manufacturer personnel conducted a HAZID study on a gas turbine propulsion system. This HAZID focused on the identification of potential hazards and risks associated with the novel features of the gas turbine propulsion system.

The scope of the HAZID analysis was defined by the systems to be evaluated, the list of hazards of concern, and the modes of operation that were to be addressed. The complete list of systems, hazards and modes of operations considered in the HAZID is provided below.

Systems to be evaluated:

- Gas compression and treatment system
- LNG forcing vaporizer
- Gas supply system
- Liquid fuel system
- Gas turbine combustion air system
- Gas combustion unit
- Pipe route from compressor to valve room
- Heat recovery steam generator
- Gas turbine
- Electric generator
- Control and monitoring
- Ship interface items, vent and relief system

Hazards of concern:

- Gas leakage / Loss of containment
- Explosion / Fire
- Loss of propulsion
- Overpressure / Under pressure / Overfilling of cargo tanks

Modes of operation:

- Cargo loading and offloading
- Laden voyage
- Ballasted voyage
- Canal passing
- Gas freeing and gassing up
- Cargo loading and unloading
- Idling at harbor

As the analysis was carried out, it turned out most of the novel issues associated with the design where in the gas supply system, and had to do with gas leakage in various modes of operation. All other systems / hazards / modes of operations where analyzed, but no novel issues were found in relation to unmitigated hazards.

As a result of the HAZID, gas leaks in the compressor room and turbine room from the high pressure fuel supply system were identified as the main hazards in the design which deserved further analysis. Otherwise, no other special safety requirements were identified compared to conventional dual fuel LNG carriers. The following sections in this paper will describe the dispersion, explosions and fire consequence analysis performed to further understand the risks involved in this type of design arrangement.

3. Dispersion and fire study

3.1. System boundary

The screw type compressor in the compressor room pressurizes natural or forced boil-off gas from the cargo tank for use in the gas turbines that provide ship propulsion. The compressor room is located on the main deck near the aft of the vessel on the starboard side as shown in Figure 1.

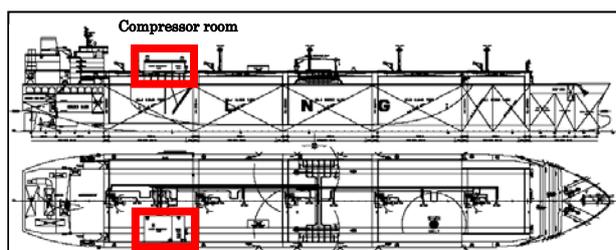


Figure 1. Compressor Room Location

The motors and compressors are separated by the bulkhead. The overall compressor room dimensions are shown in Figure 2. The approximate volume of the compressor room is estimated 1244 m³. Venting of the compressor room involved one air intake and two air exhaust fans, all located in the roof. Normal operation involved the use of one air exhaust fan, and provided approximately 30 air changes per hour. Other than the vents, no other opening, such as the door of the compressor room, were included.

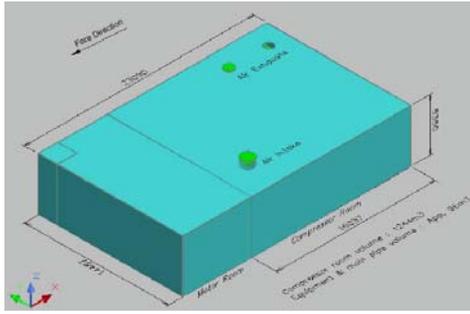


Figure 2. Compressor Room Dimensions

3.2. Methodology

The Flame Acceleration Simulator [2] (FLACS) computational fluid dynamics (CFD) computer code was used in the dispersion and explosion analyses. The FLACS code specializes in the solution of fluid dispersion and combustion problems of the type typically encountered in the oil and gas process industries. Development work on the FLACS code has been underway since the early 1980’s, primarily in response to explosions in offshore production platforms. The capabilities in FLACS include calculating the dispersion of a flammable gas due to a leak or evaporating pool of flammable substance. The dispersion calculations solve the Navier-Stokes equations for fluid flow, along with the k-ε turbulence model. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) pressure correction method is used to solve the coupled set of equations. Hjertager [3] describes the basic equations used in the FLACS model. A simplification of the resulting dispersions was made to allow for faster explosion simulations. This was the use of an equivalent stoichiometric vapor cloud. This equivalent cloud volume was calculated by FLACS taking into account considerations such as inhomogeneous mixtures and expected flame speed. This was a valid simplification, endorsed by GexCon, the company producing FLACS.

