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Validation of Recommended Emergency Actions for Liquefied Natural Gas (LNG) in the *Emergency Response Guidebook* (ERG)

This report describes research that was completed by the Fire Protection Research Foundation under contract with Transport Canada.

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Research Summary

Synopsis

This research evaluated the recommended emergency actions for liquefied natural gas (LNG) included in the 2020 edition of the ERG. Scientific and emergency response-related literature was reviewed, as well as reports from previous incidents involving LNG. The analysis considered the physical and chemical properties, means of containment, potential hazards, emergency response procedures, and available guidelines for LNG, as compared to those for liquefied petroleum gases (LPG). Research results indicated that, with some amendments, ERG Guide 115 can capture the hazards associated with LNG, and there is no need to create a new separate ERG guide for LNG at this time.

Background

LNG consists primarily of methane in a mixture with small amounts of other hydrocarbons. There has been increased use of LNG as a fuel source in recent years, and there is potential for further increase in the transport of LNG by rail and road. Therefore, it is of interest to ensure that the emergency actions recommended for LNG in the ERG are appropriate.

Dangerous goods with similar physical and chemical properties are assigned to the same guide number in the ERG because they share similar emergency response recommendations. LNG is currently assigned to Guide 115, along with other flammable gases including LPG. Therefore, the recommended emergency actions currently in the ERG are almost the same for LNG and LPG. However, there are some significant differences in the properties of LNG and LPG, as well their means of containment, that may alter their hazard profile if an incident occurs. For example, LNG is transported as a gas liquefied by cooling at cryogenic temperature, whereas LPG is transported as a gas liquefied under pressure.

Objectives

The objective of this research was to determine if the hazards of LNG and LPG differ significantly enough to warrant the establishment of new guidance for LNG in the ERG.

Methods

Scientific literature and emergency response reports were reviewed. Information on the various means of containment and the physical and chemical properties of LNG and LPG were gathered. Using all of this information, the hazards that each of the dangerous goods would present in a potential incident were compiled. The recommended emergency actions for LNG currently in the ERG were then considered to identify any gaps. From all of the data gathered, a determination was made as to whether LNG should remain in Guide 115 of the ERG, be assigned to a different ERG guide, or be placed in a new separate ERG guide.

Results

The analysis resulted in the following recommended amendments to various sections of Guide 115, to ensure that appropriate considerations for LNG are included. Each recommended amendment was discussed by Transport Canada and the other partner organizations (i.e., the U.S. Department of Transportation, *Secretaría de Infraestructura, Comunicaciones y Transportes* (SICT) of Mexico, and the *Centro de Informaciòn Quìmica para Emergencias* (CIQUIME) of Argentina) who develop the ERG together. The agreed wording to be included in the next 2024 edition of the ERG is shown below.

<u>In the section, “POTENTIAL HAZARDS – FIRE OR EXPLOSION”:</u>
Guide 115 currently does not address the rapid phase transition (RPT) phenomena that LNG may experience when in contact with water.

- Proposed addition: "*When an LNG release is on or near water, exercise caution as rapid phase transitions may occur from the liquid to vapor phase with an associated rapid pressure increase.*"
- Accepted addition: "***CAUTION: When LNG – Liquefied natural gas (UN1972) is released on or near water, product may vaporize explosively.***"
- The ERG partner organizations agreed to this accepted addition to have a concise statement for ease of readability during an incident. Rather than mentioning the RPT phenomenon directly, the potential hazard is highlighted.

In the section, "POTENTIAL HAZARDS – HEALTH":
Inhalation issues are more applicable in closed or confined areas versus in open air.

- Original statement: "*Vapors may cause dizziness or asphyxiation without warning.*"
- Proposed and accepted modification: "*Vapors may cause dizziness or asphyxiation without warning, **especially when in closed or confined areas**.*"
- This amendment will also be made in other ERG guides containing the same original text, including Guides 116, 120, 122, 126, 127, 128, 129, 130, 131, 132, 160, and 174.

Incorporate "cryogenic liquid", which is not currently mentioned in the Guide 115 statement regarding contact hazards.

- Original statement: "*Contact with gas or liquefied gas may cause burns, severe injury and/or frostbite.*"
- Proposed and accepted modification: "*Contact with gas, liquefied gas, **or cryogenic liquid** may cause burns, severe injury, and/or frostbite.*"
- This amendment will also be made in other ERG guides to which other cryogenic liquids are assigned, including Guides 120, 122, and 168.

In the section, "EMERGENCY RESPONSE – FIRE":
Under "Fire Involving Tanks", the researchers suggested that the second and third bullet points should be combined into one bullet point, so that the user reads them together for context, as pressure relief devices could be affected by icing. This is not a technical issue, but rather a human factors issue.

- Original statements:
    - *"Cool containers with flooding quantities of water until well after fire is out."*
    - *"Do not direct water at source of leak or safety devices; icing may occur."*
- Proposed modification: "***Avoiding the container's pressure relief device and the source of the leak*,** cool the container with flooding quantities of water until well after the fire is out. ***Activation of the pressure relief device may be delayed, and*** icing may occur."
- Decision by the ERG partner organizations: Keep the original statements as they are. The suggested modification is too long and reduces clarity. However, any feedback from stakeholders would be welcome for consideration for future editions of the ERG.

Conclusions

The research concluded that, **with some amendments, ERG Guide 115 can capture the hazards associated with LNG** – and this is consistent with the ERG structure of grouping together dangerous goods with similar hazards and similar emergency response procedures. **There is currently no need to develop a new separate ERG guide for LNG.**

Future action

ERG partner organizations will continue reviewing the ERG regularly to ensure that the recommended emergency actions are up-to-date with any changes in the transportation of dangerous goods landscape.

RESEARCH FOUNDATION

RESEARCH FOR THE NFPA MISSION

Validation of Recommended Emergency Actions for Liquefied Natural Gas (LNG) in the Emergency Response Guidebook (ERG)

Final Report by:

Mitchell Huffman and **Qingsheng Wang, PhD,** Texas A&M University, USA
Christina M. Baxter, PhD Emergency Response Tips, LLC, USA
Gregory G. Noll, GGN Technical Resources, LLC, USA
Michael S. Hildebrand, Emergency Management Solutions, Inc, USA

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1 Batterymarch Park, Quincy, MA 02169 | Web: www.nfpa.org/foundation | Email: foundation@nfpa.org

Foreword

The Emergency Response Guidebook (ERG) typically classifies substances with similar physical and chemical properties together. Liquefied natural gas (LNG), consisting primarily of methane in a mixture with small amounts of other hydrocarbons, has increased in use as a fuel source in recent years, and there is a potential for increased demand for the transport of LNG by rail and road. LNG is currently assigned in the ERG to Guide 115, along with liquefied petroleum gas (LPG). Therefore, the emergency actions for both LNG and LPG are currently identical. However, there are differences in the way the substances are transported that may alter their hazard profile if an incident were to occur. For example, LPG is liquefied under pressure, and is transported in single-walled containers capable of sustaining these pressures during transport. By contrast, LNG is liquefied under extremely low temperatures. The product is kept cold using double-walled tanks, with insulation, that are not suited for the higher pressures required for the transportation of LPG. There are other key differences in these two substances that could suggest that their hazard profiles are different and thus may warrant being placed in different guides in the ERG.

One of the most critical situations with LPG is one involving flame impingement of a container of the pressurized product, which could result in catastrophic failure, possibly producing a massive fireball and flying debris, known as a boiling liquid expanding vapor explosion (BLEVE). One aspect of this project that was investigated was whether the same definition of a BLEVE can be applied to LNG, based on the evidence presented through the scientific literature, previously completed testing, modelling, and/or past incident data.

Given the differences in how LPG and LNG are liquefied when transported (i.e., using pressure versus temperature, respectively) and the slightly different hazard profiles between the two products, it was recommended that the emergency guide for LNG in the ERG be re-evaluated.

The Fire Protection Research Foundation expresses gratitude to the report authors Qingsheng Wang, PhD and Mitchell Huffman, Texas A&M University; Dr. Christina Baxter, Emergency Response TIPS, LLC; Greg Noll, GGN Technical Resources, LLC; and Michael Hildebrand, Emergency Management Solutions, Inc. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by Transport Canada, and all others that contributed to this research effort.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

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About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

Keywords**:** liquefied natural gas, LNG, liquefied petroleum gas, LPG, emergency response guidebook, ERG, cryogenics, rapid phase transition

Report number: FPRF-2023-03

Project Manager: Victoria Hutchison and Sreenivasan Ranganathan, PhD

Project Technical Panel

Bob Duval, National Fire Protection Association (NFPA)

Rick Edinger, Chair of NFPA 470

Larry Jantzen, IAFC Hazmat Committee

Bernard Leong, Chevron

Anay Luketa, Sandia National Laboratories

Dave Moore, AcuTech

Eddie Murphy, Pipeline and Hazardous Materials Safety Administration (PHMSA)

Thach Nguyen, Pipeline and Hazardous Materials Safety Administration (PHMSA)

Danny Simpson, Dangerous Goods Manager Canadian National (retired)

Patrick Student, Union Pacific Railroad (retired)

Kenneth Uzeloc, Kamloops Fire Rescue

Kenneth Willette, North American Fire Training Directors (NAFTD)

Steven Zhang, Wood Group

Project Conducted for

FPRF was contracted by Transport Canada to conduct this project.

Transport Canada Representatives

Joël Poisson

Keikhosrow Tahmureszadeh

Fady Al Zarka

Anne Champagne

Karine Ghostine

Jason Poulin

Validation of recommended emergency actions for liquefied natural gas (LNG) in the Emergency Response Guidebook (ERG)

Final Report

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List of Acronyms

AAR	Association of American Railroads
ADR	European Agreement Concerning Transport of Dangerous Goods by Truck
BLEVE	Boiling Liquid Expanding Vapor Explosion
CANUTEC	Canadian Transport Emergency Centre
CFD	Computational Fluid Dynamics
CIQUIME	Centro de Informaciòn Quìmica para Emergencias
CPIMRS	Commodity Preparedness and Incident Management Reference Sheet
CSC	Cargo Services Conference
DG/HM	Dangerous Goods / Hazardous Materials
ERAP	Emergency Response Assistance Plan
ERG	Emergency Response Guidebook
ESD	Emergency Shutdown Devices
FPC	Federal Power Commission
FRA	Federal Railroad Administration
GC	Gas Carrier (Prior to 1986)
HAMMER	Hazardous Materials Emergency Response
HazMat	Hazardous Materials
HHFT	High Hazard Flammable Trains
HMRT	Hazardous Materials Response Teams
IAP	Incident Action Plan
IGC	International Gas Carrier (Post 1986)
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
INERIS	French National Institute for Industrial Environment and Risks
ISO	International Organization for Standardization
LFL	Lower Flammability Limit
LLNL	Lawrence Livermore National Laboratory
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MAWP	Maximum Allowable Working Pressure
MC	Motor Carrier
NFPA	National Fire Protection Association
PED	Pressure Equipment Directive
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPE	Personal Protective Equipment
RBR	Risk Based Response
RID	European Agreement Concerning Transport of Dangerous Goods by Rail
RPT	Rapid Phase Transition
SCBA	Self-Contained Breathing Apparatus
SCT	Secretariat of Transport and Communications of Mexico
SEP	Surface Emissive Power
SOLAS	International Convention for the Safety of Life at Sea
TC	Transport Canada
TDG	Transportation of Dangerous Goods
TDGR	Transportation of Dangerous Goods Regulations
TRANSCAER	Transportation Community Awareness and Emergency Response
UFL	Upper Flammability Limit

UN	United Nations
US DOE	United States Department of Energy
US DOT	United States Department of Transportation
US EPA	United States Environmental Protection Agency
USCG	United States Coast Guard
USGS	United States Geological Survey
VCE	Vapor Cloud Explosion
WMD	Weapons of Mass Destruction

1. Executive Summary

The Fire Protection Research Foundation was engaged by Transport Canada to validate the recommended emergency actions for liquefied natural gas (LNG) in the Emergency Response Guidebook (ERG). The primary question at hand is, do the hazards of LNG and liquefied petroleum gas (LPG) vary significantly enough to warrant establishment of new guidance for LNG in the ERG?

The ERG generally classifies substances with similar physical and chemical properties together. LNG consisting primarily of methane in a mixture with small amounts of other hydrocarbons, has increased in use as a fuel source in recent years, and there is a potential for increased demand for the transport of LNG by rail and road.

LNG is currently assigned in the ERG to Guide 115 – Flammable Gases, along with LPG (see Annex G). Therefore, the emergency actions recommended within the ERG for both LNG and LPG are currently identical. However, there are differences in the way the substances are transported that may alter their hazard profile if an incident were to occur. For example, LPG is liquefied under pressure, and is generally transported in single-walled containers capable of sustaining these pressures during transport. By contrast, LNG is liquefied under extremely low temperatures. The product is kept cold using double-walled tanks, with insulation, that are not suited for the higher pressures required for the transportation of LPG. There are other key differences in these two substances that could suggest that their hazard profiles are different and thus may warrant being placed in different guides in the ERG. For example, upon release, LPG has the potential for pool fires (depending on the composition of butane and propane, as propane-heavy LPG is not as likely to pool) as well as jet fires due to its pressurization within containment, whereas LNG is kept at cryogenic temperatures and at pressures less than LPG, and is therefore less likely to release as a pressurized jet, thus their dispersion and hazard profiles following a release are different.

The main difference between LNG and LPG is their major chemical composition. Natural gas is primarily composed of methane while LPG is primarily composed of propane or butane. The basic composition of these gases leads to many different chemical and physical properties such as energy content, density, flammable limits, and working pressure. When released to the atmosphere, LPG leads to the development of vapor clouds that are denser than air, whose dispersion and dilution is lower than that of passive atmospheric air. Such dense clouds may settle down and persist at the ground level corresponding to the height above ground where human breathing occurs. Since LNG is liquefied and kept at cryogenic temperatures, it begins to vaporize and form a cloud upon release that remains at ground level initially, then rises as the vapors warm and the density of these vapors becomes lower. The composition difference between LNG and LPG also results in different fire scenarios and explosion events, such as Boiling Liquid Expanding Vapor Explosion (BLEVE) and Vapor Cloud Explosions (VCE). To define the term BLEVE, there are two main BLEVE types: "fired" BLEVE and "unfired" or "cold" BLEVE. The first is thermally induced, and usually occurs when a tank is impinged or engulfed by an external fire. The fire increases the temperature of the tank, reducing its mechanical resistance, while the increase of internal pressure causes an increase of the stresses acting on the vessel shell. This can result in the container rupturing and undergoing a BLEVE. "Cold" BLEVE's are not thermally induced. These events can occur during sudden system changes such as a violent impact on the tank during a traffic accident or by the tank sudden failure due to a material defect or to overfilling. A VCE is an explosion that occurs mainly due to vapor confinement. If a vapor cloud with concentrations in the flammable range is confined inside a structure and ignited, damaging overpressures can occur.

Outdoor areas congested with equipment and structures can also help confine flammable vapors and may facilitate overpressure upon ignition. Both LNG and LPG are susceptible to VCEs, however LPG has a much larger incident history of BLEVE occurrence than LNG. Since the differing properties and conditions of transport of LNG and LPG lead to different risks and event scenarios, they may need different emergency response strategies. However, for these emergency response decisions to be made, more systematic studies are needed to demonstrate the differences and/or similarities between LNG and LPG.

Given the differences in how LPG and LNG are liquefied when transported (i.e., using pressure versus temperature, respectively) and the slightly different hazard profiles between the two products, a recommendation was made to Transport Canada by a stakeholder that the emergency guide for LNG in the ERG be re-evaluated. Thus, the objective of this study was to determine whether the hazard of LNG and LPG vary significantly enough to warrant the establishment of new or revised guidance for LNG in the ERG.

This study identified the following gaps:

[1] **LNG Transport Experience and Safety Considerations** – From the research conducted into the comparison of LNG and LPG, the authors find that while there is a large body of experience and knowledge in LPG transportation, LNG transportation lacks a similar knowledge base. There is also a more thorough incident history for LPG transport, whereas data for LNG transport incidents are much more sparse.

Specifically, there is a significant lack of research regarding the safety of road and rail transportation of LNG. Infrequent transport of LNG at a significant level by road and rail has led to little experience and research testing in the area. Much of the current body of knowledge is based on marine transport and the utilization of LNG as a transportation fuel (e.g., highway, rail). At the very least, frequency analysis similar to that which has been studied in the field of marine transportation, would help to provide valid comparisons, and promote understanding of the risks behind these transportation methods.

[2] **LNG BLEVE Potential –** When analyzing the primary hazards of LPG and LNG, the primary hazards are BLEVE and flammability for LPG, and flammability and cryogenic behavior for LNG. From the chemical and physical properties of LNG, BLEVE occurrence is certainly possible, however, LNG incident history reveals there are no incidents with containers constructed to North American LNG transport standards that can clearly be attributed to BLEVE. This discrepancy between theory and occurrence demonstrates a knowledge gap, and the lack of research into the BLEVE potential of LNG leaves a large uncertainty in the safety of LNG transport.

[3] **LNG Rapid Phase Transition –** There is currently a lack of consensus within research into Rapid Phase Transition (RPT) of LNG which leads to concern for the field of marine transport or where surface transport corridors are in close proximity to large waterways. RPT is a phenomenon unique to LNG in which the LNG is rapidly and almost instantaneously vaporized, typically when released onto a large volume of water, resulting in localized overpressure and, potentially, physical explosions.

Within the field of research, the interpretation of RPT risk varies greatly. Some research papers consider it a point of significant discussion, while others briefly mention the risks of RPT. These uncertainties revolve around considerations such as whether or not an RPT event will occur in a spill, how many RPT events will occur in the spill, and the strength of the explosion. Further complicating this understanding is the possibility that has been raised in literature that RPT could potentially serve as the ignition source for a cloud of released LNG vapors. Learning the RPT behavior of LNG at the scale of transport would lead to much greater certainty in the risk of LNG transport.

[4] **Research to Inform LNG Emergency Response Guidance** – There is a gap that must be addressed between the scientific community and the emergency response guidance. Within the scientific research in this area, emergency response guidance is not even mentioned, let alone sufficiently addressed. Most incident reports that are found within scientific literature do not describe the emergency response

actions taken nor provide recommendations for emergency response in similar scenarios. The knowledge gained from scientific research as well as the experience gained from incident occurrences should outline the lessons learned and outline applicable emergency response recommendations.

This study generated the following major findings:

[1] The ERG is an important and commonly used reference for first responders to LNG emergencies, however, the Risk-Based Response philosophy adopted by *NFPA 470 - Hazardous Materials Standards for Responders* supports the premise that emergency response information sources for an LNG incident should be viewed as a *system* consisting of the following elements:

- Emergency Response Guidebook, Guide 115 and/or LNG Safety Data Sheet used by Awareness and HazMat Operations personnel.
- Incident Management Field Tools, including Liquefied Natural Gas (LNG) Commodity Preparedness and Incident Management (CPIMRS) Reference Sheet (see Annex I) used by HazMat Technicians, HazMat Officers and Incident Commanders and the NFPA On-Scene Commander Field Guides.
- Implementation of Emergency Response Assistance Plan (ERAP) by Incident Commanders, as applicable (used in Canada only).

The concept of the Commodity Preparedness and Incident Management Reference Sheet (CPIMRS) or equivalent should be considered as a tool for providing product and container specific information to HazMat Technicians, HazMat Officers, and Incident Commanders. The current LNG CPIMRS that was developed for LNG rail transport and provided through HAMMER – the Volpentest Hazardous Materials Management and Emergency Response (HAMMER) Federal Training Center – can be used as a framework for developing CPIMRS for cargo tank truck transportation. The level of information provided through the CPIMRS could also be used to complement the ERAP.

Incident-specific decisions should be based upon the use of a risk-based analysis process. *NFPA 470 – Hazardous Materials Standards for Responders* defines Risk Based Response (RBR) as a systematic process, based on the facts, science and circumstances of the incident, by which responders analyze a problem involving dangerous goods (hazardous materials)/weapons of mass destruction (WMD) to assess the hazards and consequences, develop an incident action plan (IAP), and evaluate the effectiveness of the plan.

[2] Both LNG and LPG are covered under Guide 115 of the Emergency Response Guidebook. The 2020 Edition includes updates that reflect the hazards associated with LNG, including:

- FIRE - For **LNG - Liquefied natural gas (UN 1972)** pool fires, DO NOT USE water. Use dry chemical or high-expansion foam.
- SPILL OR LEAK - For **LNG - Liquefied natural gas (UN 1972)**, DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors.

[3] LNG transportation presents four potential general risk related scenarios:

- Cryogenic Behavior and Effects
- Fire (Pool Fire, Jet Fire, Vapor Cloud Fire)
- Vapor Cloud Explosion (open air vs. confined)
- Rapid Phase Transition (RPT)

[4] While there is substantial incident and research test data on the risk of BLEVE scenarios involving LPG containers, equivalent data on the BLEVE risk of bulk LNG transportation containers could not be found.

- LPG poses a greater risk of a BLEVE scenario and has a more rapid flame spread than LNG when ignited. In comparison, LNG has a substantially higher heat flux factor (3 to 5 times) than other commonly transported hydrocarbons, thereby increasing thermal impact distances.
- Most containers used for transportation of LNG have an inner tank and an outer tank, with an insulation space between the two tank shells. The "tank-within a tank design" utilized for LNG transport results in added protection for the inner container due to the annular space. The integrity of the annular space is critical in the fire performance of an LNG container. In contrast, LPG highway containers have a single-shell, non-insulated design and therefore do not have this added protection. LPG rail containers, however, have an outer jacket and thermal protection.
- The majority of incident and research test data involving LNG containers and their behavior in an emergency is based upon marine transportation.
- There are currently no incident reports or research testing of a BLEVE of a cryogenic container constructed to current North American standards (TC/MC-338, T75, TC/DOT-113). No incident experience or research test data was found to support modifying the protective action distances (increase or decrease) for LNG fire scenarios at this time.

[5] The risk of metal embrittlement of an LNG outer tank shell is not commonly encountered by emergency responders, but the hazard is highlighted in the ERG.

This study offers the following recommendations:

[1] At the present time ERG Guide 115 accurately captures the hazards associated with LNG and related flammable cryogens and it is consistent with the ERG structure of classifying refrigerated liquids into flammable gases, inert gases, and oxidizing gases. At the present, there is no need to develop a separate ERG Guide for LNG. The four-year ERG review cycle should be continued.

[2] The authors support the recommendation from the National Academy of Sciences Report to review DOT-113C120W9 tank specifications to:

- Assess the capacity of pressure relief to sufficiently vent when the tank is engulfed in fire, considering derailment conditions.
- Study the effects of adding more and different insulations into the annular space.

[3] The authors suggest that the recommendation to use CO_2 on LNG fires should be validated. CO_2 is not commonly referenced for LNG fires.

[4] Through this study, a few gaps were identified within ERG Guide 115 where slightly modified language could make the guide more inclusive of LNG. For future updates to the ERG, the authors propose one new addition and other contextual updates (or equivalent language) to be considered, to ensure considerations for LNG are adequately covered in Guide 115 for flammable gases. See Section 11.2 of this report for the specific suggested language.