The fire analysis used the computer code Fire, Release, Explosion and Dispersion (FRED) [4]. FRED belongs to a family of analytically based computer codes called Gaussian codes that are accepted by industry for evaluating fire effects.

3.3. Dispersion study

The analyses were performed for postulated leaks inside the gas compressor room that fed high pressure natural gas to the gas turbines. The analyses determined possible consequences for fire and explosion events, and looked at the effects of mitigation technologies such as ventilation fans, emergency shut down (ESD) systems, gas detection, etc.

The leak used in the study was located near the air intake around the compressor. Both upward (+Z) and downward (-Z) leak direction were modeled. Three different leak sizes were modeled, including ¼-inch,

½-inch and 1 inch diameter leaks. Leak conditions modeled 40 bar line pressure, and a natural gas temperature of 90°C. A summary of the leaks modeled is shown in Table 1. The mass flow rates of the leaks were calculated by the LEAK utility within FLACS.

Table 1. Leak Parameters and Mass Flow Rates

Leak size, inch	Mass flow, kg/sec
1/4	0.17
1/2	0.70
1	2.80

Current IGC code require gas detection and audible and visual alarms be provided for the gas compressor room and the gas detection equipment be capable of sampling and analyzing for each sampling head location sequentially at intervals not exceeding 30 minutes [5]. While this sampling requirement may be sufficient for leaks from lower pressure systems, the dispersion results show it is insufficient to limit the size of vapor clouds produced by leaks from higher pressure systems. Thus, this study also considered continuous gas sampling to obtain a fast response to a high pressure gas leak. The compressor room has two gas sampling locations. The gas samplers transport flammable gas to detectors located outside the compressor room. The time for flammable gas to reach the sampling points varies slightly, but in general was approximately 3 seconds after the leak began. Once flammables were located around the gas samplers, an additional 50 seconds was assumed for transport to the detectors. An optimized ESD system was also modeled that placed the detectors inside the compressor room, which would result in immediate gas detection. After detection, an additional 5 seconds was assumed to activate the ESD valves. Detection and activation occur when a concentration above 60% of the lower flammable limit (LFL) is present. ESD valve activation isolates the natural gas lines and shut down the compressors. The downstream isolated volume was calculated based on the line lengths and diameters until the master gas valve. The resulting mass of isolated flammable gas after ESD activation was 10.5 kg. Table 2 shows the necessary blowdown times for various leak sizes as well as the total leak times for both the existing system.

Table 2. Blowdown and Total Leak Times

Leak size, inch	Blowdown, sec	Time to leak end, sec (time to sample port + time to detectors + ESD actuation + blowdown time)	
		Existing ESD	Optimized ESD
1/4	62	120	70
1/2	15	73	23
1	4	62	12

The primary result of interest was the equivalent stoichiometric flammable volume in the room as a function of time. This equivalent stoichiometric flammable volume, which FLACS calls the Q9 volume, is a stoichiometric gas volume that corresponds to the flammable volume inside the compressor room after congestion levels and heterogeneous mixtures are taken into account. This Q9 volume ranges from quite small for the ¼-inch leaks to a significant portion of the room volume for the larger leaks.

Leak sizes of ¼-inch were shown to have no chance of forming a significant vapor cloud. In general, the maximum Q9 flammable volume for the ¼-inch leaks was less than a few cubic meters.

Leak sizes of ½-inch were shown to have a maximum flammable volume of 307 m³ for a case with existing ESD and a single exhaust fan. The use of two exhaust fans reduced this volume by 25% to 230 m³. The optimized ESD system significantly reduces the duration of the leak due to instantaneous detection once flammables are present. This results in a maximum flammable volume of between 10 and 11 m³.

Leak sizes of 1 inch were shown to have a maximum flammable volume of 766 m³ for a case with existing ESD and two exhaust fans. The use of two exhaust fans increased the flammable volume slightly (approximately 4%) for the 1 inch release compared to the single fan case by introducing more air into a fuel rich room. Again, the optimized ESD system significantly reduced the maximum flammable volume, down by 82%.

Figure 3 and 4 shows the flammable concentration contours in the compressor room.

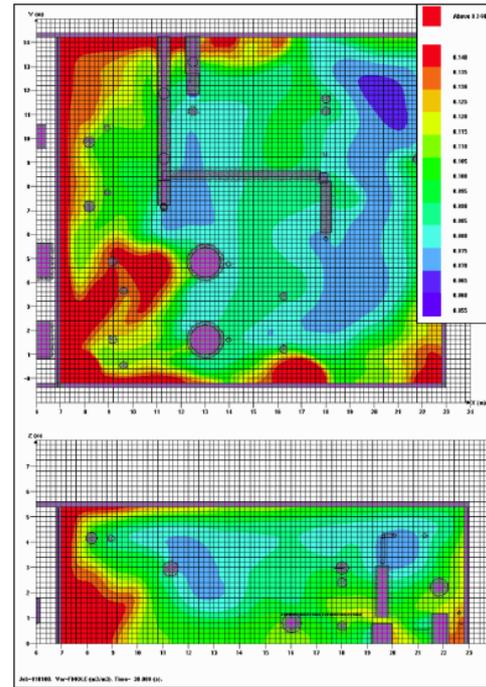


Figure 4. Flammable Concentration Contour for 1 inch Leak Size, at Z = 3 (Top) and Y = 8 (Bottom)

In most cases, the maximum flammable volume was reached right before the leak terminated. After the leak stopped, the flammable volume would decrease quickly as the ventilation diluted the gas. This was not the case for the 1 inch, +Z direction, existing ESD, 40 bar simulations. In these cases, by the time the leak stops (approximately 62 seconds), the room has become exceedingly rich with fuel, and flammable volume had previously peaked around 30 seconds and is now back to a small flammable volume due to insufficient air in the room. The continued ventilation after the leak has stopped serves to increase the air in the room and produces a second peak flammable volume at about 220 seconds. This effectively produces two time periods for worst-case explosion potential, with a period in-between when the room is essentially too fuel rich to explode. For the 1 inch, -Z direction, existing ESD, 40 bar simulations shows the second flammable volume peak at about 220 seconds was seen to be larger than the first peak at about 30 seconds. In all cases, the second peak did not exceed 115% of the first peak, and was reached within 160-180 seconds after the leak stops when one fan is present and 120 seconds after the leak stops when two fans are present.

3.4. Fire study

The fire study evaluated ¼, ½ and 1 inch leaks from inside the compressor room. The effects of an explosion, such as having a wall release and vent, were not included in this analysis. Jet fires outside the compressor room were modeled as unobstructed leaks from the exhaust fan on top of the compressor room. Leaks too small to result in a jet fire outside the compressor room were modeled as unobstructed outdoor releases since fire modeling

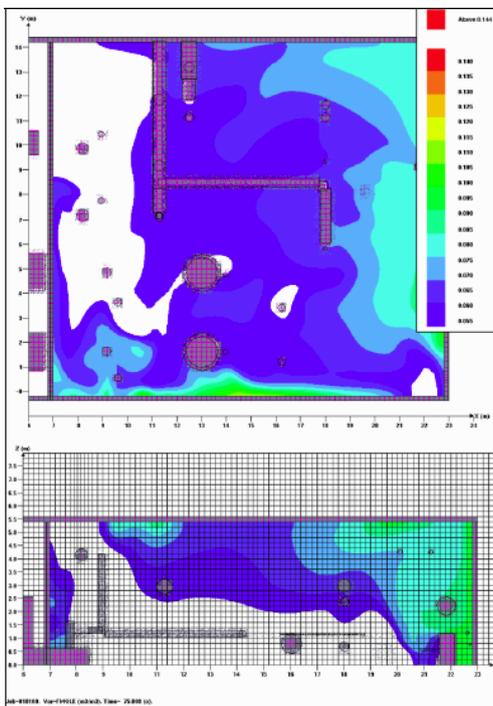


Figure 3. Flammable Concentration Contour for ½-inch Leak Size, at Z = 3 (Top) and Y = 8 (Bottom)

software could not model jet fires inside the compressor room. The 1/4-inch leak would not result in a jet fire outside the compressor room due to their low release rate. These leaks were modeled as a jet from a 1/4-inch hole in the natural gas pipe at a height of 3 feet with a 12 mph wind at 93°F. A side view of the radiant heat contours for the 40 bar releases are shown in Figure 5. The lower bound for equipment damage was defined to occur at radiation levels of 37.5 kW/m². These result shows equipment damage more than a few feet from the release would not likely occur.