2. Introduction

Liquefied Natural Gas (LNG) is well-positioned to continue to play a larger role in the supply of North American energy. Given the steadily advancing environmental sustainability goals worldwide, natural gas has gained momentum given its relatively clean burning process in comparison to coal, and therefore has the potential to continue minimizing the global warming potential of emissions within the energy sector. Natural gas supplies about 1/3 of the United States' primary energy consumption, with its primary uses being heating and generating electricity. In recent years, there has been an increased interest in LNG re-gasification terminal projects throughout Canada and the United States. While the majority of natural gas is delivered in its gaseous form via pipeline in Canada and the United States, the growth of demand in the international market for natural gas has given rise to the use of natural gas in a liquefied form or LNG. Thus, the demand for transportation of LNG by road or rail is also expected to increase. Liquefied petroleum gas (LPG) refers to the lightest (lowest density) liquid fuels produced by a refinery. It is commonly used as a fuel where it is valued for being easily transported, and it is easily vaporized at room temperature to form fuel gas. Both LNG and LPG are highly flammable substances, and the release of either of these materials into the environment is fraught with serious consequences. LNG/LPG fires and explosions have caused significant loss of life and property.

The main difference between LNG and LPG is their major chemical composition, as natural gas is primarily composed of methane while LPG is primarily composed of propane or butane. This difference leads to many different chemical and physical properties such as energy content, density, flammable limits, and working pressure. When released to the atmosphere, LPG leads to the development of vapor clouds that are denser than air, whose dispersion and dilution is lower than that of passive atmospheric air. Such dense clouds may settle down, stay, and persist at the ground level corresponding to the level of human breathing. Since LNG is liquefied and kept at cryogenic temperatures, it begins to vaporize and form a cloud upon release that remains at ground level initially, then rises as the vapors warm and the density of these vapors becomes lower. The composition difference between LNG and LPG also results in different fire scenarios and explosion events, such as Boiling Liquid Expanding Vapor Explosion (BLEVE) and Vapor Cloud Explosions (VCE). Since the differing properties of LNG and LPG lead to different risks and event scenarios, they may need different emergency response strategies. However, for these emergency response decisions to be made, more systematic studies are needed to demonstrate the differences and/or similarities between LNG and LPG.

2.1 Project Background

Transport Canada's Transportation of Dangerous Goods (TDG) Program develops risk-based safety standards and regulations, provides oversight, and gives expert advice on dangerous goods incidents to promote public safety in the transportation of dangerous goods by all modes of transport in Canada. The Canadian Transport Emergency Centre (CANUTEC) is responsible for delivering emergency response advice 24 hours a day, seven days a week, to anyone with questions or concerns involving the transportation of dangerous goods or emergencies involving dangerous goods. This includes advice on dangerous goods release mitigation strategies, the physical and chemical properties of dangerous goods, as well as protective actions (e.g., recommendations for personal protective equipment (PPE) and evacuation distances).

The Emergency Response Guidebook (ERG) is produced by CANUTEC in collaboration with the US Department of Transportation (DOT), the Secretariat of Transport and Communications of Mexico (SCT), and CIQUIME (Centro de Informaciòn Quìmica para Emergencias) of Argentina. The ERG, released every four years, is primarily a guide to aid first responders in quickly identifying the specific or generic hazards of the material(s) involved in a dangerous goods transportation incident, and in protecting themselves and the general public during the initial response phase of the incident. The guide contains emergency guide pages (orange pages) with emergency recommendations tailored to products that share certain physical and chemical properties. Each UN number included in the Transportation of Dangerous Goods Regulations (TDGR) is accounted for in the ERG. The emergency actions in the ERG are updated periodically to account for changes in the TDG landscape, such as changes in commodity flows, improvements in means of containment that reduce the likelihood of a release or failure, or the generation of new scientific knowledge that may change the assessment that applies for a particular substance.

The ERG typically classifies substances with similar physical and chemical properties together. LNG, usually consisting primarily of methane in a mixture with small amounts of other hydrocarbons, has increased in use as a fuel source in recent years, and there is a potential for increased demand for the transport of LNG by rail and road. LNG is currently assigned in the ERG to Guide 115 – Flammable Gases, along with LPG. Therefore, the recommended emergency actions for both LNG and LPG are currently identical. However, there are differences in the way the substances are transported that may alter their hazard profile if an incident were to occur. For example, LPG is liquefied under pressure, and is transported in single-walled containers capable of sustaining these pressures during transport. By contrast, LNG is liquefied under extremely low temperatures. The product is kept cold using double-walled tanks, with insulation, that are not suited for the higher pressures required for the transportation of LPG. There are other key differences in these two substances that could suggest that their hazard profiles are different and thus may warrant being placed in different guides in the ERG. For example, upon release, LPG has the potential for pool fires (depending on the composition of butane and propane, as propane-heavy LPG is not likely to pool) as well as jet fires due to its pressurization within containment, whereas LNG is kept at cryogenic temperatures rather than pressurized, thus, their dispersion profiles following a release are different.

One of the most critical scenarios with LPG is one involving flame impingement upon a container of the pressurized product, which could result in the catastrophic failure of the container, possibly producing a massive fireball and flying debris; this is called a BLEVE. One of the key aspects of this research will involve examining scientific literature, previously completed testing and/or modeling, and/or past incident data, to determine whether the same BLEVE probabilities and behaviors can be applied to LNG. While there are some studies that have shown BLEVE-like behavior under testing conditions with LNG, it is unclear whether LNG exhibits this behavior outside of a test setting (Betteridge and Phillips, 2015). Additionally, the tanks involved in the LNG tests were breached using explosive charges and not from heating the tanks to the point of failure, as is the case with most LPG-based BLEVEs. The study showed that while the fireball produced using LNG was smaller than in similar tests previously run using LPG, it persisted for a similar amount of time and the surface emissive power (SEP) generated by an LNG fireball was equivalent, or in some cases greater than those seen in tests with LPG. Interestingly, the heat given off by the LNG fireball was found to be greater near the fireball but decreased more rapidly with distance than the heat from LPG-based tests.

Given the differences in how LPG and LNG are liquefied when transported (i.e., using pressure versus temperature, respectively) and the slightly different hazard profiles between the two products, a recommendation was made to Transport Canada by a stakeholder that the emergency guide for LNG in the ERG be re-evaluated.

2.2 Project Objectives

The objective of this study is to determine whether the hazard of LNG and LPG vary significantly enough to warrant the establishment of new or revised guidance for LNG in the Emergency Response Guidebook.

2.3 Project Tasks

Task 1: Project Initiation and Formation of Project Technical Panel.
Task 2: Data Collection and Analysis

- Conduct a scientific literature review (Section 3)
  - Analyze the publication trends of LNG and LPG.
  - Identify terms co-occurrence clusters.
  - Methodology to perform intellectual base analysis.
  - Analysis of scientific literature review.
- Conduct a comparative hazard assessment of LNG and LPG during transport. (Section 4)
  - Define chemical and physical properties.
  - Hazard Identification.
- Conduct a comparative assessment of LNG / LPG containment systems (Section 5)
  - LNG Containers – General Characteristics
  - IMO / ISO portable tank containers
  - Rail transportation
  - Highway transportation
  - Marine transportation
- Comparative assessment of modeling and risk / consequence analysis data (Section 6)
- Compare emergency response procedures for LNG and LPG incidents during transport. (Section 7)
  - Identify the range of potential incident scenarios involving LNG or LPG (e.g., spills, fires, rapid phase transition, BLEVE's, volume of gas release, means of transport, etc.) and categorize them per the respective modes of transportation (e.g., road, rail, marine).
  - Emergency response hazard assessment and risk evaluation methodology for an LNG or LPG release during transport.
- Emergency Response Guidance for LNG and LPG. (Section 8)
  - Evaluate the dependence of chemical and physical properties of LNG and LPG and their potential hazards on different incident scenarios, such as fire, or a compromised or failed means of containment.
  - Assess the difference and similarity between LNG and LPG on their hazard profiles during or following a release or anticipated release, with the currently relevant emergency response guidance provided in Guide 115.
  - Identify supporting rationale and provide recommendations on emergency response guidance for LNG and LPG.

Task 3: Gap Analysis and Possible Future Research Plan

- Conduct a gap analysis. (Section 9)
- Develop a possible future research plan. (Section 10)
- Summarize key findings and establish recommendations (Section 11)

3. Scientific Literature Review

3.1 Literature Review Methodology

The methodology employed to conduct the scientific literature review consists of the following tasks:

Step 1: Analyze the publication trends of LNG and LPG (See Section 3.2). The annual outputs of publications related to LNG and LPG provide a high-level overview of the research activity and obtained incident data pertaining to trends of LNG and LPG. This is further expanded into an overview of LNG and LPG transport as well. Finally, LNG and LPG transport research that includes safety considerations are analyzed. The combination of these topics provides a thorough overview of the current state of the related research as well as the trends for what areas are prioritized over time.

Step 2: Identify terms co-occurrence clusters (See Section 3.3). Terms are defined as noun phrases, which are extracted from the content of scientific literature, previously completed tests and/or modeling, and/or past incident data (including incident summaries and action plans) specifically from the Web of Science database collection platform[1]. Terms are labeled as 'co-occurring' if they appear together in the same source. The terms co-occurrence network is clustered based on the co-occurrence strength, or number of times they co-occur within a source, using the network clustering software in VOSviewer. After the identification of large term clusters, and analyzing the terms inside the clusters, the high-level focus areas for LNG and LPG have been determined and subsequently, this provides a statistical basis for understanding the main focuses of LNG and LPG research and testing.

Step 3: Perform Intellectual Base Analysis (See Annex A). Highly cited articles can be seen as the intellectual base of a research field, on which future knowledge-seeking explorations and projects build. In the present work, a two-level intellectual base analysis is performed, using the journals and references co-citation analysis software as implemented in VOSviewer. From this, the journals, books, incident reports, or other media that are frequently cited in the research of LNG and LPG, are identified. Highly cited sources reflect the main knowledge carriers that support the research of LNG and LPG and can be regarded as its intellectual base. This provides further evidence of the topics that receive the most research focus regarding LNG and LPG.

Step 4: Analysis of scientific literature review (See Section 3.4). Based on the extensive literature review that has been performed, the key findings and critical information have been summarized. This analysis allows for a thorough background knowledge of which topics have received the greatest importance and attention, as well as which areas require the most study moving forward.

3.2 Publication Trends

3.2.1 Publication Trends for LNG and LPG

The annual outputs of scientific publications related to LNG and LPG through the Web of Science database platform are shown in the figures below. While these figures are not intended to convey the importance of each publication, they provide an overview of the scientific community's efforts toward establishing a baseline understanding of each topic through peer-reviewed publication. Additionally, while lab-scale experiments may not be as applicable to hazard scenarios, they do establish a baseline for future large-scale experiments by establishing fundamental understanding such as physical and chemical properties. This result provides a high-level overview of the research activity and the incident data pertaining to trends of LNG and LPG.

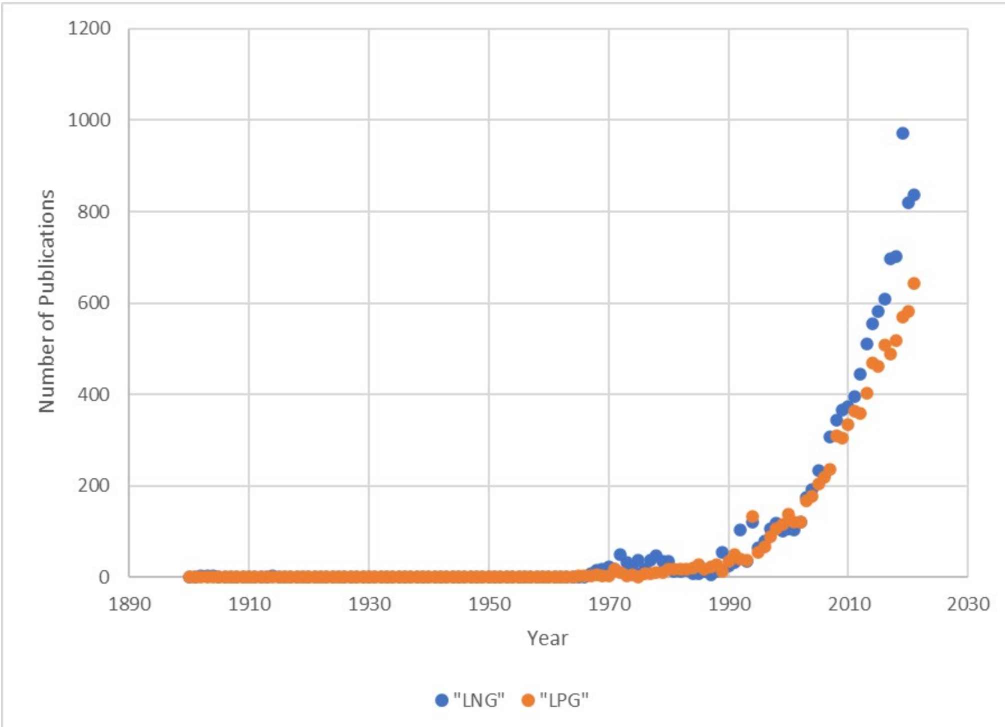

Figure 1: Publications for LNG and LPG

Publication trends follow the expected trajectories. There has been significant research into the use of LNG and LPG, demonstrating the recognized importance of both materials as an energy source. Additionally, the amount of research is increasing exponentially since 1990, demonstrating the increasing need for research related to both substances.

3.2.2 Publication Trends for LNG and LPG Transport

Focusing on LNG and LPG transport, we note that much less research has been performed relative to the total amount of research into LNG and LPG, as shown in Figure 2. The research for LNG is reduced by about a factor of 10, with LPG reduced even further as compared to the overall LNG and LPG research (Figure 1) identified from this time period. However, we observe an exponential increase in research within these trends as well. Therefore, it is clear that there is an increasing demand for research into the transport of both substances.

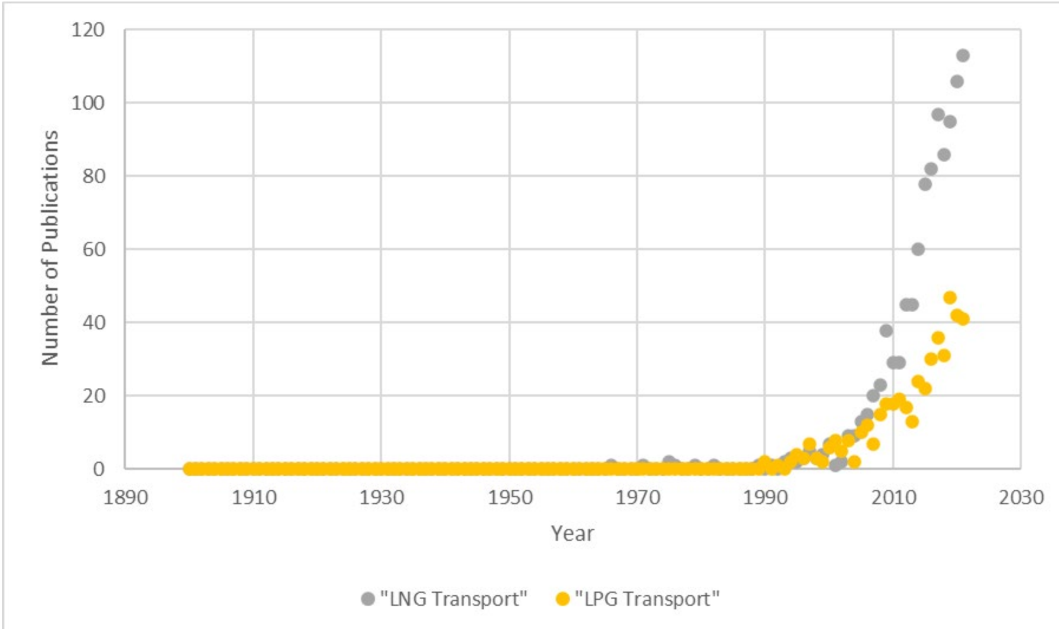

Figure 2: Publications for LNG and LPG Transport

3.2.3 Publication Trends for LNG and LPG Transport and Safety

Finally, the publication trends for transport when specifically considering "safety" are presented in Figure 3 below. It is clear that this field is immensely under-studied, with LNG transport safety having recently reached 25 publications in a year, and LPG transport safety only once reaching 10 publications in a year. Since this research has only recently begun, no clear trend can be seen. However, it does appear that this area may be following the same exponentially increasing trend that was seen for the other fields. Therefore, while sparsely explored, the field of transport safety for both LNG and LPG are beginning to become established. It is also pertinent to note how the research in the area has developed. The increase in LNG/LPG research that began around 1990 was followed by a focus into transport a decade later in 2000, which was followed by a focus into safety beginning again a decade later in 2010. This is important to note as understanding the development of the research focuses over time can help accelerate the process for future potential energy sources.

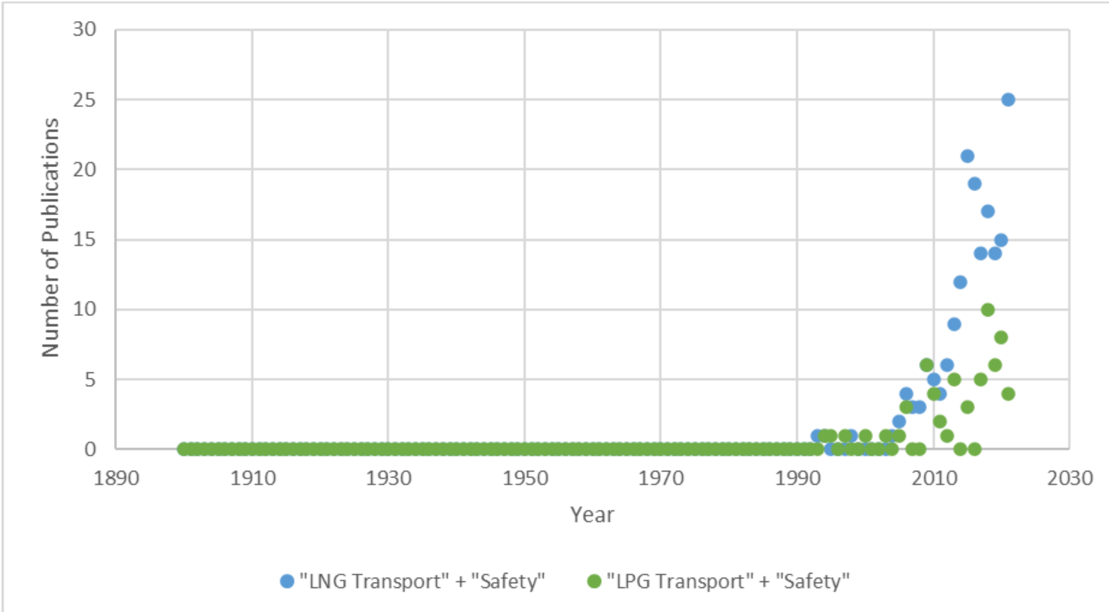

Figure 3: Publications for LNG and LPG Transport Including Safety

3.2.4 Scientific Literature Publication Trends for LNG and LPG Hazards

Scientific literature publication trends on LNG and LPG hazards are presented below in Figures 4 and 5. It was noted that, for LNG, there is a large focus upon dispersion and cryogenics. For LPG, we see a large focus upon dispersion and BLEVE. These results may be observed because dispersion modeling is a heavy focus of process safety engineers, and software can often assist these studies. Additionally, cryogenics and BLEVE may be the other focuses as the main hazards of each material.

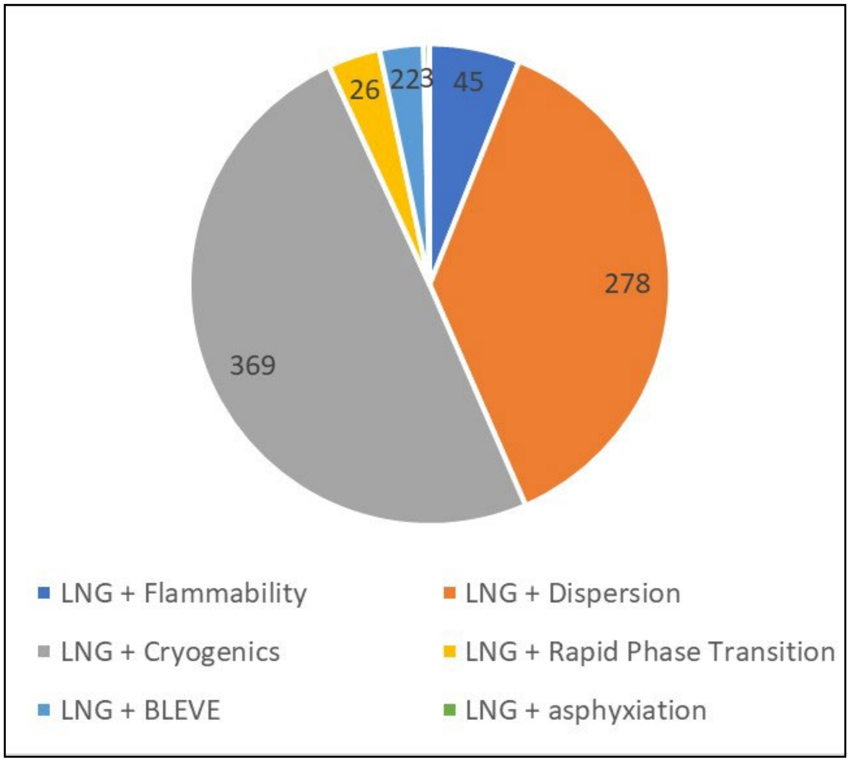

Figure 4: LNG Hazards Publication Trends

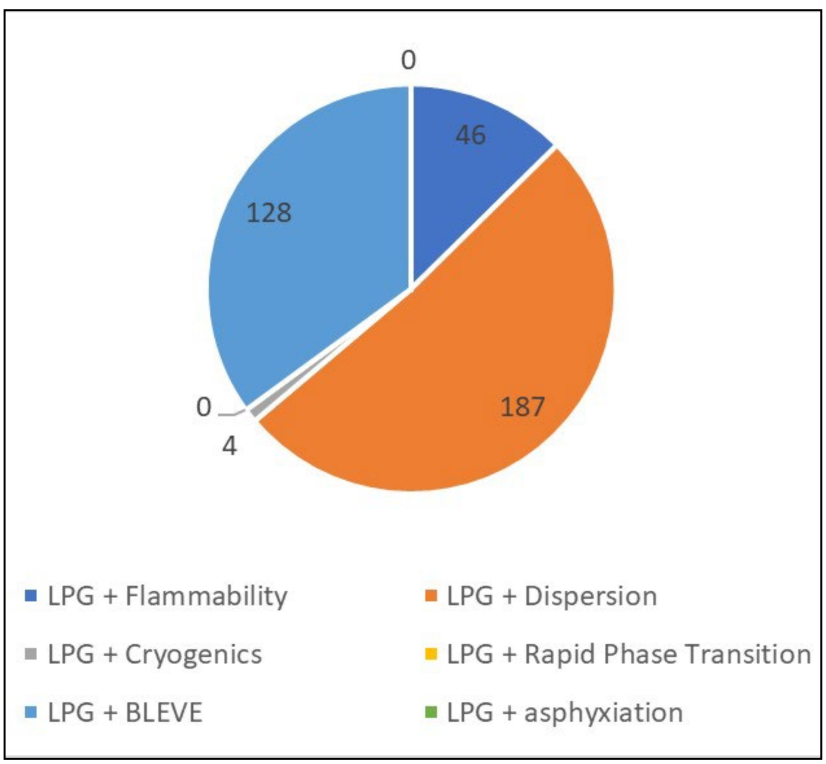

Figure 5: LPG Hazards Publication Trends

3.2.5 Publication Trends for LNG and LPG Transport Hazards Publication Trends

This section summarizes the publication trends of LNG and LPG studies that specifically focus on hazards during transport, which is depicted in Figures 6 and 7. For LNG, this analysis identified a similar focus to the LNG hazard specific publications (Figure 4) on cryogenics and dispersion, but with dispersion studies being the major focus. Flammability and BLEVE considerations can be seen as slightly more significant. For LPG, we see the publications are much more focused on BLEVE, with the rest being focused on dispersion and flammability. This verifies what has been established in the previous project task (3.2.4) as the main hazards both for LNG and LPG transport.

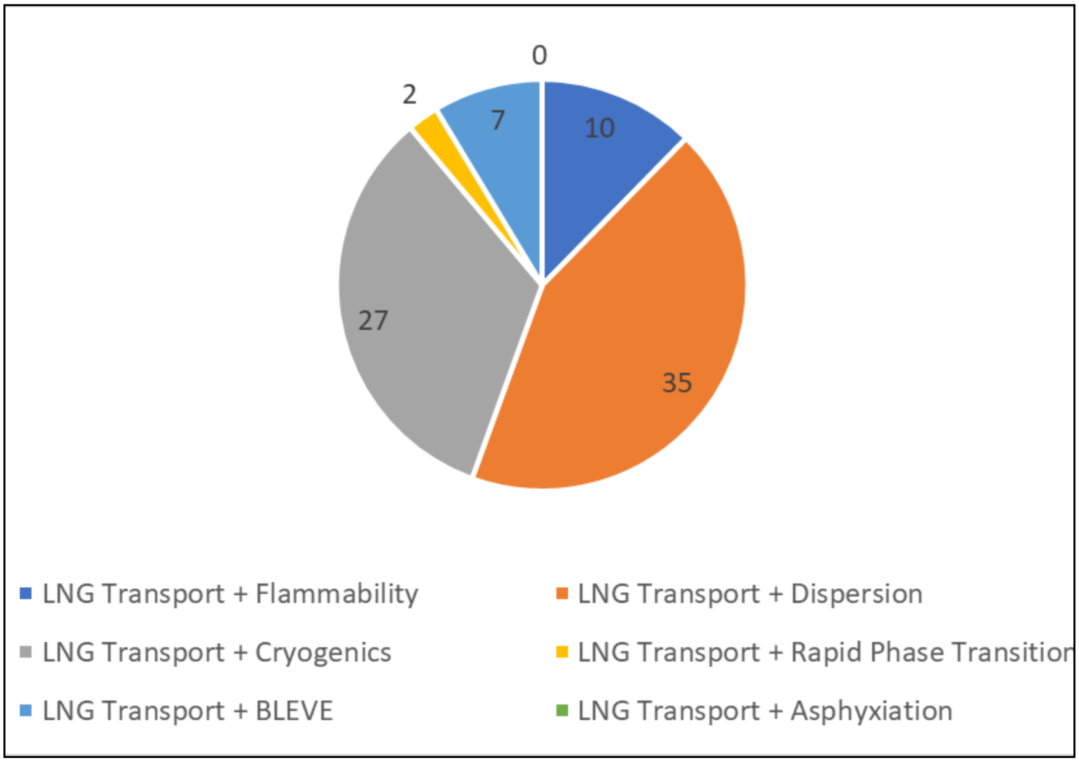

Figure 6: LNG Transport Hazards Publication Trends

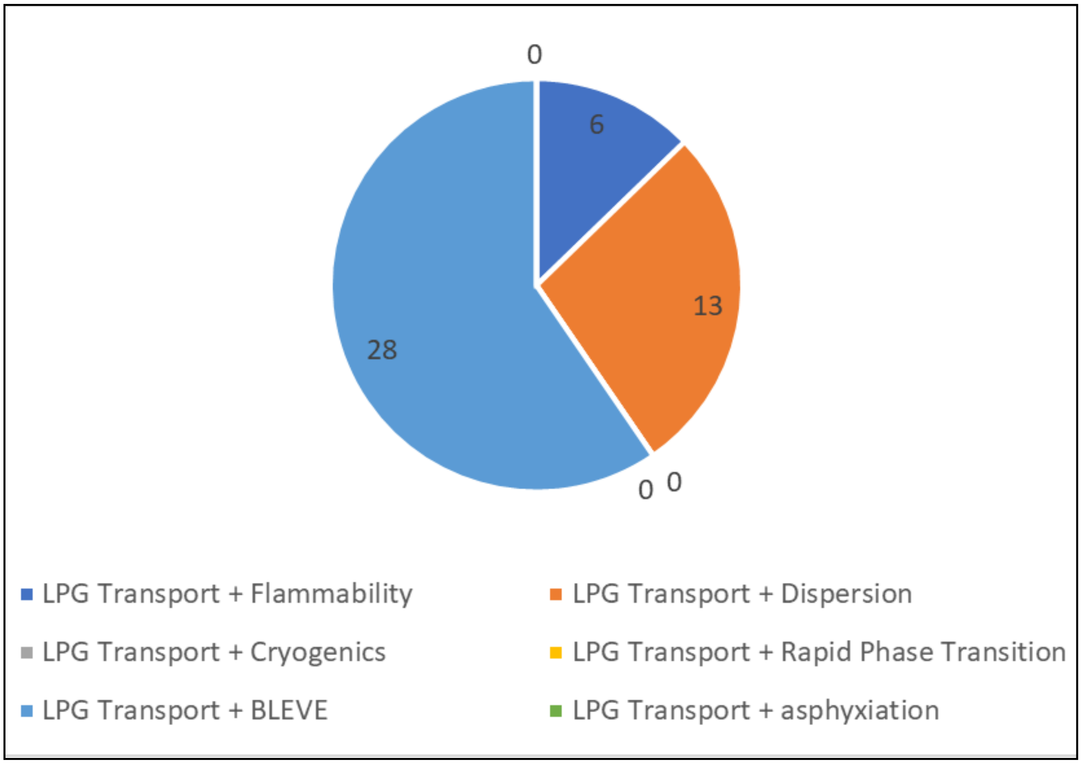

Figure 7: LPG Transport Hazards Publication Trends

3.3 Co-occurrence Clusters

This section identifies terms (i.e., noun phrases) that are extracted from the content of scientific literature, previously completed tests, or modeling and past incident data, as illustrated in Figures 8 – 11. Terms are labeled as 'co-occurring' if they appear together in the same resource. The terms co-occurrence network is clustered based on the co-occurrence strength using network clustering method in VOSviewer, which is a software that is utilized here to analyze scientific papers published in the Web of Science. After the identification of large term clusters, based on the terms inside the clusters, the high-level focus areas for LNG and LPG emerged, providing a statistical basis for understanding the main considerations of LNG and LPG.

The color of an item (either co-occurrence term or co-citation source) is determined by the cluster to which the item belongs. Lines between items represent links. The distance between two items in the visualization approximately indicates the relatedness of the items in terms of co-citation links or co-occurrence links. In general, the closer two items are located to each other, the stronger their relatedness. The strongest co-citation or co-occurrence links between items are also represented by lines. Therefore, color signifies a group of terms/citations that are often found together, and colors are not transferable between the co-occurrence and co-citation map.

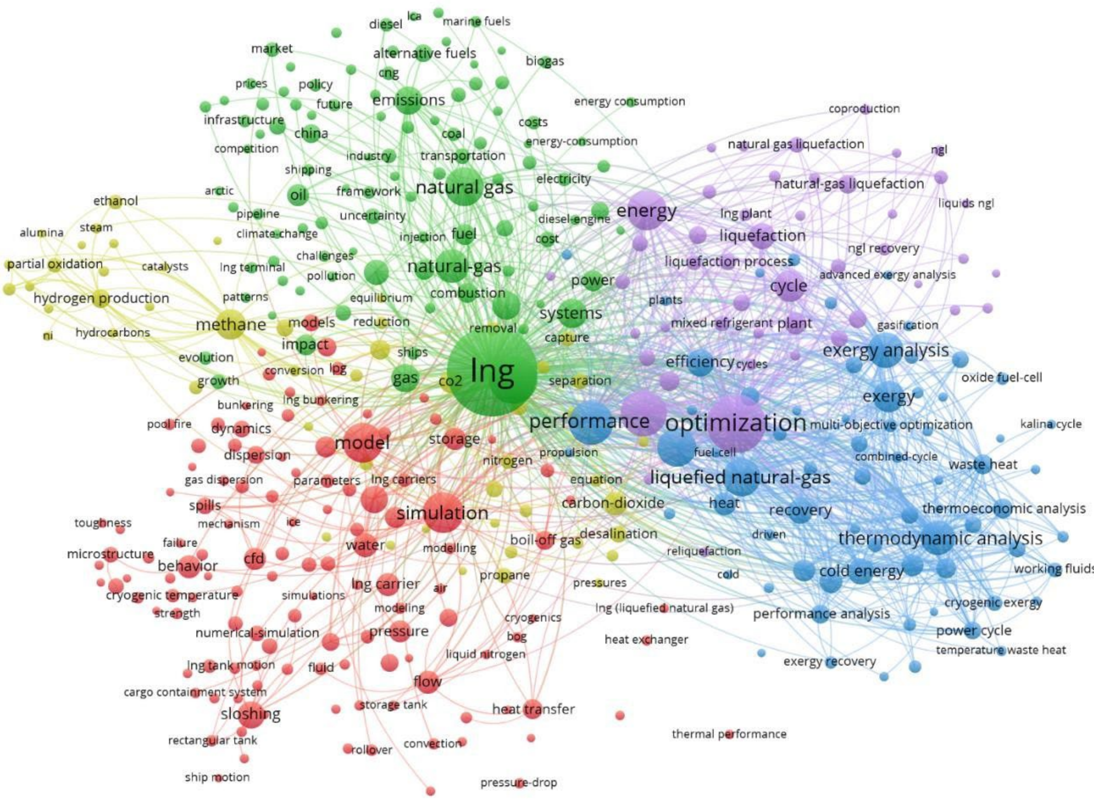

Figure 8: LNG Co-occurrence Map (15 co-occurrence minimum)

Within the research of "LNG", we see five main clusters in Figure 8:

- Clean energy source potential (top center, green)
- Optimization and liquefaction (top right, purple)
- Thermodynamics (bottom right, blue)
- Methane steam reforming and hydrogen production (middle left, yellow)
- Simulation/modeling (bottom left, red)

Within the simulation modeling, we find safety considerations such as spills, dispersion, sloshing, pressure, cryogenic temperature, and heat transfer. Also of note, is the prevalence of maritime transport, with "ship" and "LNG carrier" being included in the map, with no reference to road or rail transport.

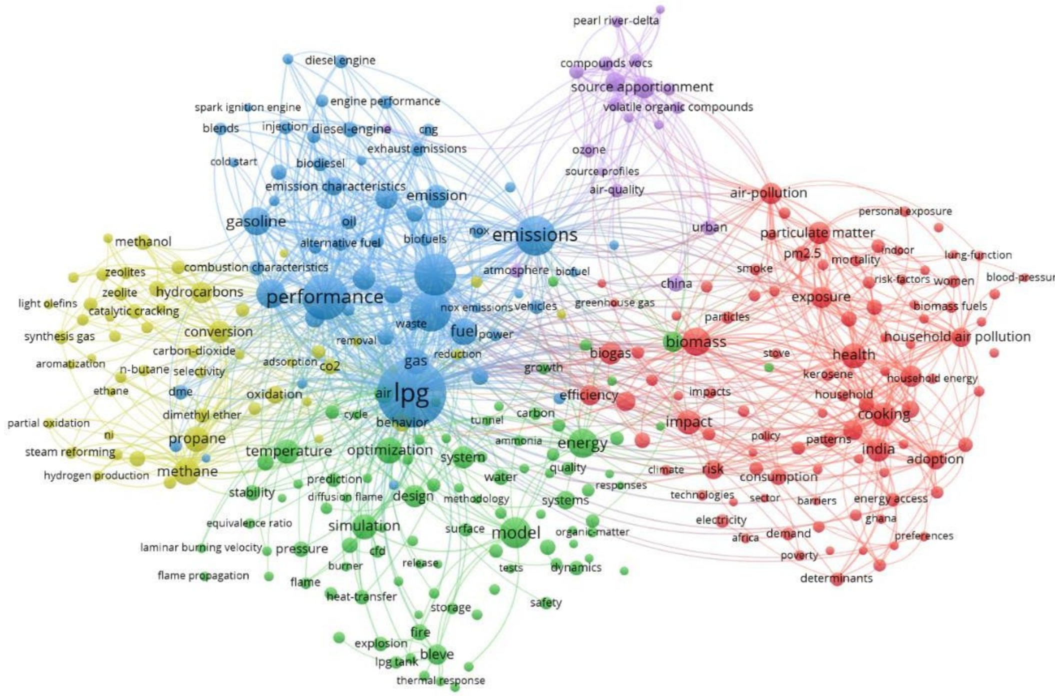

Figure 9: LPG Co-occurrence Map (15 co-occurrence minimum)

For the LPG co-occurrence map, shown as Figure 9, we see five main clusters:

- Health factors (center right, red)
- Air quality and source apportionment (top right, purple)
- Fuel performance and emissions (top left, blue)
- Hydrocarbon study (center left, yellow)
- Optimization and simulation (bottom center, green)

Within the optimization and simulation cluster, we witness some focus on safety with publication in BLEVE, explosion, fire, and flame. This is an improvement when compared to the safety considerations of the LNG map and helps us confirm the main hazards of LPG.

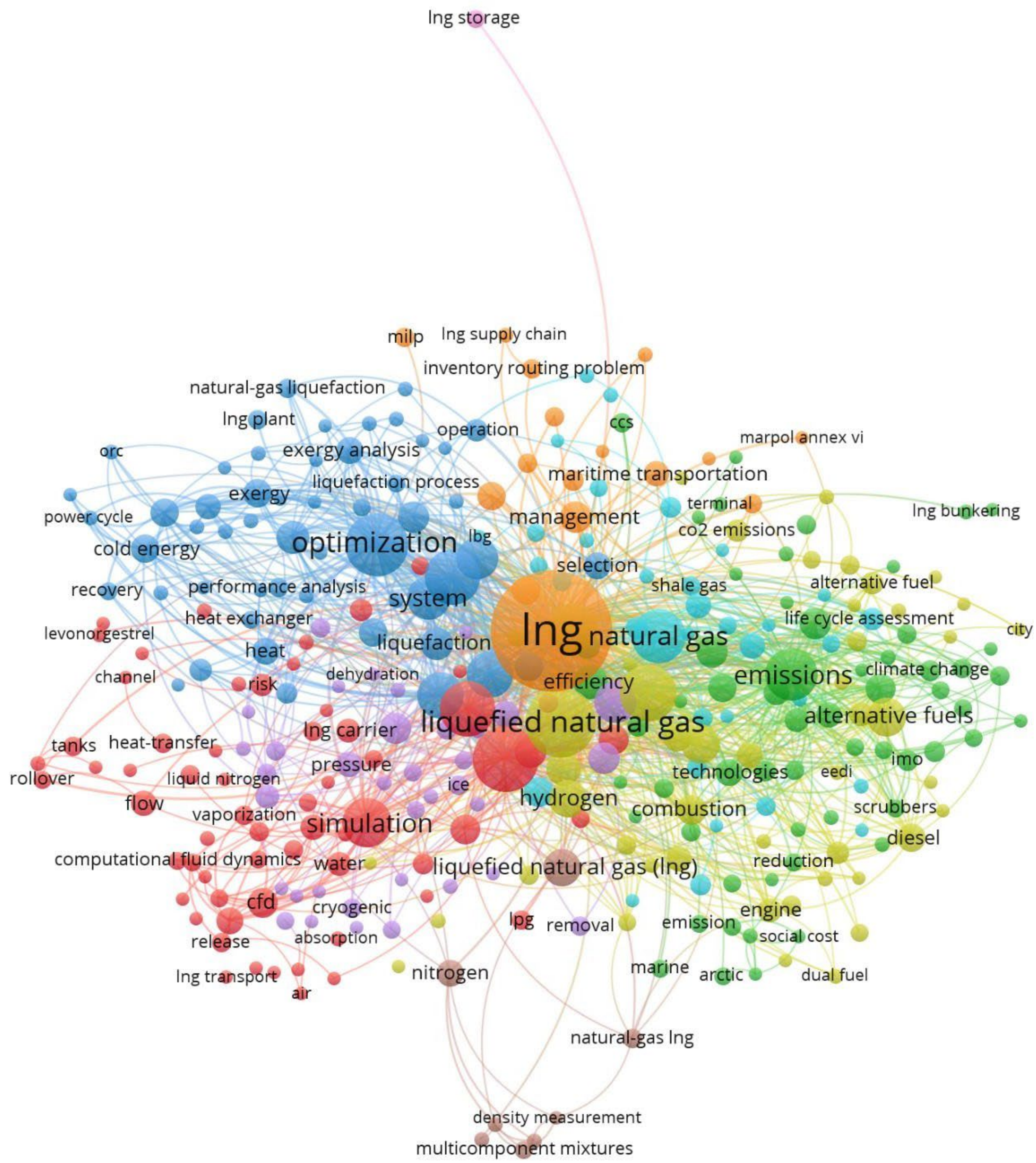

Figure 10: LNG Transport Co-occurrence Map (15 co-occurrence minimum)

For our "LNG transport" map, shown as Figure 10, we find four main topic clusters:

- Emissions and climate change (center right, green)
- Combustion (bottom right, yellow)
- Optimization and liquefaction (top left, blue)
- Simulation (bottom left, red)

The simulation cluster is again where we find safety focuses such as release, cryogenics, pressure, and vaporization. Additionally, we can find again a dot showing research focus into "maritime transportation" with no dot to signify research into road or rail transport. This verifies the results previously recognized, that maritime transport has received the majority of the research related to LNG transport to this point and demonstrates the research gap in road and rail transport.

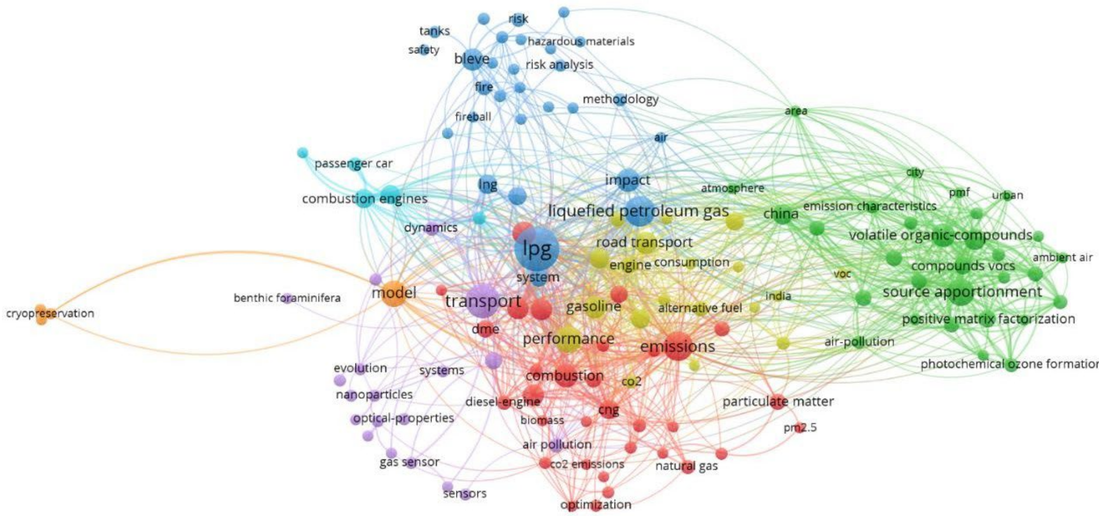

Figure 11: LPG Transport Co-occurrence Map (15 co-occurrence minimum)

For "LPG transport", we again see five main clusters in Figure 11:

- Emissions analysis (center right, green)
- Engine performance (center, yellow)
- Combustion (bottom center, red)
- Gas sensors (bottom left, purple)
- Risk (center top, blue)

It is important to note that while the engine performance cluster does include a dot for road transport, this is more focused on LPG as a fuel rather than as an item of transport. For LPG transport, we finally see a focus on the important factors that are explored in this study, with major research focus into safety, risk, BLEVE, and fire. This serves as an example of what would ideally be shown in the field of LNG as well, and more clearly demonstrates why there is difficulty studying the risk of LNG transport, as there is no similar section focusing on the safety for LNG transport.

3.4 Summary of Findings from the Literature Review

This literature review has focused on analyzing the available scientific, peer-reviewed articles on LNG and LPG hazards, risks, transport, and safety. Publication trends indicated an exponentially growing field of research for LNG and LPG, as well as the transport of each, with what appears to be the beginning of a similar trend for studies into the safety of LNG and LPG transport. Despite the beginning of this trend, however, the field of transport safety is clearly lacking research in the present. Marine transport has been more explored for LNG than other forms of transport, likely due to its prevalence in industry.

It is of interest to mention that while the research into LNG and LPG began exponentially rising in about 1990, the research into LNG and LPG transport began surging a decade later around 2000, and the safety research began to surge about a decade later again around 2010. These research focuses seemed to progress from one another in 10-year increments. This serves as a note that perhaps recognizing this trend can result in accelerated studies for future new explorations in similar fields. Additionally, the main hazards considered within these studies are clarified, with both LNG and LPG dispersion characteristics being prioritized. More distinctively, for LNG the next considerations are the cryogenics and then flammability properties, whereas for LPG the next considerations are BLEVE and then flammability properties (with BLEVE considerations more common than dispersion for LPG transport).

One of the main observations from the co-occurrence plots is how little focus there is in scientific literature toward emergency planning and response. The minimal studies on safety within these fields is clear, with small dots representing very few recognitions of flammability, dispersion, and release when compared to the areas of emissions or combustion properties of the fuels. However, even less prevalent is the consideration of emergency response procedures and guidance for handling accidental spills and fires. It is important to recognize that this analysis mostly presents the quantity of peer-reviewed publications, and a useful next step would be to complete this review with a thorough analysis of the quality of the existing publications to establish which specific areas require a focus in future research.

Despite the evidence of a lack of information on emergency response actions for LNG and LPG transport incidents in the scientific literature, the emergency response guidance, resources, and recommendations presented later in this report are based on identified reports, white papers, and emergency responder training manuals that are available in the public domain and first responder-focused task groups and organizations that the authors are intimately involved with.

3.5 Historical Incident Experience

The literature review provided an overview of the focuses within LNG and LPG research in scientific literature, as well as the hazards that have been most explored within this literature. However, it was also important to determine whether the incidents observed in industry reflect the same conclusions. Further, it is pertinent to analyze the differences between incidents that have occurred in LNG transport and operations to those during LPG transport and operations, which is summarized in Sections 3.5.1 and 3.5.2 below. While more incident records exist, this analysis provides a representative collection and sample of historical incidents, focused on those records which provided thorough details of the occurrence.

3.5.1 Representative Sample of Historical LNG Incidents

Table 1 provides a representative collection and sample of incidents that occurred during LNG transport or facility operations. These incidents have been explored to determine various aspects of the incident such as the main hazards, failure mechanism, consequences, and incident response tactics when the information was available.

Table 1: Representative Sample of Historical LNG Incidents

(Adapted and Expanded from US Coast Guard Draft Environmental Impact Statement for the Port Delfin LNG Project Deepwater Port Application, Appendix R.)