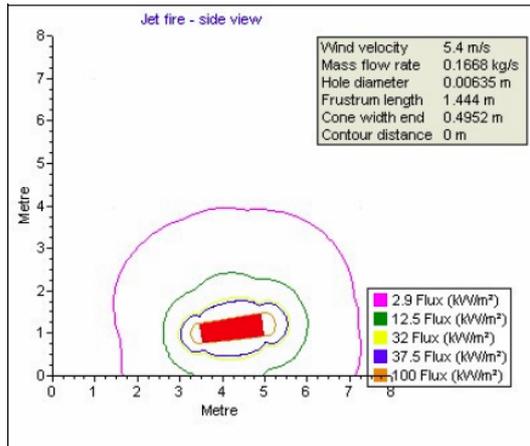


Figure 5. Side View of 1/4-inch Leak Jet Fire at 40 bar

If the flash fire from the 40 bar 1/2-inch release did not burn back to the release point and originated at the exhaust vent, the radiant heat contours at the height (8 meters) that resulted in maximum radiant heat predictions are shown in Figure 6. These show that while equipment on the roof of the compressor room would be at risk for damage, piping entering the compressor room would be damaged only if they were elevated.

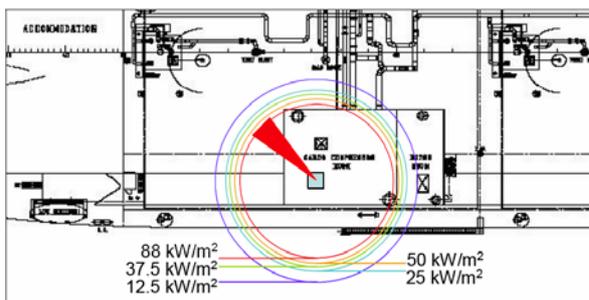


Figure 6. Plan Contours for 1/2-inch Leak at 40 bar (8m height)

Equilibrium steel temperatures were predicted for the 1/2-inch leak at 40 bar and are shown in Figure 7 Applying the screening methodology in API RP 2FB, the minimum acceptable standoffs from the jet fire was 11 m for the 40 bar leak. This indicates the accommodation block would be safe from radiant heat damage.

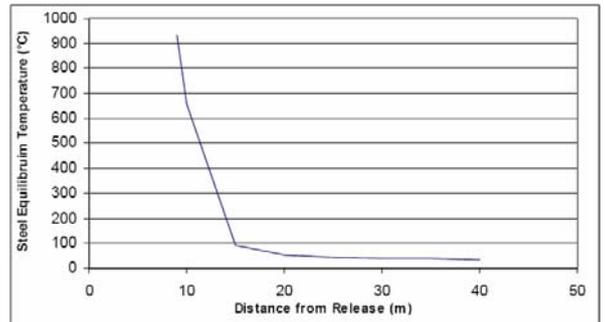


Figure 7. Equilibrium Steel temperatures for 1/2-inch Leak at 40 bar

Radiant heat contours for the 1 inch releases at the heights resulting in maximum radiant heat predictions are also investigated. These damaging radiant heat contours extending past the compressor room, but do not reach significant areas such as the accommodation block.

4. Conclusion

The dispersion study shows the best option is to move the gas detectors from outside the compressor room to inside the room, eliminating the 50 second delay needed for detection with the current system. This change reduces the maximum flammable cloud more than 95% for 1/2-inch leaks and more than 80% for 1 inch leaks. Finally, while a second ventilation fan may have some benefit for leaks 1/2-inch or smaller, there is no benefit for larger leaks as a second fan still results in insufficient air flow to adequately disperse the gas. An evaluation was not performed to determine how much increased airflow was needed to prove beneficial.

Conclusions from the fire study are that equipment outside the compressor room would not be at serious risk of heat damage for the 1/2- and 1 inch releases at 40 bar pressure unless the equipment were on the roof of the compressor room or near the compressor room and elevated. The 1/4-inch releases were found to only affect equipment inside the compressor room within a few feet of the release. All equipment inside the compressor room would be at risk of fire damage from the 1/2- and 1 inch releases. The accommodation block was not found at risk of fire damage from any of these scenarios. Additionally, results were not affected by the number of exhaust fans.

Acknowledgment

“This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD)” (KRF- 2005-213-D00026).

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