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
1944	Cleveland, Ohio, USA	Vapor clouds formed and filled the surrounding streets and storm sewer system. Natural gas in the vaporizing LNG pool.	Cryogenics, Flammability, and Explosivity	2,042,040 Gallons	Tank metal not sufficiently designed for the cryogenic temperatures.	128 deaths, many injured, much property damage and homes destroyed.	Full evacuation from the surrounding area	Fixed facility
1964 1965	Arzew, Algeria Ship name: Methane Progress	A lightning strike to the forward vent riser of the Methane Progress ship ignited vapor which was being routinely vented through the venting system at the time. A similar event occurred later in 1965.	Flammability	Unknown	Unknown	None	Purged with Nitrogen	Marine vessel
1965	Canvey Island, United Kingdom	During LNG transfer, an error resulted in the release of LNG. The release was ignited, causing one person to be seriously burned.	Flammability	Unknown	Unknown	1 seriously burned	Unknown	Fixed facility

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
1965	Arzew, Algeria	LNG liquid spill caused by overflowing of a cargo tank that resulted in the fracture of the cover plating of the tank and adjacent deck plating.	Cryogenics	Unknown	Overfilling of a cargo tank.	Tank and deck plating fracture.	Unknown	Marine vessel
1965	Ship name: Methane Princess	LNG discharging arms were disconnected prematurely before the lines had been completely drained, causing LNG liquid to pass through a partially opened valve and onto a stainless-steel drip pan placed underneath the arms.	Cryogenics	Unknown	Valve leakage.	Deck Fracture.	Unknown	Marine vessel
1969	Portland, Oregon, USA	An explosion occurred in an LNG tank under construction. No LNG had ever been introduced into the tank. The cause of the accident was the accidental removal of blinds from natural gas pipelines which were connected to the tank. This led to the flow of natural gas into the tank while it was being constructed.	Flammability and Explosivity	Unknown	Accidental removal of blinds from natural gas pipelines.	Property damage	Unknown	Fixed facility
1971	Italy	Caused by product rollover, where two layers of LNG with different densities form (in this instance, the heel of density 541.7 kg/m^3 and the cargo of density 545.6 kg/m^3), the mixing of which results in the release of vapor. LNG vapor discharged from the tanks pressure relief valves and vents. No ignition	Cryogenics and rollover	2,000 tons	Tank developed a sudden increase in pressure and underwent rollover.	Tank roof slightly damaged.	Unknown	Marine vessel

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
1972	Montreal, Québec, Canada	During defrosting, a back flow of natural gas from the compressor to the nitrogen valve when the valve remained unclosed caused over-pressurization of the compressor. This led to a leak and subsequent ignition.	Flammability	Unknown	Back flow of natural gas leading to compressor over-pressurization	Unknown	Unknown	Fixed facility
1973	Canvey Island, United Kingdom	Small amount of LNG spilled upon a puddle of rainwater, and the resulting flameless vapor explosion, called a rapid phase transition (RPT), caused the loud explosions.	Rapid Phase Transition	Unknown	Glass breakage.	Ship/Property damage	Unknown	Fixed facility
1974	USA Ship name: Massachusetts Barge	LNG leaked during loading, as a result of a power failure and the resulting automatic closure of the safety valves. The leak resulted in several fractures to the deck plates.	Cryogenics	40 Gallons	Automatic closure of safety valves during power failure.	Several deck plate fractures.	Unknown	Marine vessel
1977	Azrew, Algeria	Aluminum valve failure on contact with cryogenic temperatures. Wrong aluminum alloy was used on replacement valve. LNG released, but no vapor ignition.	Cryogenics	Unknown	Valve failure with wrong alloy on replacement valve.	1 death	Unknown	Fixed facility
1977	Bontang, Indonesia	During filling, LNG overflowed through the vent mast. Possible cause was difficulties in the liquid level gauge system	Cryogenics, volume released	Unknown	Alarm system mistakes and liquid level gauge system difficulties.	Ship damage.	Unknown	Marine vessel
1978	Das Island, U.A.E.	The bottom pipe connection of an LNG tank failed. Vapor from the outer shell of the tank formed a cloud which did not ignite.	Unknown	Unknown	Bottom pipe connection failure	None	Unknown	Fixed facility

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
1979	Cove Point, Maryland, USA	An explosion occurred within an electrical substation. LNG leaked through LNG pump electrical penetration seal, vaporized, passed through 200 feet of underground electrical conduit, and entered the substation. Since natural gas was never expected in this building, there were no gas detectors installed in the building. The normal arcing contacts of a circuit breaker ignited the natural gas-air mixture, resulting in an explosion.	Flammability and Explosivity	Unknown	Design defect in a pump.	1 death, 1 serious injury, $3 million in damages.	Unknown	Fixed facility
1979	USA, Ship name: Mostafa Ben Bouliad	While discharging cargo, a check valve in the piping system of the vessel failed, releasing a small quantity of LNG.	Cryogenics	Unknown	Valve leakage.	Minor deck plating fractures.	Unknown	Marine vessel
1979	Ship name: Pollenger	Tank cover plate fractures.	Cryogenics	Unknown	Valve leakage.	Ship/Property damage	Unknown	Marine vessel
1983	Bontang, Indonesia	A rupture in an LNG plant occurred as a result of over-pressurization of the heat exchanger caused by a closed valve on a blow-down line. The exchanger was designed for a pressure of 25.5 psig but the pressure reached 500 psig. Therefore, the exchanger failed and an explosion occurred.	Flammability and Explosivity	Unknown	Incorrect operating pressure	Property damage	Unknown	Fixed facility
1985	Ship name: Isabella	Cargo overflow. Deck fractures.	Cryogenics	Unknown	Cargo valve failure.	Ship/Property damage	Unknown	Marine vessel
1987	Mercury, Nevada, USA	An accidental ignition of an LNG vapor cloud occurred at the US Department of Energy Nevada test site during large-scale tests involving spills of LNG.	Flammability and Explosivity	Unknown	Accidental ignition during testing.	Damaged and propelled polyurethane pipe insulation outside the fence.	Unknown	Testing facility
1989	Ship name: Tellier	Hull and deck fractures.	Cryogenics	Unknown	Broke moorings.	Ship/Property damage	Unknown	Marine vessel

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
1989	Thurley, United Kingdom	While cooling down vaporizers in preparation for sending out natural gas, low-point drain valves were opened. One of these valves was not closed when pumps were started and LNG entered the vaporizers. LNG was released into the atmosphere and the resulting vapor cloud ignited, causing a flash fire.	Flammability	Unknown	Valve left open when pumps were started.	2 injuries	Unknown	Fixed facility
1993	Indonesia	LNG leak from open run-down line during a pipe modification project. LNG entered an underground concrete storm sewer system and underwent a rapid vapor expansion that caused overpressure and ruptured the sewer pipes. Storm sewer system substantially damaged.	Volume released	Unknown	LNG leak from open run-down line during a pipe modification project.	Property damage	Unknown	Fixed facility
2002	Catalonia, Spain	An LNG tanker lost control, turned over, and came to a halt. Immediately, flames appeared between the cabin and the trailer. The flames grew, and approximately 20 minutes after the accident, the tank exploded with a small explosion, then a large explosion. Finally, a leaking cloud ignited and created a fireball.	Flammability, Explosivity, potential BLEVE	47.6m^3	Formation of an initiating crack by thermal stress followed by discharge	1 death, 2 injuries	Unknown	Road

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
2004	Algeria	A leak in the hydrocarbon refrigerant system formed a vapor cloud that entered a steam boiler. The increased fuel caused rapidly rising pressure which exceeded the capacity of the boiler's safety valve, and the steam drum ruptured. The boiler rupture ignited the vapor cloud and produce an explosion due the confined nature of the gas leak. Unit 40 and adjacent Units 20 and 30 also exploded. The blast spread outward, damaging surrounding structures and facilities.	Flammability and Explosivity	Unknown	Leak in the hydrocarbon refrigerant system.	27 deaths, 72 injuries, Property damage and material damage outside the plant's boundaries	Unknown	Fixed facility
2004	Ghislenghien, Belgium	A pipeline carrying natural gas from the Belgian port of Zeebrugge to northern France exploded.	Flammability and Explosivity	Unknown	Contractor accidentally damaged the pipe.	23 deaths, pipeline damage	Unknown	Pipeline
2004	Trinidad & Tobago	Workers were evacuated after a gas turbine at Atlantic LNG's Train 3 facility exploded, leading to an LNG fire.	Flammability	Unknown	Turbine fire explosion	Property damage	Unknown	Fixed facility
2005	Nigeria	A 28-inch LNG underground pipeline exploded in Nigeria and the resulting fire engulfed an estimated 27 square kilometers.	Flammability and Explosivity	Unknown	Minor leak remained unaddressed	11 deaths	Unknown	Pipeline
2009	United Kingdom	A maximum of ten litres of LNG was spilled and "immediately vapourised", because of the unintended activation of the emergency shutdown system, which caused powered emergency release couplings to separate, discharging LNG.	Volume released	Maximum of 10L	Unintended activation of the emergency shutdown system.	Property damage	Unknown	Fixed facility

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
2010	France	The incident occurred when liquid passed into the gas take-off line during discharge operations. The damage sustained extended to part of the ship's manifold and its feed lines.	Cryogenics	Unknown	Unintended LNG flow during discharge.	Ship/Property damage	Unknown	Marine vessel
2010	Australia	The ship suffered cryogenic burns when 2,000 to 4,000 litres of LNG were spilt.	Cryogenics	2,000-4,000L	Unknown	Ship/Property damage	Unknown	Marine vessel
2011	Murcia, Spain	An LNG tanker collided with a stationary lorry, immediately starting a fire. The fire engulfed the cargo tank, which was a single wall container rather than the double wall container that is recommended for LNG transport in the US. A pipe connection leading from the tank to the exterior was damaged in the collision. The fire burned for 71 minutes, then the tank exploded and created a fireball.	Flammability, Explosivity, potentially BLEVE (specifically attributed to single-walled container)	$46m^3$	Broken pipe connection due to collision	1 death, property damage	Unknown	Road

Date	Location/ Ship Name	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment
2014	Plymouth, Washington, USA	Pressure purges were performed to 5psig rather than industry recognized 0-1psig, so oxygen remained in the system. A valve had been slowly leaking natural gas into the system after the purge. The system was brought back online, and the pressurization of the air-gas mixture increased heat of the system further. Air-gas mixture was allowed to enter the salt bath heater in which it auto-ignited and led to explosion.	Flammability and Explosivity	234 barrels	Purge failed to remove a mixture from the system	5 injuries, $45 million costs	Plant evacuation procedure and emergency shutdown was started, upon first responders' arrival everyone was moved to a more remote point, and citizens were evacuated to a 2- mile radius.	Fixed facility

3.5.2 Representative Sample of Historical LPG Incidents

A representative collection of historical incident experience with LPG, including an incident summary, the main hazards exhibited, release volume, failure mechanism, consequences and incident response tactics utilized is summarized in Table 2 below.

Table 2: Representative Sample of Historical LPG incidents

Date	Location	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment	Source
1959	Deer Lake, Pennsylvania, USA	LPG tank truck was struck in the rear by a tractor trailer. Firefighters focused on protecting structure exposures and not cooling the tank, leading to a BLEVE.	Flammability BLEVE	7,000 gallons	Tank rupture	13 deaths, 10 injuries	Firefighters protected structure exposures.	Road	(Glore, 2014), (Fire Engineering, 2007)
1966	Feyzin, France	LPG leak in a refinery ignited, and the fire around the LPG tank caused a BLEVE.	Flammability, BLEVE	Unknown	Unknown	18 deaths, 81 injuries	Unknown	Fixed facility	(Salamonowicz & Majder-Lopatka, 2013)
1974	Oneonta, New York, USA	An LPG train derailed; five LPG freight cars exploded.	Flammability, BLEVE	Unknown	Train derailment.	54 injuries	Firefighters remained close to the fire attempting to cool the tank cars, leading to injury upon explosion.	Rail	(Cudmore, 2020), (New York Times, 1974)
1978	Donnellson, Iowa, USA	Propane vaporized and spread widely (about 75 acres of land covered) after being released from a ruptured pipeline. The vapors were ignited, leading to an intense fire.	Flammability	157,500 gallons	Rupture of a weakened pipe	3 deaths, 2 injuries	Unknown	Pipeline	(National Transportation Safety Board, 1978)

Date	Location	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment	Source
1978	Waverly, Tennessee, USA	Train derailment led to a mechanical BLEVE 24+ hours after the derailment	BLEVE	Unknown	Unknown	16 deaths, 43 injuries	Unknown	Rail	(Nolan, 2022), (Burke, 2003)
1984	Mexico City, Mexico	A large LPG leak was ignited at a terminal, leading to a multitude of explosions.	Flammability, BLEVE	11,000 m^3	Unknown	About 650 deaths and 7,000 injuries	Unknown	Fixed facility	(Salamonowicz & Majder-Lopatka, 2013) (Arturson, 1987)
1989	Ufa, USSR	Sparks from two passing trains caused gas leaking from an LPG pipeline to explode.	Flammability, VCE	Unknown	Workers noticed a pressure drop, but increased pressure rather than looking for a leak.	645 deaths	Unknown	Pipeline	(Akoeff, 2009)
1990	North Blenheim, New York, USA	Work using a backhoe had caused a rupture in an LPG pipeline, leading to an LPG leak that travelled far, and was eventually ignited, and exploded.	Flammability, VCE	Unknown	Improper pipe installation and monitoring.	2 deaths, 5 injuries	Unknown	Pipeline	(Mahoney, 2015)
1992	Brenham, Texas, USA	A valve issue led to a gas leak of LPG, which then accumulated, and was ignited. This led to further explosion.	Flammability, VCE	Unknown	Valve issue	3 deaths, 21 injuries	Unknown	Pipeline	(UPI Archives, 1992), (Suro, 1992)
1992	Tuen Mun, Hong Kong	Kerosene was being transported with LPG, and it is believed that the kerosene was deliberately ignited.	Flammability, BLEVE	Unknown	Deliberate ignition	Unknown	Unknown	Road	(Boult, 2000)

Date	Location	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment	Source
1997	Warsaw, Poland	A drunk driver collided with an LPG storage tank, leading to a gas leak and fire, then explosion.	Flammability, BLEVE	Unknown	Tank rupture.	2 deaths, multiple injured	Unknown	Fixed facility	(Salamonowicz & Majder-Lopatka, 2013)
1998	Bucheon, Korea	When unloading butane from a tank lorry into an underground storage tank, the lorry driver began the process without the safety officer present, and improperly connected a hose to the tank, leading to a large gas leak and catastrophic explosions.	Flammability, BLEVE	4.5 tons	Faulty joining of hose couplings in butane unloading process	1 death, 83 injuries	Unknown	Fixed facility	(Park et al., 2006)
2003	Melrose, Ontario, Canada	7 rail cars carrying LPG derailed from a train, collided with another locomotive, and multiple explosions occurred upon impact.	Flammability, potential BLEVE	Approximately 407,000 kg	Tank rupture due to impact	Property damage	300 residents in the immediate area were evacuated	Rail	(Transportation Safety Board of Canada, 2004)
2007	Naftobaza, Poland	A bottom valve split in a rail cistern, leading to gas leakage. The gas ignited due to an unextinguished fire and led to a jet fire.	Flammability	Unknown	Valve leakage.	1 injury	Unknown	Rail	(Salamonowicz & Majder-Lopatka, 2013)
2011	Chiba, Japan	Five BLEVEs occurred from the loss of 17 LPG storage vessels.	Flammability, BLEVE	Unknown	Tohoku earthquakes caused BLEVE	Property Damage	Full emergency evacuation, water mist and fire fighters evacuated.	Fixed facility	(Cosmo Energy Holdings Co., Ltd., 2011), (Krausmann & Cruz, 2013)

Date	Location	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment	Source
2012	Amuay, Venezuela	Pipe leak led to an extended LPG leak and spread, which was eventually ignited, exploding and leading to the ignition of other fuel storage tanks.	Flammability, potential BLEVE	Unknown	Unknown	47 deaths	Neighboring plants evacuated, operators at this plant leave the control booth and visually inspect the leak.	Fixed facility	(Kraul & Mogollon, 2012), (Schmidt et al., 2016), (Parraga, 2013)
2012	Kerala, India	LPG tanker collided with a road divider and exploded three times.	Flammability, BLEVE	16 tons	Unknown	20 deaths, 21 injured	Unknown	Road	(Kumar, 2013)
2013	Louisiana, USA	A tug towing a barge ruptured an LPG pipeline, and escaping gas ignited.	Flammability	Unknown	Pipeline rupture	1 death	Unknown	Pipeline	(CSB, 2016)
2013	Milford, Texas, USA	An LPG pipeline was ruptured by contractors that were installing a cathodic protection system. The leak was ignited.	Flammability	183,000 gallons	Pipeline rupture	Property damage	Evacuation of Milford and a nearby school.	Pipeline	(Seba, 2013)
2013	LaPorte, Texas, USA	Contractor cut a live LPG pipeline during demolition work at a pipeline facility, and the leak ignited.	Flammability	30,000 gallons	Pipeline rupture	2 injured	Unknown	Pipeline	(Lezon & Shauk, 2013)
2014	Lice, Diyarbaklr, Turkey	A tanker truck carrying LPG overturned and exploded on a highway.	Flammability, BLEVE	Unknown	Unknown	33 deaths, 37 injured	Unknown	Road	(Zengin et al., 2015)
2017	Sekondi/Takoradi, Ghana	LPG was being discharged from a tanker to large receptacles, when one receptacle was leaking. This led to ignition and explosion.	Flammability, BLEVE	Unknown	Missing bolts on a receptacle.	8 injuries	Unknown	Fixed facility	(Shaban, 2017), (Iyare & Stevens, 2017)

Date	Location	Incident Summary	Main Hazards	Release Volume	Failure Mechanism	Consequences	Incident Response Tactics	Means of Containment	Source
2020	Wenling City, China	An LPG tanker caught fire and exploded on an expressway. The blast sent the tank into a nearby workshop, causing a second explosion.	Flammability, BLEVE	Unknown	Unknown	20 deaths, 172 injuries	Unknown	Road	(CGTN, 2020)
2021	Montana, USA	The driver of a gas truck slid on ice and ran into one of two tanks that were to be filled. This caused an immediate fire, and eventually explosion.	Flammability, potential BLEVE	2,000 gallons	Unknown	Moderate property damage.	Unknown	Road	(Monares, 2021)
2022	Johannesburg, South Africa	An LPG tanker became stuck beneath a low-lying bridge, which sparked flames. As firefighters attempted to extinguish them, the tanker exploded.	Flammability, potential BLEVE	60,000 L	Unknown	34 deaths, 321 injuries	Firefighters attempted to extinguish the flames prior to the explosion.	Road	(AP News, 2023)

From Table 1 and Table 2, some trends can be identified that are consistent with the key findings from the literature review. For example, when analyzing previous LNG incidents, flammability, explosivity, and cryogenics are present as the main hazards in most of the incidents identified. Meanwhile, for the LPG incidents, flammability hazards are present in all events and BLEVE hazards are present for many of the incidents as well. It is worth noting that from the identified incidents with 10 or more deaths, LPG related incidents experienced more frequent high-consequence events in comparison to LNG. Specifically, this review identified ten LPG incidents with 10 or more deaths, whereas only four were identified for LNG incidents. LNG incidents have resulted more often in property or ship damage. The additional safety provided by the specific containers used for LNG can be observed as well, as the main failure mechanism for the LNG incidents is leakage, whereas the main failure mechanism for the LPG incidents is tank rupture. These results emphasize that the differing hazard focus within literature between LNG and LPG mirrors the observation of real incidents, that LPG incidents have more often had higher fatalities than LNG incidents, and that LNG containers provide a much stronger barrier with lower likelihood of rupture when compared to LPG containers. Finally, it is important to note that incident response tactics were often not included within these reports, despite the benefits that would come from being able to analyze both successful and unsuccessful tactics.

4. Comparative Hazard Assessment of LNG/LPG During Transport

4.1 Chemical and Physical Properties

To compare the hazards of LNG and LPG during transport, it is imperative to define and compare the chemical and physical properties of LNG and LPG. Hazards reflect the physical properties (i.e., how a material behaves) and chemical properties (i.e., how a material harms). A comparative assessment of the chemical and physical properties of LNG and LPG is summarized below in Table 3. Many of the important properties associated with both LNG and LPG have been highlighted. LPG is a mixture of aliphatic and aromatic hydrocarbons, mostly butane or propane, with a typical composition of at least 95% propane or 95% butane but can also be composed of many different mixture compositions per customer order. Therefore, the properties of LPG can be found anywhere within the range of propane and butane properties. Table 3 presents properties for the more common propane-rich LPG, and a comparison of pure butane and propane properties can be seen in Annex B.

Since both LPG and LNG are hydrocarbon mixtures, naturally they have many similar properties. For example, their vapors are noncorrosive, nontoxic, asphyxiants that exist as colorless gases at room temperature. Both produce visible flames which must be controlled with dry chemicals rather than water. However, there are vital differences between LNG and LPG which heavily influence their inherent hazards, as seen through the highlighted sections in the table.

Table 3: Chemical and Physical Properties of LNG and LPG

Property	LNG	LPG (propane-rich)
Composition	Almost purely methane	Mainly propane and/or butane
Molecular Weight (g/mol)	16.85	44.097
Liquid Density (kg/m^3) (at 25 ºC)	426	495
Gas Density (kg/m^3) (at 25 ºC)	0.656	1.808
Gas Density (kg/m^3) (at boiling point)	1.75	2.43
Liquid Viscosity (Pa*s)	1.2 x 10^-4	2.0 x 10^-4
Vapor Viscosity (Pa*s)	4.4 x 10^-6	7.4 x 10^-6
Liquid Surface Tension (N/m)	0.013	0.015
Specific Gravity (at 25 ºC)	0.554	0.495
Energy Content (MJ/L)	21	25

Property	LNG	LPG (propane-rich)
Heat of Combustion (MJ/kg)	50.2	46.34
Boiling Point (ºC)	-162 (-260 °F)	-42 (-44 °F)
Flash Point (ºC)	-188 (-306 °F)	-104 (-155 °F)
Critical Temperature (ºC)	-147 (-233 °F)	96.7 (206.2 °F)
Auto Ignition Temperature (ºC)	540 (1004 °F)	450 to 510 (842 to 950 °F)
Lower Flammability Limit	5%	2.15%
Upper Flammability Limit	15%	9.60%
Combustion Flame Temperature (ºC)	1960 (3560 °F)	1980 (3596 °F)
Average Pool Fire Flame Temperature (ºC)	1197 (2187 °F) Pool Diameter 21.7 ± 2.9 m (Luketa and Blanchat, 2015)	1219 (2226 °F) Pool Diameter 16.9 m (Yi et al., 2019)
Average Surface Heat Flux for 20m diameter pool (kW/m^2)	153	48
Stoichiometric Air/Fuel Ratio	17.3	15.7
Thermal Conductivity of Vapor [W/(m*K)]	0.0127	0.014
Volume Reduction by Liquefaction	600x	270x
Health (NFPA diamond)	3	1
Flammability (NFPA diamond)	4	4
Instability (NFPA diamond)	0	0
Appearance	Colorless	Colorless
Physical State at 20 ºC	Gas	Gas

Property	LNG	LPG (propane-rich)
Odor	Odorless. Does not contain the characteristic odor of natural gas	Faint Gasoline/Rotten Eggs/Rotten Cabbage odor
Germ cell mutagenicity	No	Yes
Carcinogenicity	No	Yes
Reactivity	When LNG vapors mix with appropriate amounts of oxidizing agents, including air and oxygen, in the presence of an ignition source, an uncontrolled explosive reaction can occur. Will also burn or explode in the presence of strong oxidizing agents such as chlorine, chlorine dioxide, bromine pentafluoride, oxygen difluoride, liquid oxygen, and nitrogen trifluoride. LNG will spontaneously ignite when mixed with chlorine dioxide. Also avoid contact with acids, aluminum chloride, and halogens.	Saturated aliphatic and aromatic hydrocarbons, contained in LPG, may be incompatible with strong oxidizing agents such as chlorine, chlorine dioxide, bromine pentafluoride, oxygen difluoride, liquid oxygen, and nitrogen triflouride. Charring may occur followed by ignition of unreacted hydrocarbon and other nearby combustibles. In other settings, mostly unreactive. Not affected by aqueous solutions of acids, alkalis, most oxidizing agents, and most reducing agents.
Inhalation	Nontoxic vapors, but can displace air and cause asphyxiation in enclosed spaces	Nontoxic vapors, but can displace air and cause asphyxiation in enclosed spaces
Skin contact	Frostbite due to cryogenic liquid	Frostbite due to sub-freezing liquid
BLEVE	Yes, but less risk than LPG	Yes, risk of BLEVE
Rises when released	Yes, eventually	No
Visible flame	Yes	Yes
Dissipate quickly	Yes, once less dense than air	No
Rapid Phase Transition	Yes	No
Fire fighting	Dry chemicals (water can excite the fire)	Dry chemicals (more difficult than LNG)
Corrosive	No	No

Note: Grey highlight signifies properties with significant differences between LNG and LPG.

Key insights and differences between the properties of LNG and LPG are summarized below:

- LNG is not odorized, as ethyl mercaptan will freeze at -148 °C (-234 °F) and LNG is shipped at -162 °C (-260 °F). Therefore, LNG releases are odorless vapor, while LPG is typically odorized prior to transport. However, non-odorized LPG can be found in transportation but must be specifically noted on either the rail or cargo tank container or shipping documents.

- A substance cannot exist as a liquid above its critical temperature. Due to its low critical temperature (-147 °C [-233 °F]), LNG must be liquefied by cooling. LPG has a much higher critical temperature (propane-rich: 96.7 °C [206.2 °F], butane-rich: 152.0 °C [305.6 °F]), and therefore can be liquefied by pressurization at ambient temperatures. Additionally, the boiling point difference between LNG and LPG (-162 °C [-260 °F] vs -42 °C [-44 °F] for propane-rich LPG and -1 °C [30 °F] for butane-rich LPG) means that LNG vaporizes much earlier than LPG when exposed to environmental temperature.
- Both substances are liquefied during transport, as LNG is kept at cryogenic temperatures and LPG is kept under high pressure. Contact with cryogenic liquid or vapors can cause severe damage to the skin and eyes. Normal structural firefighting clothing will not provide skin protection against liquid LNG due to its extremely low temperature. Breathing cold vapors can damage lung tissue. LNG contact with carbon steel can lead to material embrittlement and fracture, thereby requiring specialized containers and piping.
- Upon compression, LNG is compressed by a factor of 600x by volume, and LPG is compressed by a factor of 270x by volume.
- LNG has a much lower vapor density than LPG at standard temperature (0.656 kg/m^3 vs propane-rich LPG: 1.808 kg/m^3, butane-rich LPG: 2.59 kg/m^3). This leads to LNG rising (once the temperature is greater than -110 °C [-166 °F]) whereas LPG stays low to the ground. Therefore, once heated, LNG dissipates more rapidly than LPG. LNG vapors are heavier than air until approximately -110 °C (-166 °F), so while natural gas is lighter than air, initial LNG vapors will be heavier than air due to their cold temperatures and remain as a vapor cloud. LNG vapors can accumulate in low areas and travel some distance to a source of ignition. If LNG vapors are ignited, they will burn back to the source.
- There exist very distinct differences in the combustion properties of the two substances. LNG has a significantly higher auto-ignition temperature than LPG (540°C [1004 °F] vs propane-rich LPG: 450-510°C [842-950 °F], butane-rich LPG: 287 °C [549 °F]), therefore LPG will auto-ignite at much lower temperatures. LPG becomes flammable at a lower concentration (propane-rich LPG: 2.15% LFL, butane-rich LPG: 1.86% LFL), however, LNG has a wider range of concentrations at which it is flammable in air (5% LFL and 15% UFL). Additionally, LPG has a slightly higher average pool fire flame temperature than LNG (1219 °C [2226 °F] vs 1197 °C [2187 °F]), and LNG has a higher average surface heat flux when burning than LPG (153 kW/m^2 vs 48 kW/m^2).
- However, the byproducts of burning are the same for both LNG and LPG. When hydrocarbon burns, the main products of combustion will be CO_2 and H_2O for complete combustion, and CO will be produced during incomplete combustion. Due to these properties, it is difficult to conclude either LNG or LPG as having a higher flammability risk, and any comparison should be scenario-based.
- LNG and LPG tend to have similar reactions upon exposure to various chemicals as seen below:
    - When either LNG or LPG vapors mix with appropriate amounts of oxidizing agents, including air and oxygen, in the presence of an ignition source, an uncontrolled explosive reaction can occur.

    - Both LNG and LPG will burn or explode in the presence of strong oxidizing agents such as chlorine, chlorine dioxide, bromine pentafluoride, oxygen difluoride, liquid oxygen, and nitrogen trifluoride.
    - Both LNG and LPG will spontaneously ignite when mixed with chlorine dioxide.
- The two substances also have different event potentials.
    - LNG has a distinct phenomenon known as rapid phase transition (RPT). If large volumes of LNG are released on water, it may vaporize quickly causing a RPT. A RPT can only occur if there is mixing between the LNG and water. RPTs may be referred to as a physical explosion without combustion and can range from small pops to blasts large enough to damage structures. RPTs may also occur under very specific scenarios on land or other solid surfaces where LNG collects in a depression. The potential hazard to emergency responders of a rapid phase transition from an LNG spill onto a body of water requires further analysis, as it may be a hazard to emergency responders working in close proximity to the release.
    - LPG has a large risk of BLEVE in the case that its container is exposed to a fire. While LNG is not included in the Emergency Response Guidebook as having a risk of BLEVE occurrence, it contains all the properties that imply a risk of BLEVE, so it does in fact contain that inherent hazard.
- When evaluating the burning of LNG and LPG, their combustions and therefore their byproducts are quite similar, as seen below. It is important to note that these are ideal stoichiometric equations, and the reactions will proceed with different mechanisms in practice due to incomplete combustion and impurities.
    - Stoichiometric combustion of LNG (methane): $CH_4[g] + 2O_2[g] \rightarrow CO_2[g] + 2\ H_2O[l]$
    - Stoichiometric combustion of LPG (propane): $C_3H_8[g] + 5O_2[g] \rightarrow 3CO_2[g] + 4H_2O[l]$

- Note: Some properties such as heat flux and flame temperature vary depending on the situation, therefore these measurements were based on published values from literature.

4.2 Hazards of LNG and LPG Releases

Due to the various physical and chemical properties that were identified in the previous section, we can see that there are distinct differences between LNG and LPG. In application, the differences between these materials are important, but it is most important to identify how these differing properties affect the hazards for each substance.

The primary hazards presented during LNG transport include flammability, dispersion, and cryogenic temperatures. Meanwhile, flammability, explosion and dispersion are the core hazards presented during LPG transport. While these are the dominant hazards of LNG and LPG, it should be recognized that there are still other hazards emergency responders need to be aware of and prepared for. For instance, explosion is not listed here as a primary hazard of LNG, but it still poses an explosion hazard, particularly when there is confinement or semi-confinement, such as the presence of obstacles. It may be more difficult to achieve a supersonic explosion (also known as detonation) than LPG, however, sub-sonic explosions (deflagrations) with damaging over pressures have occurred with LNG.

These differences are captured within Table 4 and Table 5 below. Where Table 4 summarizes the differences in chemical properties, with respect to the three primary hazards of flammability, dispersion and cryogenics, Table 5 provides a comparison of heat transfer considerations for LNG and LPG releases (i.e., flashing liquid, pool spread, vaporization, and dispersion). Similar to Table 3, Table 4 utilizes propane properties to describe LPG, as propane-rich LPG is more common.

Table 4: Properties of LNG and LPG Categorized by Hazards

Hazard	Chemical Property	LNG	LPG (propane-rich)
Flammability	Flash Point	-188 ºC (-306 °F)	-104 ºC (-155 °F)
	Boiling Point	-162 ºC (-260 °F)	-42 ºC (-44 °F)
	Flammability Range	5% LFL - 15% UFL	2.15% LFL - 9.6% UFL
	Autoignition Temperature	540 ºC (1004 °F)	450 ºC to 510 ºC (842 to 950 °F)
	Combustion Flame Temperature	1960 ºC (3560 °F)	1980 ºC (3596 °F)
	Average Pool Fire Flame Temperature	1197 ºC (2187 °F) Pool Diameter 21.7±2.9m	1219 ºC (2226 °F) Pool Diameter 16.9m
	Average Surface Heat Flux for 20 m diameter pool	153 kW/m^2	48 kW/m^2
Dispersion	Expansion Ratio	600:1	270:1
	Gas Density at 25 °C	0.656 kg/m^3	1.808 kg/m^3
	Gas Density at Boiling Point	1.75 kg/m^3	2.43 kg/m^3
	Liquid Density	426 kg/m^3	495 kg/m^3
Cryogenics	Specific Gravity (Liquid Phase)	0.554	0.495
	Solubility in Water	Negligible (below 0.1%)	Negligible (below 0.1%)
	Critical Temperature	-147 ºC (-233 °F)	96.7 ºC (206.2 °F)
	Heat of Combustion	50.2 MJ/kg	46.3 MJ/kg

Analysis of these various hazard categories provides a clear understanding that the properties of LNG and LPG lead to very different hazards and levels of risk. For example, regarding flammability hazards, LPG becomes flammable at a lower concentration, auto-ignites at a lower temperature, and burns at a higher temperature. However, at the same time, LNG provides a larger flame surface flux than LPG, has a larger range of concentrations at which it is flammable, and both boils and flashes at a lower temperature than LPG. Therefore, the flammability hazards presented by each substance are different and a comparison must be made in a scenario-based approach, as demonstrated in Section 8.

Regarding dispersion hazards, LNG expands more than twice as much as LPG upon vaporization, leading to a larger volume of LNG vapor being present upon release. Additionally, the lower vapor density of LNG is crucially important, as LNG is denser than air when first vaporized but much less dense than air once heated. In contrast, LPG remains denser than air throughout this temperature range.

With respect to the cryogenics hazards, the critical temperature difference stands out, as the critical temperature of LNG is approximately 250 °C (91 °F) below that of LPG. It is because of this low critical temperature of LNG (-147 °C [-233 °F]) that LNG is liquefied by cooling, whereas the much higher critical temperature of LPG (propane-rich: 96.7 °C [206.2 °F], butane-rich 152.0 °C [305.6 °F]) results in LPG being able to liquefy through pressurization.

Table 5: Heat Transfer Hazard Comparison for LNG and LPG Releases

Hazard	LNG	LPG	Comments
Flashing Liquid			
For a pressurized liquid above its boiling point, exposure to atmospheric pressure leads to sudden depressurization, and therefore rapid vaporization that can lead to an explosion.	LNG is at a lower risk of flashing than LPG. For marine transport, it is transported below its boiling point (-162 °C [-260 °F]) and is not transported under pressure. Therefore, LNG will not have a higher probability of explosion due to flashing. For road and rail transport, LNG can be transported under pressure above its boiling point, leading to the possibility of a flashing liquid scenario. Under HM-264 methane can be offered for rail transportation at a maximum pressure of 15 psig. This corresponds to a transport temperature of approximately -242 ºF, and an increased probability of flashing. For rail transport, cryogens are typically offered above their boiling points. The inner vessel of LNG cargo tank trucks (TC/MC-338) and ISO-Containers for refrigerated liquefied gases (T75) are designed for pressures up to 70 psig, allowing LNG to be	LPG is at high risk of flashing, due to being transported at well above its boiling point (-42 °C [-44 °F]) and being almost exclusively transported under pressure. This leads to a high probability of instantaneous vaporization and the potential for an open-air vapor explosion.	None

Hazard	LNG	LPG	Comments
	transported at higher pressures. A higher pressure results in a higher risk of flashing.		
Pool Spread, Vaporization, and Dispersion			
The formation of a pool leads to an area of high concentration of the substance, which serves as a large flammability risk. The dispersion of vapor directly affects the asphyxiation and flammability risks posed.	Due to being at cryogenic conditions, LNG is likely to cool down the surroundings, which would then lead to LNG staying as liquid and forming a pool. However, due to the much lower boiling point of LNG, this would eventually vaporize as the environment warms up and heats the LNG. Additionally, once it is eventually vaporized, LNG is lighter than air and disperses upward and at that point dissipates.	LPG is most likely to release as a jet due to its pressurization. As LPG is released, it depressurizes and absorbs heat from the environment in order to evaporate. This cools down the environment to the point of frozen condensation being found around LPG tanks, and pool formation due to the reduced ambient temperature. This pool formation certainly depends on the ambient conditions, as butane has a boiling point around -1 °C (30 °F), and therefore an LPG mixture that contains significantly more butane will form a pool if the ambient temperature is below -1 °C (30 °F). Upon vaporization, LPG remains a dense gas, and stays low to the ground.	LNG and LPG have similar liquid surface tensions, leading to similar pool spread. Butane has a higher boiling point than propane (-1 °C [30 °F] vs. -42 °C [-44 °F]) and can pool when ambient temperatures are below -1 °C (30 °F).

In consideration of the various heat transfer hazards of LNG and LPG, liquid flashing, liquid pools, and dispersion are high priority concerns that must be accounted for. LPG, unlike LNG, is at a high risk of flashing, which can readily result in open air vapor explosions. The pool creation of these substances can depend greatly on the ambient surroundings. Under different conditions, both LNG and LPG can have varying likelihood of pool formation. However, upon vaporization, the behavior is far different. As mentioned above, when LNG vapors eventually warm up, they become lighter than air and will then rise and dissipate quickly. LPG vapors remain close to the ground as a dense gas, providing a consistent flammable vapor cloud at ground level for an extended period of time.

When a cryogenic liquid is expelled into the atmosphere during a release, it will release as a combination of liquid and vapor. This mixture is highly flammable in the case of LNG. Additionally, due to the sudden pressure drop, the liquid will be rapidly vaporized in a phenomenon known as "flashing". The liquid that does not vaporize forms a puddle on the ground that is called "rain out". The higher the tank pressure prior to release, the more intense flashing that occurs. More intense flashing corresponds to stronger liquid fragmentation and higher vaporization rates. Liquid fragmentation is the process of a stream or jet eventually ending in droplets; therefore, a stronger liquid fragmentation is a quicker transition from liquid stream to vapor droplets.

The French National Institute for Industrial Environment and Risks (INERIS) studied the effect of physical impingement on jet releases and their rain outs using semi outdoor large-scale experiments to emulate industrial conditions (Lim & Ng, 2021). These studies concluded that mechanical fragmentation (the liquid released becoming droplets during expulsion) rather than flashing (rapid vaporization through pressure drop upon release) is the main mechanism for vapor fragmentation (droplet formation), and that rain out was minimal for propane. Due to the low boiling point of propane, there was hardly any rain out for non-impinged leaks. Separately, INERIS performed experiments on LNG leaks up to 9 mm orifices which found that orifice leaks less than 3 mm in diameter will always be in two phases at up to 9 bar pressures, and that LNG releases from a tank pressure above 1.5 bar will have no rain out.

Simulations have been performed to model the properties of cryogenic liquid pools under atmospheric conditions (Nawaz et al., 2014). The temperature and vaporization rate of the pool were of particular interest. It was found that the pools initially remain at the boiling temperature and the pool temperature eventually drops as heat taken from the environment to initiate evaporation exceeds convection and conduction heat transfer. These results were verified by comparing to experimental data.

When LNG forms a pool on the ground this can be quite dangerous, as it is a source of evaporating LNG and therefore a source of flammable vapor clouds (Basha et al., 2012). Therefore, studies have been undertaken to understand the spread of these pools. When LNG liquid pools begin spreading, the pool is influenced by gravity, surface tension, inertia, and viscous friction. These competing forces lead to multiple flow regimes: the gravity-inertia regime in which gravitational forces are equal to inertial forces, the gravity-viscous regime in which gravitational forces are equal to viscous resistance (more applicable for spills on water), and the surface tension regime in which viscous drag forces are equal to the surface tension (more applicable for spills on land).

Experimental studies have been carried out by INERIS to mimic accidental industrial LPG releases (Bonnet & Lacome, 2006). The main results include rain out measurements for free and physically impinged jets of propane and butane. For free jets, only butane gave measurable rain out results. This is most likely due to the lower boiling point of propane. Propane saturation temperature lower at ambient temperature (8.3 bar at 20 °C) is higher than that of butane (2.1 bar with 20 °C). Higher pressure led to less significant rain out because the jet speed also increases, leading to the droplets evaporating more easily. For impinged jets, a longer distance to an obstacle leads to smaller rain out. This is because more time in the air prior to impact means more time for the droplets to evaporate. The findings from this testing described that for a two-phase jet, one can considerer that all the droplets during the first minute of release are vaporized in contact with the obstacles, and that beyond the first minute, part of the droplets will be captured by the obstacles. These droplets captured by the obstacles then become cold enough to contribute to the pool formation.

Luketa-Hanlin has provided a detailed review of many field test experiments for LNG transport hazards. This paper provided an overview of various experiments on dispersion, fires from spills on land and water, explosion, pool boiling, and RPT studies, as well as insight into models used for dispersion and thermal hazard distances. The review established the need for controlled parameters in experimental testing and recommended that the approach to field tests be adjusted to permit a larger amount of well-instrumented trials in order to vary the key parameters in a controlled setting (Luketa-Hanlin, 2006). This is vital as the review demonstrated the compounding effects of uncertainty on predicted hazard distances when multiple parameters have significant uncertainty.

5. Comparative Assessment of LNG/LPG Containment Systems

This section identifies the range of bulk transportation containers that may be used for the transport of LNG. Understanding the basic design, construction and behavior of the dangerous goods / hazardous materials container is a critical element in implementing a risk-based response protocol.

Containers used for the bulk transportation of LNG will have an inner tank constructed of a cold-resistant metal, an outer tank providing mechanical protection, and an insulation space between the two tank shells providing thermal protection. Given LNG's boiling point of -162 °C (-260 °F), the inner tank is constructed of a high-grade stainless-steel metal, with the outer tank shell generally constructed of carbon steel due to its increased mechanical strength (e.g., TC128 for rail cars). LNG containers must be capable of maintaining both temperature and pressure; if LNG is allowed to warm, it will begin to convert to a gas and would increase the pressure within the container.

Container factors that should be considered in analyzing and estimating the potential impact of the emergency response problem include:

- How has the container been stressed? Is it mechanical stress due to the energy associated with an accident or derailment, or thermal stress associated with flame impingement or metal embrittlement?
- Has the container been breached? If so, what is the nature of the breach (e.g., breach of the outer tank, activation of pressure relief device or ambient heating)?
- What type of release is occurring – liquid or vapor? Is LNG pooling or creating a vapor release?
- What harm will the container and its contents cause?
- What is the proximity of the release to exposures – people, property, environment, critical infrastructure?
- Does the problem involve fire? What is the nature of the fire (e.g., pool fire, jet fire). Are other LNG or dangerous goods / hazardous materials containers at risk of becoming involved?
- While water can be used to cool LPG containers, its effectiveness on LNG double-wall containers is limited and can actually lead to heating and increasing the internal tank pressure.
- Do responders have the capability of successfully controlling vapor or fire spread?

5.1 LNG Containers – General Characteristics

Cryogenic materials pose unique challenges for selecting the appropriate transportation packaging / container. General container characteristics that are applicable to all LNG bulk transportation containers regardless of the mode of transportation include:

- The extremely cold temperatures render most types of packaging materials too brittle to maintain during transportation. Therefore, all inner tanks of cryogenic means of containment are required to be constructed from stainless steel packaging that enables the container to retain their strength and ductility at extremely low temperatures. The outer tank is constructed of either stainless steel or carbon steel or combinations thereof and is focused towards providing mechanical and thermal protection.

- Ensuring that the product being transported remains at these cold temperatures during transportation is necessary to prevent product expansion and overpressure conditions, or possible activation of the container's pressure relief device.

- Bulk containers authorized for the transportation of flammable cryogenic materials are built as a

"tank within a tank" design and include:
  - TC/DOT-113 tank cars (capacity of 30,700 gallons and water capacity of 34,500 gallons)
  - TC/MC-338 cargo tank trucks (capacity of 12,700 and 16,300 gallons)
  - T75 UN portable tanks (capacity of 5,000 gallons for a 20 ft. container to 11,000 gallons for a 40 ft. container)
  - Marine vessel with either independent LNG tanks or membrane tanks (capacity of 35 to 55-million gallons).

- If an LNG container is breached in the liquid phase during an accident, the LNG will be released as a very cold liquid, thereby creating an LNG pool that could ignite. Employing a thicker normalized outer tank shell will reduce the puncture probability of the inner tank. In a rail accident scenario, a puncture of the inner tank can only occur after the outer tank is breached.

- There are currently no reports in the literature of a BLEVE of a cryogenic bulk container constructed to current standards for TC/MC-338 cargo tank trucks, portable tank containers, or rail tank cars. While possible, a BLEVE is viewed as a lower probability event given the following factors:
  - The tank car insulation system, as the double-shell container construction is more robust than non-cryogenic container designs such as found with LPG bulk containers.
  - The annular space works in combination with a properly functioning pressure relief system to reduce the likelihood of a high-energy event such as a BLEVE.
  - The requirement set forth in US Code of Federal Regulations Title 49 Part 173 Section 318 (49 CFR 173.318) for redundant pressure relief systems (i.e., pressure relief valve and burst discs).

5.2 IMO/ISO Portable Tank Containers

- The ISO UN T75 portable tank has been used to transport cryogenic liquids for decades and is suitable for transportation and use of LNG in marine, rail, and truck applications. Both Canada and Europe have approved the use of the ISO UN T75 portable tank for the rail transport of LNG. In the United States, smaller operations where LNG is used as a locomotive fuel have been in place in Alaska and Florida. There are no records of rail incidents involving LNG being shipped in ISO UN T75 UN portable tanks.

- In 2018, the US Department of Transportation's Pipeline and Hazardous Materials Safety Administration (US DOT/PHMSA) conducted a propane pool fire test on a 40-ft. ISO UN T75 portable tank filled with liquid nitrogen. During the 200+ minute fire exposure, pressure relief valves (PRV) opened successfully and relieved the internal pressure to avoid a BLEVE event.

- Test surface heat flux measurements using LPG are significantly lower than the heat flux expected during an LNG pool fire or natural gas torch fire. Therefore, it is conceivable that the thermal insulation may fail when subject to the intense heat flux of an LNG fire earlier than seen with LPG.

- In June 2022 PHMSA conducted additional fire tests on the ISO UN T75 portable tank. The results of the fire tests have not yet been released publicly.

5.3 Rail Transportation

Transport Canada allows for the transport of LNG by rail via a TC-113C120W or TC-113C140W tank car. Within the United States, US DOT/PHMSA has approved the DOT-113C120W9 with its enhanced jacket material and thickness for the rail transport of LNG. Note, at the time of writing, while the DOT-

113C120W9 meets the requirements for transporting cryogenic liquids, it is not yet approved for the transport of LNG in Canada. However, key construction features of this tank car include the following:

- This tank car is a vacuum-insulated "tank-within a tank" design similar to a thermos bottle consisting of a stainless-steel inner tank supported within a carbon steel jacket, herein after referred to as the outer tank, and specifically designed for the transport of cryogenic materials (e.g., liquid hydrogen, oxygen, ethylene, nitrogen and argon).

- The delimiter letter "C" indicates that the tank car is designed for loading and shipping temperatures as low as -162 °C (-260 °F).

- The suffix number "9" indicates that the tank car meets PHMSA's enhanced jacket material and thickness requirements. The outer tank is a minimum of 9/16-inch thick TC128 Grade B normalized. TC128 steel has a tensile strength of 81,000 pounds as compared to a yield strength of 36,000 pounds for an A1011 steel. This is the main differentiation between the TC-113C120W/140W and the new DOT-113C120W9.

- The inner tank is constructed of an austenitic stainless-steel alloy with a minimum thickness of 3/16-inch.

- The outer tank shell is 9/16-inch thickness constructed of normalized carbon steel (AAR TC-128 Grade B). This is the same steel as used for high hazard materials such as in the TC/DOT-105 (chlorine) and TC/DOT-117 (crude oil and ethanol) tank cars.

- The annular space between the inner tank and the outer tank is approximately 6-inches and is under vacuum. The insulated annular space minimizes the rate of heat transfer from the atmosphere to the liquid inside during transport and provides the majority of insulation value.

- Pressure relief devices include a self-closing pressure relief valve with a start-to-discharge pressure of 75 psig, and a non-reclosing pressure relief device (i.e., burst disc) set to discharge at the tank test pressure or an alternate pressure relief valve set to discharge at 90 psig. These tank cars may also have regulator valves (aka road valves) that function in transit to reduce the pressure and cool the liquid.

- TC/DOT-113 tank cars have a safety record of over 50 years and over 100,000 rail shipments with no reported fatalities or serious injuries occurring due to a train-accident caused release of product. Risk assessment research has shown the following:

    - Ninety-nine percent of the incidents involving TC/DOT-113 or AAR-204W (tank car similar in design to the TC/DOT-113 tank car) involved the non-accidental release of product attributed to defective or improperly secured valves and not a breach of the tank. Two significant rail incidents involving release of cryogenic liquids have occurred – one in Moran, KS (USA) and the other in Mer Rouge, LA (USA).
    - Moran, KS Derailment (2011) – Three DOT-113 ethylene tank cars derailed and two of the cars were breached and caught fire. The fire consumed the contents of the #1 ethylene tank car, while the #3 tank car containing ethylene did not breach but began venting through its pressure relief valve. The #2 and #3 tank cars eventually were breached by a controlled vent and burn process employed by tank car specialists to minimize the risks to responders and expedite the clean-up process.
    - Mer Rouge, LA Derailment (2014) – Two tank cars transporting refrigerated liquid argon

(DOT-113 and AAR-204W) derailed due to a truck stalling on the tracks and neither tank car was breached. Approximately 47,000 gallons of liquid argon was released through their pressure relief systems.

In some locations there currently exist locomotives that are powered by LNG. These liquefied natural gas-fueled locomotives are best identified by their connection to natural gas tenders, typically coupled in a locomotive / tender / locomotive configuration. The tender provides pressurized (125 psi) non-odorized gaseous natural gas to the locomotive at 4.4 °C (40 °F) to 46.1 °C (115 °F). LNG is not present on the locomotive(s).

Key design and construction features of the tenders include the following:

- LNG tenders are constructed to TC/DOT-113C120W specification as a minimum.
- Tenders are equipped with pressure relief devices similar to those found on cryogenic tank cars.
- Connections between the tender and the natural gas fueled locomotive consist of a gaseous natural gas fuel line and two heat exchange fluid lines (delivery and return) at temperatures between 4.4 °C (40 °F) to 52 °C (125 °F).
- Heat exchanger fluid is a 60% propylene glycol / water mixture.
- Emergency tender cut-offs are designed to stop the flow of gaseous natural gas to its coupled locomotives. Gaseous natural gas may still be present in piping and railroad personnel should be contacted if the pipes need to be vented and/or purged.
- Some external piping within rectangular protective housings may be cold and frosted due to the presence of LNG in the pipe. All cryogenic piping external to a protective housing that is accessible from ground level and/or adjacent to safety appliances is protected from incidental contact (e.g., jacketed or guarded). Piping used for tender-fill operations is excluded from jacketing or guarding requirements, as this component is free of liquefied natural gas after tender-fill operations. Proper PPE is required when handling these cryogenic components.
- The natural gas fuel line and the heat exchange fluid line are semi-permanently connected to the tender and are attached to the locomotive by use of dry quick-disconnect couplers. These lines may have manual shut-off valves behind the locomotive end plate and will have manual shut-off valves behind the tender end plate.

5.4 Highway Transportation

Within North America, the TC/MC-338 container specification has been used for the transportation of a wide range of cryogenic liquids, including LNG. LNG has been safely transported without reported incidents of container failure by truck in TC/MC-338 cargo tank trailers and its predecessors for more than 50 years. Key construction features of the TC/MC-338 cargo tank truck include the following:

- Like the T75 portable tank container and the TC/DOT-113, the TC/MC-338 relies on a vacuum-insulation design to maintain cryogenic temperatures.
- The inner tank is constructed of stainless steel.
- The outer tank is constructed of steel.
- The maximum allowable working pressure (MAWP) is 70 psi, with the relief valves set at 75 psi.

5.5 Marine Transportation

Internationally, LNG has been approved for marine vessel transportation use for over 60 years. Greater than 80,000 shipments by sea have occurred without major accidents (Pitblado, 2004). Throughout the lifetime of the maritime LNG shipping industry, eight marine incidents worldwide have resulted in LNG spills, and no cargo fires or fatalities from LNG spills have occurred (Beard, 1982; SIGTTO, 2003).

If LNG were to be released to the water, it would eventually volatize and convert to a vapor, warm, and rise. The vaporization can occur in such a rapid manner that it creates a localized overpressure that can result in physical explosions in the phenomenon known as RPT, as described in section 4.1.

There is a very robust and mature regulatory system for marine transportation. The International Maritime Organization (IMO) and the International Standards Organization (ISO) are the international governing bodies responsible for the specifications and standards for building vessels and containers for marine transport. Much of the technical observations, findings, and risk analyses in reference to transportation of LNG have been based upon work conducted in the maritime industry.

Safety systems and procedures that are integrated into maritime transportation include:

- All LNG ships have two hulls to protect the cargo in the event of a collision.
- A thick layer of insulation with two barriers exists on every ship's LNG tank.
- LNG vapors that boil off are burned as fuel for the vessel.
- All vessels have emergency shutdown devices (ESD), as well as fire and gas detection and firefighting systems.

There are two types of marine vessels:

- Membrane Ships – these are the more recent designs for LNG carriers.
- Moss-Rosenberg – have an easily identified spherical or domed design and were the earliest type of bulk LNG transport ship. This design is heavier than the newer membrane ships and burns more fuel. This design is still active as well.

Table 6: Comparison of LNG vs LPG Containers

	LNG	**LPG**
Road		
Cargo Tank Truck Specification	TC/MC-338 (Vacuum insulation design with outer jacket)	TC/MC-331 (Single-shell, non-insulated)
ISO Portable Tank Container Specification (also applicable to rail and marine)	UN T75 (Cryogenic Liquid – refrigerated liquefied gases)	UN T50 (Pressure – used for non-refrigerated liquefied compressed gases)
Rail		
Tank Car Specification	TC/DOT-113	TC/DOT- 105, 112, 114, 120
Tank Car Inner Tank Construction	3/16-inch 304 Stainless Steel	Greater of 9/16-inch to 11/16- inch minimum or by formula
Tank Car Outer Tank Construction	9/16-inch T128 Carbon Steel (for DOT-113C120W9 and anticipated TC-113C120W9)	Thermal insulation and jacketing
Tank Car - Thermal Insulation	Approximate 6-inch vacuum insulation	Meet 100 min. pool fire and 30 min. torch fire requirement

Tank Car - Maximum Allowable Working Pressure (MAWP)	60 psig	224 psig (TC/DOT-112A340W)

Marine		
Marine Tank Specifications	Moss or Membrane tanks	ISO tank containers 1CC, 1BB, 1AA
Marine – Maximum Allowable Working Pressure (MAWP)	Moss: 3.2 psig Membrane: 29 psig	237 psig
International Standards	IMO, USCG, MARPOL, IGC 1986 code and SOLAS 74 chapter VII part C	PED, ISO 1496-3, CSC, IMDG, RID, ADR, GC 1986 code, SOLAS 74 chapter VII part C
Operating Temperature	Below −162 ℃ (−260 °F)	-40 to 50 °C (-40 to 122 °F)

6. Comparative Assessment of Modeling and Risk Analysis

Currently, incident knowledge is insufficient to fully characterize the risk involved during the release of LNG/LPG. Data from models can be used to inform future projects and to explore outstanding gaps. This section identifies fundamental or empirical equations, source models and release mechanisms representing the chemical and physical processes occurring during the release of LNG/LPG.

6.1 Relevant Equations

After identifying and reviewing the properties of LNG and LPG, as well as their corresponding hazards and means of containment, empirical equations can be utilized to define the relationship between given quantities or factors which are required to develop models for potential situations. Specifically, in order to compare the risk and consequence of different release scenarios for LNG vs LPG, the equations in Table 7, as well as those in Annex C, can be used to calculate key variables. For the purposes of this study, equations characterizing the following factors were deemed most relevant as emergency response considerations in the initial phases of a release:

- Rate of release through an orifice
- Radiant heat flux
- Diameter of a pool
- Spreading of a pool
- Cloud travel (instantaneous puff, continuous plume)

Table 7 below identifies the fundamental equations for the key factors identified above. The primary differences between LNG and LPG spills within these equations have been defined, in order to identify the key properties that lead to differing behavior of LNG and LPG for the specified factors. Further equations that may be useful to understand LNG/LPG spills can be found in Annex C.

Table 7: Selection of Relevant Equations

Factor	Equation	Application	LNG/LPG Difference	Source
Rate of release through an orifice	$Q = C_d \cdot \rho_l \cdot A_h \cdot \sqrt{2 \cdot g \cdot H}$ Q = mass flow rate [kg/s] C_d = discharge coefficient, assumed to be 0.65 ρ_l = density of the substance $[\frac{kg}{m^3}]$ A_h = area of the hole $[m^2]$ g = gravitational constant, 9.81 $\frac{m}{s^2}$ H = liquid height above hole [m]	This provides the mass flow rate at which LNG/LPG would be expelled from a vessel in the case of a puncture.	The different liquid densities ρ_l of LNG and LPG lead to different mass flow rates at similar conditions.	Johnson & Cornwell, 2017
Radiant heat flux	$q = \tau \cdot F \cdot E$ q = radiant heat flux τ = atmospheric transmissivity F = view factor between the flame and the receptor E = surface emissive power of the flame $[\frac{kW}{m^2}]$	This provides the heat flux being thermally radiated from a fire involving LNG/LPG.	The surface emissive flame power E provides the difference in heat flux between LNG and LPG fires.	Johnson & Cornwell, 2017
Diameter of a pool	$D_{pool} = 2 \cdot \sqrt{\frac{Q}{\pi \cdot \dot{y}}}$ D_{pool} = diameter of a pool Q = released liquid volumetric flow rate $[\frac{m^3}{s}]$ $\dot{y}$ = vertical rate of liquid level decrease $[\frac{m}{s}]$	This assumes steady state conditions and provides the diameter of an unconfined pool in the case of LNG/LPG release.	The released liquid flow rate Q provides the difference in pool formation between LNG and LPG.	Bubbico & Marchini, 2008

Factor	Equation	Application	LNG/LPG Difference	Source
Spreading of a pool	$\frac{\partial^2 r}{\partial t^2} = [\frac{4 \cdot g_r \cdot \phi \cdot h}{r}] - C_f$ r = pool radius [m] t = time [s] $g_r = \frac{g \cdot (\rho_w - \rho_l)}{\rho_w} [\frac{m}{s^2}]$ g = gravitational constant, 9.81 $[\frac{m}{s^2}]$ ρ_w = density of liquid substrate $[\frac{kg}{m^3}]$ ρ_l = density of the substance $[\frac{kg}{m^3}]$ ϕ = coefficient of height h = mean pool height [m] C_f = frictional resistance force $[\frac{m}{s^2}]$	This provides the rate at which a pool spreads.	The g_r variable provides the difference between LNG and LPG in this equation, as $g_r = \frac{g \cdot (\rho_w - \rho_l)}{\rho_w}$ and ρ_l, the density of the substance, is different between LNG and LPG.	Johnson & Cornwell, 2017
Cloud travel	Instantaneous puff: $C = \frac{Q_m}{\sqrt{2} \cdot \pi^{\frac{3}{2}} \cdot \sigma_x \cdot \sigma_y \cdot \sigma_z} \cdot \exp\{-\frac{1}{2} \cdot [\frac{(x-u \cdot t)^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}]\}$ Q_m = total mass released $[kg]$ t = time since release [s] Continuous plume: $C = \frac{\dot{Q}_m}{\pi \cdot \sigma_y \cdot \sigma_z \cdot u} \cdot \exp\{-\frac{1}{2} \cdot [(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2})]\}$ C = concentration $[\frac{kg}{m^3}]$ $\dot{Q}_m$ = mass release rate $[\frac{kg}{s}]$ u = downwind velocity $[\frac{m}{s}]$ $\sigma_x, \sigma_y, \sigma_z$ = dispersion coefficients in x, y, and z directions x = downwind distance [m] y = crosswind distance [m] z = distance above ground [m]	These equations provide the concentration of a vapor cloud at various distances from the point of release.	The variable Q_m in both equations provides the difference between LNG and LPG. For an instantaneous puff, this corresponds to the mass released. For a continuous plume, this is the mass flow rate of the release.	Crowl & Louvar, 2019

6.2 Modeling LNG and LPG Releases

The ability to simulate potential incident scenarios would provide valuable insights to evaluate the severity and to optimize emergency response, and these types of simulations can be created in the form of models. Once various equations have been identified that are vital in the case of LNG/LPG incidents, it becomes more imperative to develop a method of automating these calculations, as well as finding the optimal method to display the results. These developments can come from modeling, of which there are many potential general model bases to use (see Table 8). Further discussion on the background and details of these models can be found in Annex D.

Table 8: General Model Descriptions

Model Type	Advantages	Disadvantages
Integral Models	• Predict the specific data required for hazard analysis • Very quick to run • Simple to use	• Extra features such as obstacles require additional effort to include • Assumptions for these extra features require further testing against experimental data • Usually limited to circular pools, flat substrates, and heat transfer only from the substrates
Computational Fluid Dynamics (CFD) Models	• Obstacles and terrain can be relatively straightforward to model • Can model complex situations with more detail	• Models are labor intensive • Setting up the problem requires skill and experience • Results are sensitive to the problem setup • Validation is also very labor and computer intensive
Shallow Layer Models	• Can be suited to obstacles and terrain • Less time intensive than CFD models • Assume horizontal spread is greater than vertical, therefore good for dense vapors	• More time intensive than integral models • Less accurate for vapors that disperse upwards

(Source: Ivings et al., 2016; Ikealumba & Wu, 2014)

These many options have led to multiple specific models, which have been identified in Table 9 below. Due to the tradeoffs between these models, it can be difficult to choose the most applicable option, therefore PHMSA has approved the LNGFIRE3 for radiant heat flux modeling, and the DEGADIS 2.1, FEM3A, FLACS v9.1r2, and PHAST software for vapor dispersion modeling, therefore these models are analyzed in Table 9. This approval is provided after the software has gone through a model evaluation protocol set forth by PHMSA as an assessment[2]. While ALOHA software is not among those approved by PHMSA, it is included in this comparison as it is widely used for safety engineering modeling applications in industry.

[2] https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-exclusion-zones

Table 9: Specific Models Comparison

Model Name	Advantages	Disadvantages
LNGFIRE3 (GTI Energy)	• Created to model thermal radiation from LNG pool fires	• Very limited in its applications and user inputs • May be difficult to apply to LNG spills on water
DEGADIS (Integral Model, US EPA)	• Quick to use • Has undergone significant validation • Vapor blanket estimates upwind and crosswind spreading at the source (uncommon feature)	• Obstacles and terrain not modeled • Doubts from some validation exercises
FEM3A (CFD Model, US DOE, LLNL)	• Based on previously tested and published numerical and physical sub-models • The physical sub-models are specifically tailored to the modeling of LNG vapor dispersion • Pre-processing tools can permit more rapid model set-up • User manual is available • Validation against field trials and wind tunnel data has been positive	• No user interface, only text file input and output • Modeling non-flat terrain, obstacles, or non-rectangular area source may not be practical • Very limited error handling while model is running • Quality of results very sensitive to model application • Requires user CFD and atmospheric dispersion knowledge • Run times are lengthy (24 hours or more)
FLACS (CFD Model, Gexcon)	• Flexible model, can be widely applied • Can handle complex geometries and terrain • LNG module based on previously published physical sub-models • Very up-to-date and support is available for the foreseeable future	• Limited range of validation cases • Quality of results very sensitive to model application • Requires user CFD and atmospheric dispersion knowledge • Run times are lengthy (24 hours or more) • Base model is proprietary and must be licensed
PHAST (Integral Model, USGS)	• Includes models for discharge, pool formation and evaporation, dense and buoyant gas dispersion, jet and pool fires, BLEVE's, and vapor cloud explosions • Pool spread model accounts for pool being on water or land, and instantaneous or continuous release • Model has been validated for a wide range of materials	• Source term has limited maximum temperature, so the source term must be calculated at a point with temperature below 600°C, otherwise, adequate source emissions model capability • Limited ability to model complex situations, chemical mixtures, and byproducts • Limited accuracy at low wind speeds and stable atmospheric conditions

Model Name	Advantages	Disadvantages
ALOHA (Integral Model, US EPA)	• Simple to operate • Estimates threat zones for toxic gas releases, flammable gas releases, BLEVEs, jet fires, pool fires, and vapor cloud explosions • Relatively fast computational time	• Limited ability to model complex situations, chemical mixtures, and byproducts • Limited accuracy at low wind speeds and stable atmospheric conditions • Limited source emissions model capability • Only includes heavy (high density) gas model (therefore LNG modeling is inaccurate compared to LPG)

(Source: Ivings et al., 2016; Ikealumba & Wu, 2014)

6.3 Risk Analysis

The risk of a process or activity is defined as a function of the likelihood of incident occurrence and the severity of the potential incident and is quantified as the product of probability and consequence. When evaluating the safety of a given process or activity, it is imperative to establish an understanding of the overall risk. This is typically achieved by conducting a risk analysis. This consists of a thorough analysis of the probabilities of different incident occurrences as well as the consequence or severity of these incidents. Once the probability and potential outcomes are recognized, preventative and mitigative barriers can be established in order to reduce both the probability and consequences. Finally, once these are implemented, the risk of a process can be well understood. Therefore, it is important to understand the research that has been undertaken in regard to either the probability or consequence analysis in this field, in order to understand the gaps in research that must be addressed to perform a full risk analysis.

- A research study by Beheshti et al. has explored the usage of ALOHA software to understand the consequence scenarios for a LPG leakage, fire, and explosion (Beheshti et al., 2018). Specifically, this was explored for 26-, 60-, 78-, and 107-liter containers.
    - FINDINGS: While these are much smaller than transport scale, it gives precedent to the usage of ALOHA software for risk modeling of LPG leaks.
    - GAPS: Little information is available on the use of current models for lighter gases such as LNG.

- An article by Jan Stawczyk helps expand our knowledge of the hazards, and therefore consequences, related to LPG tank explosions (Stawczyk, 2003). The study determined that the blast wave in an open space does not create an immediate threat to life but may cause material damage. The serious threat was projectiles launched from the explosion, with most projectiles from an 11 kg tank being dispersed in a radius of 100 m from the tank with a 300 m maximum. This is higher than the previous maximum range of 200 m delivered in literature, most likely due to the differences in tank build.
    - FINDINGS: Projectiles launched from an LPG tank explosion were previously underestimated. Most projectiles from an 11 kg tank would be dispersed within a radius of 100 m from the tank with a 300 m maximum.

- GAPS: Similar knowledge of projectiles launched from an LNG tank explosion does not currently exist.

- A study by Paltrinieri et al. focuses in detail on LPG transportation by road, which is intense in Europe (Paltrinieri et al., 2009). Specifically, the study explores the effect of passive fire protections on small scale vessels engulfed by fire and scaling this up to real road and rail tank cars. These passive fire protections are additional measures that work without active intervention, such as pressure relief valves and thermal coatings. A main focus of the study was also to explore whether these methods could actively reduce the probability of a "fired" BLEVE event. To define what this means, there are two main BLEVE types: "fired" BLEVE and "unfired" or "cold" BLEVE. The first is thermally induced, and usually occurs when a tank is impinged or engulfed by an external fire. The fire increases the temperature of the tank, reducing its mechanical resistance, while the increase of internal pressure causes an increase of the stresses acting on the vessel shell. This can result in the container rupturing and undergoing a BLEVE. "Cold" BLEVE's are not thermally induced. These events can occur during sudden system changes such as a violent impact on the tank during a traffic accident or by the tank's sudden failure due to a material defect or to overfilling. This study reports that more than 85% of BLEVEs recorded in past accidents are thermally induced.
    - FINDINGS: "Fired" BLEVEs can be considered the main BLEVE risk for LPG transport. The results from this research confirmed that passive fire protection strategies significantly reduced risk by up to an order of magnitude. Additionally, this study established that for the area being explored, an accident frequency of 3.31×10^{-7} events/km/vehicle can be utilized, and the probability of a release after an accident was assumed to be 0.05. These measures together provide an accident frequency estimation to be used for risk analysis.
    - GAPS: Similar studies on the potential for a BLEVE during the transportation of LNG do not currently exist.

- A study by Murray et al. provided a discussion of hazards associated with the importation of liquefied natural gas (Murray et al., 1976). When discussing the history of LNG operation, the period from 1959 to 1974 resulted in no significant LNG incidents. When analyzing this information to produce a risk level, the report states the following: "An Environmental Impact Statement (EIS) prepared for the Staten Island LNG terminal by the Federal Power Commission (FPC) estimates for marine transport of LNG that 2.144×10^{-7} is the probability for a serious LNG accident in each trip. If we accept that figure, the probability of 800 voyages with no accidents is 0.9983 (this probability is actually 0.9998). At a much larger probability, of say 2.144×10^{-4}, the probability of no serious accident in 800 trips would be 0.8424. Thus, the actual record is also consistent with this larger probability, with a confidence limit of 84%. Simply stated, the 800 accident-free voyages do not represent enough data to justify making estimate in this range of accident probabilities near zero." The values utilized for this probability of 2.144×10^{-7} serious LNG accidents per trip, however, was based on existing data for crude oil spills. This report also provided insight on the risk associated with sabotage and terrorism, saying that many analysts believe that the potential acts of terrorism and sabotage contribute significantly more probability to LNG risks than the design or operation.

- FINDINGS: Due to the fact that limited data exists on significant LNG incidents during transport, an estimation of the probability of a serious LNG accident occurring per trip was determined to be 2.144 x 10^{-7}. However, it is worth noting that this probability is extrapolated from existing data on crude oil spills.
- GAPS: Due to the differences between the properties of LNG and oil during a spill, this probability should be taken with skepticism although the results were later support by work from Margulies (Margulies, 1982).

- A study mostly focused on railroad transport of LNG was published in Delaware Currents (Mele, 2022). In a 21-year period (1997-2018) in Bradford County, PA., there were nine casualties in railroad accidents, two of which were fatal. Both fatalities were related to individuals trespassing on the tracks rather than an incident involving the rail cars. From 1977-99, however, there were three derailments that resulted in unspecified hazardous materials being leaked. While this is a large number of derailments and leaks, the rail tank cars permitted to transport LNG would utilize both an inner tank and an outer shell, which would be much more resistant to rupture. The existing models upon which those tank cars are based do have a history of incident, however.
  - FINDINGS: This article stated that from 1980 to 2017 (37 years), there were 14 cases of TC/DOT-113 tank cars being damaged. In two of those cases, the outer jacket and inner tank were breached – the most serious kind of damage. This is important as for an LNG leak, both inner tank and outer jacket would need to be breached. Two breaches in a period of 37 years is certainly promising.
  - GAPS: The article does not state how many trips, or the total miles traveled by tank cars during this time. Therefore, a probability cannot be established.

- A paper by Vanem et al. attempts to create a generic risk assessment for the global usage of marine LNG transport (Vanem et al., 2008). When analyzing the incident history of marine transport, various statistics on the different tanker types were gathered, which can be seen in Table 10. It is important to note that the authors concluded that accident frequency is independent of carrier type for their study since the available statistics are very sparse and any conclusion should include the population of each carrier type.

Table 10: Statistics of LNG Carrier Operations

	Makeup of fleet (%)	**Incident distribution (%)**	**Incident Distribution - Limited to 1985 and later (%)**
Membrane tankers	50	37	61
Spherical tankers	45	51	33
Others	5	11	4
Unknown		2	2

(Source of data in Table 10: Vanem et al., 2008)

Further, in Table 11, it can be seen that despite more transported LNG, the frequency of incidents is being reduced over time. For example, the number of ship-years doubles between the time range of 1986-1995 and 1996-2005, however there were only 2 more incidents in the latter time period. To define a shipyear, this is one ship in use for one year, so the unit per shipyear can be understood as per ship per year. This demonstrates that the already low probability of LNG carrier incident is still decreasing.

Table 11: Breakdown of Historic Accident Data based on Accident Categories and Periods of Time

Time Range	1964-1975	1976-1985	1986-1995	1996-2005
Ship-years	116	585	770	1367
Collision	1	10	4	4
Grounding	1	6	-	1
Contact	-	4	-	4
Fire and Explosion	2	5	-	3
Equipment/Machinery Failure	-	39	7	9
Heavy Weather	-	6	3	-
Failure of Cargo Containment System	7	15	5	-
Total	11	85	19	21

(Data in Table 11 from Vanem et al., Analysing the risk of LNG carrier operations)

Finally, in Table 12, a direct comparison is delivered of accidents and frequency from 1964-1995 and 1996-2005. It is important to remember that the limited number of incidents related to LNG transport makes it difficult to make conclusions about risk, however, the reduction in events over time is promising for further LNG transport in the future.

- FINDINGS: Despite more transported LNG, the frequency of incidents is being reduced over time.
- GAPS: The authors concluded that accident frequency is independent of carrier type for their study since the available statistics are very sparse and any conclusion should include the population of each carrier type. The limited numbers of incident related to LNG transport make conclusions about risk difficult.

Table 12: Distribution of Historic LNG Accidents on Categories.

Accident Type	Number of accidents 1964-1995	Number of accidents in 1996-2005	Frequency 1964-1995 (per shipyear)	Frequency for 1996-2005 (per shipyear)
Collision	15	4	$1.0 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$
Grounding	7	1	$4.7 \cdot 10^{-3}$	$7.3 \cdot 10^{-4}$
Contact	4	4	$2.7 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
Fire and Explosion	7	3	$4.8 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$
Equipment and Machinery Failure	46	9	$3.1 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Heavy Weather	9	-	$6.1 \cdot 10^{-3}$	NA
Failure of Cargo Containment System	27	-	$1.8 \cdot 10^{-2}$	NA

(Table 12 expanded from Vanem et al., Analysing the risk of LNG carrier operations)

- In a study by Margulies, the number of LNG marine transport voyages without any large releases was updated to 5200 voyages (Margulies, 1982). To update the examples above from the Federal Power Commission (FPC), with a failure probability of $2.144x10^{-7}$ the probability of 5200 successful voyages with no large release is 0.9989. If the failure probability were instead $2.144x10^{-4}$ the probability reduces to 0.3279. Therefore, with this many successful voyages, it becomes much more likely that the failure probability is closer to the initial, much smaller estimate. This study also established the probability of general ship failure scenarios (not LNG specific) for Cove Point, Maryland. The estimated probability of ship rupture at the dock is $4.1x10^{-6}$, and the probability of ship collision and rupture in transit is $5.5x10^{-6}$. These statistics assume 92 voyages per year.
    - FINDINGS: The data in this report supports the failure probability of LNG transport voyages determined by Murray et al. (Murray et al., 1976) to be $2.144x10^{-7}$. This is far less than the estimated probability for general ship failures at the dock ($4.1x10^{-6}$) and the probability of general ship collision and rupture in transit ($5.5x10^{-6}$).
    - GAPS: Similar studies establishing the probability of road and rail transport failure for LNG do not currently exist.

- In the PHMSA assessment of LNG rail transport, incidents involving ethylene, refrigerated liquid (UN1038) in DOT-113 tank cars in the PHMSA Incident Reports Database were analyzed (Cambridge Systematics, Inc., 2019). Seventy-three incidents were identified involving cryogenic ethylene tank cars between 1977 and 2015. Only 5 incidents were listed as "HMS Serious Incident." Several of the less serious incidents are related to venting from residue cars. The authors stated that these types of incidents have rather simple mitigation options such as increasing the start-to-discharge pressure of the main safety relief valve by 15 psi (20 percent), thereby reducing the number of times cars vent and the amount they vent.
    - FINDINGS: Perhaps the most important conclusion from this study related to LNG rail transport is that there are no reports of inner vessel punctures. Since LNG utilizes an inner tank and outer tank with an especially strong inner vessel, a very low probability of catastrophic events is shown through that statistic.
    - GAPS: Data is extrapolated from cryogenic ethylene, as insufficient data exists for LNG transport.

- The Sandia reports provides a thorough exploration into the vital aspects of risk analysis for marine exploration, and therefore the findings were integrated into future regulations. The report published in 2004 evaluated the smaller-capacity vessels (125,000-140,000m^3) while the report published in 2008 evaluated large-capacity vessels (250,000m^3) (Hightower et al., 2004; Luketa et al., 2008). The Sandia studies also provide insightful guidance and risk reduction strategies for the transport of LNG over water.
    - FINDINGS: The report established for different leak hole sizes and different amounts of breached tanks the pool diameter, burn time, distance to specific heat fluxes, and distance to the lower flammability limit (LFL). This is some of the most applicable testing for LNG transport done to this point.
    - GAPS: Similar testing for the land transport of LNG should be performed.

- Due to the lack of data surrounding LNG transport risk, a publication from Exponent discussed the relative risk of LNG compared to LPG in bulk transport (Hart & Morrison, 2015). This study established that since LPG is pressurized and LNG is insulated, LPG releases at a much higher velocity than LNG leaks. This is important in the consideration of jet leaks, in which the fluid is expelled at a high velocity. LPG has a long history of transport as a commodity in North America and the transportation risks are widely known and accepted, while the transportation risk of LNG is less known. For the road transport annual vehicular accident rate, the rate for all pressure tank cars was labelled as identical to that of LPG pressure tank cars in specific, therefore the report established an accident rate of $9x10^{-8}$ accident per mile per year for both LNG and LPG tanker trucks. For rail transport, the cryogenic tank accident data are sparse, therefore the same method was utilized to assume an identical accident rate of $6x10^{-7}$ accidents per mile per year for both LNG and LPG rail tank cars. These accident rates were derived from the US DOT Commodity Flow Surveys[3] and the PHMSA annual accidents data[4]. While admittedly likely overestimating the risk of LNG leak, the report established the probability of no release for a rail accident to be 0.95, and the probability of no release for a road accident to be 0.77. These values most likely overestimate the risk for both rail and road accidents causing release due to the double walled, reinforced design that LNG cryogenic tank cars utilize. Similarly, it was found that while no data exists for LNG BLEVE occurrence, the risk should be considered as a possibility. The report did also note that the rail incident rate on a per mile basis was approximately five times higher than that of road transport. However, within this determination they also stated the difference in mileage being of concern despite the rate already taking mileage into account, and therefore this concern is baseless.
    - FINDINGS: The authors concluded that the individual and societal risk for LNG transport would be similar to or less than that of LPG. It is also important to note that when taking into account the aspects that were disregarded such as the lack of observed LNG BLEVEs and the double walled tanks, the risk is potentially much lower for LNG transport than LPG transport.
    - GAPS: Testing to support these conclusions has not been performed.

When analyzing the research in the area of LNG and LPG transport, the lack of risk analysis for LNG transport becomes apparent. General accident frequency analysis has been found for LPG transport, with some studies providing the severity of leakage incidents as well. For LNG transport, frequency analysis has solely been located for marine transport. Most of these frequency analyses have been based-off of very sparse data as well, leading to large uncertainties in the determined probabilities. It is also apparent that consequence analyses have not been sufficiently addressed, and therefore LNG is greatly lacking in any form of risk analysis. However, a lack of incident data may prove a high degree of safety to these transport processes, as the low amount of rail incidents and marine incidents in LNG transport would imply.

[3] https://www7.bts.dot.gov/cfs

[4] https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics

7. Emergency Response: Risk-Based Response Principles and Scenarios

The focus of this section is to present likely LNG emergency response scenarios in bulk transportation, and the application and utilization of risk-based response principles for these scenarios. Section 8 will build upon this information and will evaluate the recommended emergency actions for an LNG incident as outlined in the Emergency Response Guidebook (ERG) – 2020 edition.

The ERG guidance is primarily targeted towards personnel and emergency responders operating at the Awareness and First Responder Operations levels. However, it may also be utilized by responders operating at the Hazardous Materials Technician and HazMat Incident Commander levels, as defined in *NFPA 470 – Hazardous Materials / Weapons of Mass Destruction (WMD) Standard for Responders,* especially in the initial size-up of the incident.

Other sources of LNG emergency response guidance or issues referenced in this section include:

- HAMMER Federal Training Center – Liquefied Natural Gas (LNG) Commodity Preparedness and Incident Management Reference Sheet - CPIMRS (December 15, 2001) (see Annex I)
- TRANSCAER LNG Safety and Emergency Response Training Program (May 12, 2022) (see Annex H)
- National Academies of Sciences, Engineering and Medicine Report – Safe Transportation of Liquefied Natural Gas by Rail Tank Car (September 6, 2022) - https://www.nationalacademies.org/our-work/safe-transportation-of-liquefied-natural-gas-by-railroad-tank-car
- Transport Canada Emergency Response Assistance Plan (ERAP) requirements - https://tc.canada.ca/en/dangerous-goods/emergency-response-assistance-plans-eraps
    - Although not a focus of this study, bulk shipments of certain Class 2 dangerous goods, including LNG and LPG, are subject to Transport Canada's ERAP requirements. Where required, the ERAP provides the foundation for a risk-based response to certain higher-risk dangerous goods while they are in transport. These plans are commonly produced by producers, manufacturers or distributors of dangerous goods, and are specific to certain dangerous goods, modes of transport, containers and packaging, and the geographical area in which the dangerous goods will be transported.

    - ERAPs are plans that are pre-approved by Transport Canada and can identify specialized personnel and equipment needed for responding to an incident, including the prompt provision of technical and emergency response advice. They may also be used in conjunction with emergency response plans from carriers or provincial authorities. An incident management system should be used to ensure coordination between the ERAP and other emergency response plans.

Risk-Based Response (RBR) Principles. Incident specific decisions should be based upon the use of a risk-based analysis process. *NFPA 470 – Hazardous Materials Standards for Responders* defines Risk Based Response (RBR) as a systematic process, based on the facts, science, and circumstances of the incident, by which responders analyze a problem involving Dangerous Goods/Hazardous Materials (DG/HM)/Weapons of Mass Destruction (WMD) to assess the hazards and consequences, develop an incident action plan (IAP), and evaluate the effectiveness of the plan. Key input factors that must be considered include the following:

- Incident Facts – include the HM/DG involved and the quantity, the type of container (bulk, non-bulk), its construction and integrity, and the circumstances of the incident including location, proximity of exposures and the nature of the terrain.

- Science - the physical properties (i.e., how it behaves) and chemical properties (i.e., how it can harm) of the materials involved.

- Circumstances - type of stress applied to the container and its breach / release behavior, emergency responder's level of training, experience and expertise based upon the incident scenario, and the level and response time of available emergency response resources and operational capabilities

The incident scenarios outlined later in this section were assessed through the lens of the RBR methodology, emphasizing the operational emergency response factors that may influence the size and/or complexity of an LNG or LPG incident involving bulk transportation. Among the factors that should be considered in analyzing and estimating the potential impact of an incident include:

- Most containers used for transportation of LNG have an inner tank and an outer tank, with an insulation space between the two tank shells.
- How has the container been stressed? Is it mechanical stress due to the energy associated with an accident or derailment, or thermal stress associated with flame impingement?
- Has the container been breached? If so, what is the nature of the breach (e.g., activation of pressure relief device or ambient heating, leak or puncture)?
- What type of release is occurring – liquid or vapor? Is LNG pooling or creating a vapor release?
- What harm will the container and its contents cause?
- What is the proximity of the release to exposures, including people, property, environment, and critical infrastructure?
- Does the problem involve fire? Are other LNG or dangerous goods containers at risk of becoming involved?
- Do responders have the operational capability to successfully control the vapor release or fire spread?

RBR Observations Specific to LNG and LPG

- The highest priority risk during the transport of LNG and LPG is the potential for fire. Despite the differing flammability properties relative to LPG, fire remains the largest threat in the event of an LNG container breach and release. For LNG, these risks exist for both jet fire and pool fed fire scenarios. When the LNG vaporizes and escapes through a breach, the product can lower the ground temperature, thereby leading to a pool forming on the ground and less likelihood of evaporation. Therefore, if the vapor cloud is ignited, the fire will spread back to both the pool on the ground and then to the source of the LNG breach, thereby creating a jet fire. In comparison, LPG has a much higher likelihood of a jet fire due to being a pressurized liquefied gas. Additionally, despite the lower flammable properties of LNG, the risks posed by an LNG fire scenario may be greater due to its higher radiant heat flux.

- Following fire, the risk of a BLEVE must be evaluated. For LPG, the BLEVE risk is extremely high and are only considered a second risk priority after flammability, given that the initial fire can act as an ignition source in a cascading response scenario, such as a train derailment, where multiple containers are involved. For an LNG release, the volume of vapor released will potentially impact both the flammability risk and the asphyxiation risk, especially if the vapors are released in a confined environment such as during marine transportation.

- Rapid phase transition (RPT) must be considered for LNG maritime incidents, if the incident is directly in contact with a waterway, or if there is a deep ground depression in the vicinity. While RPT may lead to an explosion without any flames, it has been recognized in literature that RTP may have served as an ignition source for a vapor cloud explosion (Mokhatab et al, 2014).

- LNG transportation via marine vessels can cause unique challenges not encountered in other modes of transport. Exposure to cryogenic liquids could be hazardous as the vessel's hull structure cannot withstand the extremely cold conditions. Compounding this issue is the fact that there are few Hazardous Materials Response Teams (HMRT) or specialized response units specializing in the transportation of cryogenic liquids.

- In 2019, the U.S. Department of Transportation - Federal Railroad Administration (FRA) published an emergency responder guidance brochure for the transport of LNG via rail after the approval to use LNG as a locomotive fuel tender (Raj et al., 2019). The brochure complements the general response information for flammable gases found in the ERG, Guide 115 – Flammable Gases.

- As part of its LNG by Rail rulemaking process, the U.S. Department of Transportation – Pipeline and Hazardous Materials Safety Administration (PHMSA) published a risk assessment on the surface transport of LNG in 2019 (Cambridge Systematics, Inc., 2019). Included was a section pertaining discussing emergency response to LNG. Crude oil and ethanol derailments in the United States and Canada led to more involvement from first responders in training sessions, particularly those related to high hazard flammable trains (HHFT) and have influenced emergency preparedness to dangerous goods incidents along railroads.

LNG Emergency Response Scenarios

LNG can present a range of potential emergency response scenarios which can be analyzed based upon the potential impact of the incident and categorized based upon their prioritization for each mode of transportation. The following tables compare the response factors for LPG and LNG for LNG-specific hazards. Four potential general risk-related scenarios that are outlined later in this section, include:

- Cryogenic Behavior and Effects (see Table 13).
- Fires (Pool Fire, Jet Fire, Vapor Cloud Fire and BLEVE) (see Table 14).
- Vapor Cloud Explosions - open air vs. confined (see Table 15).
- Rapid Phase Transition (see Table 16).

Table 13: Emergency Response Scenarios: Cryogenic Behavior and Effects

Cryogenic Behavior	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
The cryogenic material is released from its container in a liquid phase and will then start to vaporize as it absorbs heat. Cryogenic containers are manufactured from high quality metals intended for their storage and transport.	Many gases are heavier than air and will spread along the ground and collect in low or confined areas (sewers, basements, tanks, etc.). ELIMINATE all ignition sources (no smoking, flares, sparks or flames) from immediate area. Do not touch or walk through spilled material. Stop leak if you can do it without risk. Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material. Do not direct water at source of leak or safety devices; icing may occur. **CAUTION:** For **LNG - Liquefied natural gas (UN1972),** DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors. **CAUTION: When in contact with refrigerated**	LPG can sometimes pool (i.e., if butane-heavy) and will float on water. LPG gas has 270:1 liquid to vapor expansion ratio. LPG vapors are heavier than air. If ignited, LPG will flash back to the source. Auto-refrigeration can become a response issue depending upon the breach. Although asphyxiation can be an issue in confined locations, flammability is a greater hazard.	LNG will pool on hard surface and will float on water, causing the water to look like it is boiling as the LNG transitions back to vapor. This vapor can persist for an extended time as a low-lying cloud as it warms. LNG gas has 600:1 liquid to vapor expansion ratio. As LNG vaporizes back to a gas, it creates hazards similar to a natural gas release. While natural gas is lighter than air, LNG vapors will accumulate in low areas due to low temperatures. If ignited, will burn back to source. Auto-refrigeration can become a response issue depending upon the type of breach. Although asphyxiation can be an issue in confined locations, flammability is a greater hazard. DO NOT apply water, regular or alcohol resistant foam directly on spill. Use a high expansion foam if	Guide 115 incorporates a range of flammable refrigerated / cryogenic liquids (Methane, Ethane, Ethane / Propane Mixtures, Ethylene, Hydrogen). How significant is the embrittlement risk on container integrity if there is a breach of the inner tank and outer tank? Air monitoring and detection will be critical in assessing vapor travel, the effectiveness of water streams, and hazard control zones. LPG may be odorized with ethyl mercaptan depending upon its application and use. LNG is not odorized because ethyl mercaptan has a higher freeze point than LNG.	Embrittlement risk on container integrity is an issue, however the extent of that issue has not been fully evaluated. Traditional Class B firefighting foams utilized fluorinated compounds as wetting agents. These compounds have been found to be environmentally persistent and therefore are being replaced with non-fluorinated alternatives. However, these legacy foams were never recommended for use on LNG releases. It would be prudent to evaluate the new synthetic firefighting foams to see how they will behave in contact with LNG.

	/ cryogenic liquids, many materials become brittle and are likely to break without warning.		available to reduce vapors. When in contact with refrigerated / cryogenic liquids, many materials become brittle and are likely to break without warning. Spill control considerations will be based upon the spill surface (dirt, solid surface, water).		

Table 14: Emergency Response Scenarios: Fires (Pool Fire, Jet Fire, BLEVE and Vapor Cloud Fire)

Fire Scenario	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
Pool Fire Materials are released from their container in a liquid phase, which is confined and pools on a hard surface. If an ignition source is encountered, the vapors will ignite and travel back to the origin of the release resulting in the pool fire.	**DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED.** **Small Fire** – Dry chemical or CO_2 **Large Fire** – Water spray or fog **Fire Involving Tanks** Fight fire from maximum distance or use unmanned master stream devices or monitor nozzles. Cool containers with flooding quantities of water until well after fire is out. Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank.	Due to its physical properties and transport conditions, LPG (propane) is less likely to pool and more likely that any released liquid will vaporize and burn off. LPG can sometimes pool (i.e., if butane-heavy) and will float on water. This pool formation certainly depends on ambient conditions, as butane has a boiling point around -1 ^{o}C (30 ^{o}F), and therefore an LPG mixture that contains significantly more butane will form a pool if the ambient temperature is below -1 ^{o}C (30 ^{o}F). Cooling of any exposed containers will be critical in minimizing growth of the fire problem.	LNG is more likely to have pooling due to lower transport temperatures than LPG. If the spill occurs in an unconfined area, the burning pool fire is free to flow based upon the topography and geometry of the spill. Do not apply water to pooled LNG, as it will heat up and increase rate of LNG vaporization and the intensity of the fire. Water may have limited effectiveness in cooling exposed LNG or cryogenic liquid containers that have maintained their integrity due to the tank within a tank design. High-expansion foam may be helpful in suppressing LNG vapors in dike and impoundment areas at LNG storage and transfer locations.	Air monitoring and detection will be critical in assessing vapor travel, the effectiveness of water streams, and hazard control zones. The visible vapor cloud is not a reliable indicator of vapor location. While potassium bicarbonate (Purple K) is the preferred extinguishing agent for a small LNG fire, re-ignition is a distinct possibility. When high-expansion foam is initially applied to an LNG spill there is some initial warming and an increase in vaporization, but the rate of vaporization eventually stabilizes and slows down the escaping LNG vapor so that the flammable area of the release is much smaller.	None

Fire Scenario	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
Jet Fire Fire occurs during loading or unloading operations when pressures are increased by pumping, or with the ignition of vapors from the pressure relief valve (PRV) discharge. In a cascading derailment / accident scenario, a second container is impinged upon by fire, heats up and its PRV is activated. A jet fire from the PRV discharge could impinge upon adjoining containers and increase the severity of the scenario.	**DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED**. **Small Fire** – Dry chemical or CO_2 **Large Fire** – Water spray or fog **Fire Involving Tanks** Fight fire from maximum distance or use unmanned master stream devices or monitor nozzles. Cool containers with flooding quantities of water until well after fire is out. Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank.	ERG BLEVE SAFETY - PRECAUTIONS and ERG BLEVE TOOL provide summary of tank properties, critical times, critical distances, and cooling water flow rates for various tank sizes. Data is primarily based upon LPG. Critical factor is application of sufficient water at the point of thermal impingement of the exposed container. Can only be controlled by isolating the source or product flow, while protecting exposures (as possible).	ERG BLEVE SAFETY - PRECAUTIONS and ERG BLEVE TOOL provide summary of tank properties, critical times, critical distances, and cooling water flow rates for various tank sizes. Data is primarily based upon LPG and is not LNG specific. Status of the annular vacuum space is critical in the fire performance of the LNG containers. Water streams may have reduced effectiveness in cooling container contents due to cryogenic liquid container design. Can only be controlled by isolating the source or product flow, while protecting exposures (as possible). Due to the design and construction of LNG containers, LNG jet fires are less likely to occur.	Due to the design and construction of cryogenic liquid containers, water streams may have reduced effectiveness in cooling container contents. Status of the annular vacuum space is critical in the fire performance of the LNG containers.	None

Fire Scenario	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
BLEVE	In fires involving Liquefied Petroleum Gases (LPG) (UN1075), Butane (UN1011), Butylene (UN1012), Isobutylene (UN1055), Propylene (UN1077), Isobutane (UN1969), and Propane (UN1978), also refer to BLEVE – SAFETY PRECAUTIONS	Significant incident history and research testing of LPG and related flammable gases. BLEVE Safety Precautions and Capacities outlined in ERG.	There are currently no incident reports or research testing of a cryogenic container constructed to current North American standards (TC/MC-338, T75, TC/DOT-113) that resulted in a BLEVE.	PHMSA has recently conducted pool fire tests on the T75 portable tank container in June 2022. ERG Guide 115 covers a range of flammable gases, with emphasis upon LPG and related liquefied gases. It also references the supplemental BLEVE – Safety Precautions section (page 366) and accompanying tables.	Recommend incorporate findings, if applicable, from PHMSA T75 portable tank tests once reports are publicly available.
Vapor Cloud Fire Gaseous materials release into the atmosphere forming a vapor cloud and dispersing by mixing with air. If the vapor cloud ignites before the vapor cloud is diluted below the LEL, a flash fire may occur.	**DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED.** **Small Fire** – Dry chemical or CO_2 **Large Fire** – Water spray or fog	When ignited, LPG will flash back to an ignition source. Do not extinguish a leaking gas fire unless leak can be stopped. Water fog streams will be critical for fire control and exposure protection.	LNG will vaporize rapidly forming a cold gas cloud that is initially heavier than air, spreading and carrying downwind until it reaches neutral buoyancy as it warms up. When ignited, LNG will flash back to an ignition source. Do not extinguish a leaking gas fire unless leak can be stopped. Water fog streams will be critical for fire control and exposure protection. Flash fire can burn back to the release point producing either a pool fire or a jet fire (or both) but will not generate damaging over-pressures if unconfined.	Heat flux and flame spread are important factors influencing the emergency response to an LNG incident.	Determine the impact of differences in heat flux for LPG and LNG on emergency response. Determine the impact of differences in flame spread for LPG and LNG on emergency response.

Table 15: Emergency Response Scenarios: Vapor Cloud Explosions

Vapor Cloud Explosion	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
If a vapor cloud with concentrations in the flammable range is confined inside a structure and ignited, damaging overpressures can occur. Outdoor areas congested with equipment and structures can also help confine flammable vapors and may facilitate overpressure upon ignition.	Many gases are heavier than air and will spread along the ground and collect in low or confined areas (sewers, basements, tanks, etc.). ELIMINATE all ignition sources (no smoking, flares, sparks or flames) from immediate area. Do not touch or walk through spilled material. Stop leak if you can do it without risk. Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material. Do not direct water at source of leak or safety devices; icing may occur.	Liquefied gases such as LPG are more susceptible to vapor cloud explosions. LPG vapors are heavier than air. Water fog streams can be used to control / knock down vapors Directing water at source of leak or safety device may cause icing to occur. If ignited, fire will flash back from the ignition source to the release point. Auto-refrigeration can become a response issue depending upon the breach. Although asphyxiation can be an issue in confined locations, flammability is a greater hazard.	Inversion of vapors will initially occur as extremely cold gases and vapors are denser and heavier than air. While natural gas is lighter than air, LNG vapors will initially accumulate in low areas due to low temperatures. Water fog streams can be used to control / knock down vapors. Do not direct water at source of leak or safety device; icing may occur. If ignited, fire will flash back from the ignition source to the release point. Auto-refrigeration can become a response issue depending upon the breach. Although asphyxiation can be an issue in confined locations, flammability is a greater hazard.	Guide 115 incorporates a range of flammable refrigerated / cryogenic liquids (Methane, Ethane, Ethane / Propane Mixtures, Ethylene, Hydrogen). Air monitoring and detection will be critical in assessing vapor travel, the effectiveness of water streams, and hazard control zones. Visible vapor cloud is not a reliable indicator of vapor location.	None

Table 16: Emergency Response Scenarios: Rapid Phase Transition

Rapid Phase Transition	ERG Guidance (Guide No. 115)	LPG Response Factors	LNG Response Factors	Comments	Gaps
Involves the nearly simultaneous transition from the liquid to vapor phase with an associated rapid pressure increase typically associated with releases on or near bodies of water.	No hazard or response guidance on RPT provided.	No information on RPT experience with LPG's referenced.	RPT scenarios involving LNG primarily referenced in the marine environment. RPT may result in two types of effects: (1) localized overpressure resulting from rapid phase change, and (2) dispersion of the "puff" of LNG expelled to the atmosphere. RPT energy comes from a physical change and is much less than the energy available from a chemical combustion reaction (e.g., explosion, BLEVE, etc.).	ERG provides no information on RPT incident or testing experience. RPT changes have been observed in several LNG spill experiments on water; they have not resulted in any known incidents involving LNG surface transport. RPT's may also occur on land or other solid surfaces where LNG collects in a depression.	Add a statement to the ERG Guide statement referencing Rapid Phase Transitions is lacking. For example, a suggested addition is: "When an LNG release is on or near water, exercise caution as rapid phase transitions may occur from the liquid to vapor phase with an associated rapid pressure increase."

Figure 12 categorizes and compares various types of incident scenarios and hazards for the modes of LNG and LPG transportation in a matrix format that depicts incident potential. The purpose of this incident potential matrix is to consider both the frequency and possible severity of an incident occurrence to provide a scenario-based comparison. Therefore, Figure 12 presents a qualitative comparison of the hazards associated with different LNG/LPG incidents for the different means of transport. Within each incident classification, the boxes are each given a color to correspond to the general incident potential in comparison to other boxes. The scale consists of green for least impact, yellow for moderate impact, orange for moderately high impact, and red for highest impact. While this matrix is not a quantitative comparison, it compares the relevant hazards for LNG and LPG, as well as a general comparison of these hazards for each mode of transport. In summary, Figure 12 provides a comparison of the potential scenarios possible for each mode of transport of LNG and LPG. A description and explanation of the reasoning used to create the matrix is also provided below.

		LNG			LPG		
INCIDENT SCENARIOS	**SCENARIO CONSIDERATIONS**	**ROAD**	**RAIL**	**MARINE**	**ROAD**	**RAIL**	**MARINE**
SPILLS	Probability of spill occurrence	L	L	L	M	M	M
FIRES	Flammability hazard comparison	H	H	H	H	H	H
VOLUME RELEASED	The hazard related to the volume of vapor produced upon release	M	M	M-H	L	L	M
BLEVE	The probability and severity of BLEVE occurrence	M	M	M	H	H	H
RAPID PHASE TRANSITION	The probability and severity of RPT occurrence	L	L	H	N/A	N/A	N/A
CONTAINER FAILURE	The probability and severity of a failure affecting the means of containment	L	L	M-H	M	L	L

Figure 12: Comparison of Potential LNG/LPG Incident Scenarios by Transportation Mode

i. The incident potential scale consists of N/A for not applicable, green for least impact (L), yellow for moderate impact (M), orange for moderately high impact (M-H), and red for highest impact (H).
ii. This matrix does not represent an outcome of a full risk assessment, with all considerations of probability and consequence, but rather presents an incident potential matrix which categorizes and relatively compares the various types of incident scenarios and hazards for different modes of LNG and LPG transportation.

The matrix of potential incident scenarios (Figure 12) is based upon the following factors:

Spills

- From the limited incident history within LNG transport, the impressive safety record of LNG maritime transport specifically, and the various safety protocols including the added protection from double-shell tanks with insulation, LNG has a low spill probability and is given a low-impact ranking. LPG transport typically occurs in single-walled pressurized tanks and has a much more thorough incident history than LNG transport. Therefore, LPG presents a higher spill probability, and a higher ranking.

Fires

- In the event of a release, LNG and LPG are both highly flammable substances and merit a high-impact rating. However, due to the behavior of LNG releases (i.e., heating over time and eventually rising and dispersing in most cases), along with the higher likelihood of tank rupture for LPG tanks relative to LNG tanks, this is a very scenario-dependent comparison. For example, the wider flammability limits of LNG would make LNG more dangerous in the case of a spill. However, in the case of a pinhole leak, the substance with the lower concentration necessary to ignite (lower LFL) would be more dangerous, which is LPG. Therefore, both substances received a high-impact rating for flammability. Also, the mode of transport does not affect the probability of fire in the case of release.

Volume Released

- Due to its greater liquid to vapor expansion ratio, LNG receives a higher impact ranking for volume release than LPG. The amount of volume release is also greater for those transport modes that have larger capacities. Finally, transport within a ship means that a spill would be naturally confined within the ship, and confinement can lead to higher VCE risk as well as the confined vapors presenting greater hazard in terms of asphyxiation than release into open air.

Boiling Liquid Expanding Vapor Explosion (BLEVE)

- While BLEVE scenarios are a critical risk for both of these materials, LPG receives a higher impact ranking due to its high pressure during transport and difference in container construction.
- LNG is viewed as having a lower risk of a BLEVE due to its vapor behavior of rising and dispersing once heated, lower pressures, and container design and construction (double-wall container, insulation, pressure relief protection). However, due to the high-volume reduction during liquefaction compared to LPG, there is the possibility of a pressure buildup from LNG vaporization during an incident that can therefore lead to BLEVE. Consequently, LNG receives a moderate impact categorization for BLEVE.

Rapid Phase Transition (RPT)

- RPT is a well-known phenomenon for LNG being released into water. The consequence for RPT occurrence can be high, as it produces physical explosions in many cases. However, due to the requirement of release onto water it has a low probability of being released into a waterway during road or rail transport and therefore a lower impact ranking.
- Due to the prevalence of water during marine shipping as well as the risk ramifications involved, transport of LNG by ship receives a high-impact category for RPT. In contrast, LPG has no risk of RPT and therefore the hazard is not applicable (N/A).

Container Failure

- LNG and LPG have different effects on their transport container upon release. LNG bulk containers must account for both the cryogenic conditions of LNG and the potential of fire, whereas LPG containers must account for the potential of fire and the corresponding increase in container pressure.

- Given the inherent safety factors integrated into LNG containers, they are considered to pose similar risks to those posed by LPG during transport and therefore are given the same impact rating categories as the LPG transport, except in the case of marine transportation. In the case of ship transport, the LNG container is surrounded by the ship itself; in a leak scenario the means of transport (the ship) will be exposed to cryogenic hazards as well.
- LPG road transport uses single shell, non-insulated containers, and therefore is more susceptible to a failure affecting the means of containment. The accident performance of LPG rail transport has significantly improved over the last several decades as the containers now have thermal insulation, jacketing, headshields, and shelf couplers that reduce stress behaviors. Marine transport of LPG also has additional safety measures and is considered in line with the safety of rail transport. Therefore, LPG road transport receives a moderate impact ranking and LPG rail transport receives a low impact ranking in the containment failure section.

In summary, while LPG appears to be the more hazardous substance, LNG has a number of hazards that must be considered and evaluated. These include flammable cryogenic liquid behavior, a much higher heat flux than LPG, metal embrittlement of the container and, especially in the case of maritime transport, the effect on the surroundings.

Scenarios - General Comments and Observations on Scenarios

The Health and Safety Laboratory, now Solutions from HSE, published a report reviewing LNG phenomena and source term models that provides a perspective on the multitude of factors to consider in an LNG leak (Webber et al., 2012). The main considerations for source terms are jet releases, pool formation, vaporization within containment area, rapid phase transition, pool spread, and pool evaporation. Jets vary in their composition, with the potential to be released as liquid, a vapor spray, or as a two-phase jet.

When LNG is spilled, a pool has potential to form due to the low temperatures that can cool the ground. This pool can then become the source of a vapor cloud, which is vital to understand due to the risk of vapor cloud explosion. Vaporization within the container can come either from roll-over or water ingress.

RPT occurs when spilled LNG is heated at such a rate that the vaporization expands the fluid fast enough to produce a pressure wave. The pressure wave is usually not considered significant enough to damage surrounding structures, however it has been noted in literature that there is some concern that RPT could serve as an ignition source for the LNG vapor cloud being formed simultaneously. Pool spread consists of multiple competing forces that must be considered such as gravity, resistance to flow, puddle formation, vaporization rate, and friction if the pool is on land.

8. Comparative Assessment of LNG/LPG Emergency Response Guidance

The focus of this assessment is the Emergency Response Guidebook (2020 edition), which is the primary emergency response reference guidance used by Awareness and Operations-level responders. The ERG provides Guide Pages for the following hazard classes of cryogenic / refrigerated liquids:

- Guide 115 - Gases – Flammable (including Refrigerated Liquids)
- Guide 120 - Gases – Inert (including Refrigerated Liquids)
- Guide 122 - Gases – Oxidizing (including Refrigerated Liquids)

Each ERG Guide contains emergency response guidance for dangerous goods with similar properties and hazards. LNG and LPG are both covered under Guide 115. The 2020 Edition includes updates that reflect the hazards associated with LNG, including:

- FIRE - For **LNG - Liquefied natural gas (UN 1972)** pool fires, DO NOT USE water. Use dry chemical or high- expansion foam.
- SPILL OR LEAK - For **LNG - Liquefied natural gas (UN 1972)**, DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapor.

Table 17: Review of Emergency Response Guidebook (2020 Edition), Guide 115, Gases – Flammable (including refrigerated liquids)

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
POTENTIAL HAZARDS FIRE OR EXPLOSION	**EXTREMELY FLAMMABLE** Will be easily ignited by heat, sparks or flames. Will form explosive mixtures with air. Vapors from liquefied gas are initially heavier than air and spread along ground. Vapors may travel to source of ignition and flash back. Cylinders exposed to fire may vent and release flammable gas through pressure relief devices. Containers may explode when heated.	All are applicable.	All are applicable.	LNG has a higher heat flux factor (3-5 times) than other commonly transported hydrocarbons. LPG has a more rapid flame spread than LNG when ignited.	None

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
	Ruptured cylinders may rocket.				
POTENTIAL HAZARDS HEALTH	Vapors may cause dizziness or asphyxiation without warning. Some may be irritating if inhaled at high concentrations. Contact with gas or liquefied gas may cause burns, severe injury and/or frostbite. Fire may produce irritating and/or toxic gases.	All are applicable.	All are applicable although cryogenic liquid hazards / contact could be enhanced (see gaps).	None	Inhalation issues are more applicable in closed / confined areas versus open air release. For example, change to read "Vapors may cause dizziness or asphyxiation without warning, especially when in closed or confined areas." Incorporate cryogenic liquid. For example, change to read: "Contact with gas, liquefied gas, or cryogenic liquids may cause burns, severe injury, and/or frostbite."
PUBLIC SAFETY GENERAL GUIDANCE	**CALL 911. Then call emergency response telephone number on shipping paper.** If shipping paper not available or no answer, refer to appropriate telephone number listed on the inside back cover. Keep unauthorized personnel away. Stay upwind, uphill and/or upstream. Many gases are heavier than air and will spread along the ground and	All are applicable and are basic Dangerous Goods / Hazardous Materials (DG/HM) response initial guidance.	All are applicable and are basic DG/HM response initial guidance.	None	None

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
	collect in low or confined areas (sewers, basements, tanks, etc.).				
PUBLIC SAFETY PROTECTIVE CLOTHING	Wear positive pressure self-contained breathing apparatus (SCBA). Structural firefighters' protective clothing provides thermal protection **but only limited chemical protection.** Always wear thermal protective clothing when handling refrigerated / cryogenic liquids.	All are applicable.	All are applicable.	None	None
PUBLIC SAFETY EVACUATION	**Immediate precautionary measure -** Isolate spill or leak area for at least 100 meters (330 feet) in all directions. **Large Spill** – consider initial downwind evacuation for at least 800 meters (1/2 mile). **Fire** – If tank, rail car or tank truck is involved in a fire, ISOLATE for 1600 meters (1 mile) in all directions; also, consider initial evacuation for 1600 meters (1 mile) in all directions. In fires involving Liquefied Petroleum Gases (LPG) (UN1075), Butane (UN1011), Butylene (UN1012), Isobutylene (UN1055), Propylene (UN1077), Isobutane (UN1969), and Propane (UN1978), also refer to BLEVE SAFETY PRECAUTIONS.	All are applicable and reference ERG BLEVE TOOL which is applicable to LPG.	Majority of response guidance is applicable to all flammable gases, but there are no specific references to LNG.	There are no specific references to LNG within the ERG BLEVE TOOL. All guidance is primarily focused upon LPG and related liquefied gases. Therefore, adding a linkage to LNG would not be suitable at this time as no data exists. (i.e., the data in ERG BLEVE TOOL is specific to LPG). No incident experience or test data was found to support modifying the protective action distances for LNG fire scenarios.	Experiments must be performed to determine whether LNG represents a lower or greater BLEVE risk (in comparison to LPG) in the appropriate operational context of transportation incidents. Currently, insufficient data exists to make LNG-specific recommendations.
EMERGENCY RESPONSE FIRE	**DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED.** **Small Fire** – Dry chemical or CO_2.	All are applicable.	All are applicable.	Potassium bicarbonate (Purple K) would be the preferred dry chemical agent for LNG pool fires.	CO_2 is not commonly referenced for LNG fires; this recommendation needs to be validated.

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
	Large Fire – Water spray or fog. If it can be done safely, move undamaged containers away from the area around the fire. **CAUTION**: For **LNG – Liquefied natural gas (UN1972)** pool fires, DO NOT USE water. Use dry chemical or high-expansion foam.				
	Fire Involving Tanks - Fight fire from maximum distance or use unmanned master stream devices or monitor nozzles. - Cool containers with flooding quantities of water until well after fire is out. - Do not direct water at source of leak or safety devices; icing may occur. - Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank. - ALWAYS stay away from tanks engulfed in fire. - For massive fire, use unmanned master stream devices or monitor nozzles; if this is impossible, withdraw from area and let fire burn.	All are applicable.	All are applicable.	Thermos-type packaging used for the transport of cryogens. Pressure relief devices used on compressed gas cylinders (e.g., CNG) may be temperature or pressure actuated, while those found on flammable liquefied gas (e.g., LPG) and flammable cryogenic liquid containers (e.g., LNG) are pressure actuated. Care must be taken to not direct water towards pressure relief devices.	Bullets 2 and 3 should be combined into one bullet so that the user reads them together and doesn't miss the context of bullet 3, since the pressure relief device may be temperature or pressure actuated for flammable compressed gas cylinders (e.g., CNG) and pressure actuated for flammable liquefied gas (e.g., LPG) and flammable cryogenic liquid (e.g., LNG) containers. This is not a technical issue, but rather a human factors issue. For example, change to: "Avoiding the container's pressure relief device and the source of the leak, cool the container with flooding quantities of water until well after the fire is out. Activation of the pressure relief device

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
					may be delayed and icing may occur."
EMERGENCY RESPONSE SPILL OR LEAK	ELIMINATE all ignition sources (no smoking, flares, sparks or flames) from immediate area. All equipment used when handling the product must be grounded. Do not touch or walk through spilled material. Stop leak if you can do it without risk. If possible, turn leaking containers so that gas escapes rather than liquid. Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material. Do not direct water at spill or source of leak. **CAUTION:** For **LNG – Liquefied natural gas (UN1972),** DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors. Prevent spreading of vapors through sewers, ventilation systems and confined areas. Isolate area until gas has dispersed. **CAUTION: When in contact with refrigerated / cryogenic liquids, many materials become brittle and are likely to break without warning.**	All are applicable and are basic DG/HM guidance for flammable liquid scenarios.	All are applicable. Included specific reference to the metal embrittlement issue and the use of water or Class B firefighting foams on a spill. Includes reference to the use of high-expansion foam.	Exposure to LNG can cause the embrittlement of steel, especially to the tank car outer shell in a cascading scenario. The inner tank is specifically designed for cryogenic liquid exposure. The outer tank is designed to protect the inner tank from thermal and mechanical stress. If the outer tank is damaged due to embrittlement, the inner tank becomes more susceptible to potential damages. Embrittlement and use of firefighting foams issues are not limited to LNG but would also impact other flammable cryogenic liquids. The 2nd CAUTION statement is currently included in all areas where cryogenic liquids are addressed within the ERG (Guides 115 (flammable gases), 120 (gases, inert), 122 (gases, oxidizing)).	None

ERG Response Factor	ERG GUIDANCE (Guide No. 115)	ERG Guidance Applicable to LPG	ERG Guidance Applicable to LNG	Comments	Gaps
EMERGENCY RESPONSE FIRST AID	Call 911 or emergency medical service. Ensure that medical personnel are aware of the material(s) involved and take precautions to protect themselves. Move victim to fresh air if it can be done safely. Give artificial respiration if victim is not breathing. Administer oxygen if breathing is difficult. Remove and isolate contaminated clothing and shoes. Clothing frozen to the skin should be thawed before being removed. In case of contact with liquefied gas, thaw frosted parts with lukewarm water. In case of burns, immediately cool affected skin for as long as possible with cold water. Do not remove clothing if adhering to skin. Keep victim calm and warm.	All are applicable.	All are applicable.	None	None

9. Gap Analysis

[1] **LNG Transport Experience and Safety Considerations**. From the research conducted into the comparison of LNG and LPG, we find that while there is a large body of experience and knowledge in LPG transportation, LNG transportation lacks a similar knowledge base. For example, there is much experience and testing of means of containment for LPG in rail and road transport, and LPG pipeline incident behavior builds upon the knowledge gained from operating fixed facilities. However, LNG transportation does not have a similar knowledge base. Of the modes of transport, marine transport is the most explored; however, in terms of safety this knowledge lies primarily in the frequency analysis rather than consequence analysis (therefore a complete risk analysis cannot be performed), and the consequence analyses that have been performed by different institutions vary widely in their interpretation (see Annex F). There is also a more thorough incident history for LPG transport, whereas data for LNG transport incidents are much more sparse. Therefore, a consistent body of information is required to establish risk quantification.

When regarding the safety of road and rail transportation of LNG, research in the area is heavily lacking. The lack of transport at a significant level by these modes has led to little experience and research testing in the area. Much of the current body of knowledge is based on marine transport and the utilization of LNG as a transportation fuel (e.g., highway, rail). At the very least a frequency analysis, similar to that which has been studied in the field of marine transportation, would help to provide valid comparisons and promote understanding of the risks behind these transportation methods.

[2] **LNG BLEVE Potential**. When analyzing the primary hazards of LPG and LNG, the clear primary hazards are BLEVE and flammability for LPG, and flammability and cryogenic behavior for LNG. However, this analysis assumes that the lack of BLEVE occurrences in industry for LNG are indicative of a true low likelihood of occurrence. As described within this report, from strictly the chemical and physical properties of LNG, BLEVE occurrence is certainly possible, as seen in the 2002 and 2011 incidents in Table 1. However, within LNG incident history, we can find no incidents involving containers constructed to North American LNG transport standards that can clearly be attributed to a BLEVE. This discrepancy between theory and occurrence demonstrates a knowledge gap, and the lack of research into the BLEVE potential of LNG leaves a large uncertainty in the safety of LNG transport.

[3] **LNG Rapid Phase Transition (RPT).** Additionally, the lack of consensus within research into Rapid Phase Transition (RPT) of LNG leads to concern for the field of marine transport or where surface transport corridors are in close proximity to large waterways. Within the field of research, the interpretation of the RPT risk varies greatly, with some papers considering it a point of significant discussion, and others no more than briefly mentioning it. These uncertainties revolve around considerations such as whether or not an RPT event will occur in a spill, how many RPT events will occur in the spill, and the strength of explosion. Further complicating this understanding is the possibility that has been raised in literature that RPT could potentially serve as the ignition source for a cloud of released LNG vapors. Additionally, while RPT has been studied at a small scale in research and testing environments, any documentation in real world practice is very sparse, whether this is due to a lack of incidents as a whole or potentially due to a phenomenon that reduces the likelihood of RPT

at larger scale. Learning the RPT behavior of LNG at the scale of transport would lead to much greater certainty in the risk of LNG transport.

[4] **Research to inform LNG Emergency Response Guidance**. Finally, there is a gap that must be addressed between the scientific community and the emergency response guidance. Within the scientific research in this area, emergency response guidance is not even mentioned, let alone sufficiently addressed. In fact, most incident reports that are found within scientific literature do not describe the emergency response actions taken nor provide recommendations for emergency response in similar scenarios. The knowledge gained from scientific research as well as the experience gained from incident occurrences should outline the lessons learned and outline applicable emergency response recommendations.

10. Possible Future Research

From the results found within this study, there are possible research endeavors, considerations, and further suggestions that the authors would like to put forth as important scientific explorations that could be undertaken.

Possible Research:

- To address gaps 1 and 2: The BLEVE potential of LNG should be explored at the operating conditions of LNG transportation. The conditions for BLEVE occurrence of LNG can be experimentally identified, then modeled in order to scale up to transport conditions. Note: This testing can be very dangerous and must be done in a very well controlled environment with testing safety procedures.
- To address gaps 1 and 3: The RPT potential, consequence analysis, and metal embrittlement failures all associated with the release of LNG at the operating conditions of marine LNG transport should be explored. The conditions necessary for RPT to occur in a larger scale setting should be tested experimentally, then modeled in order to develop the consequences involved in varying amounts of release.
- To address gap 1: A complete risk analysis of LNG transport via road and rail should be conducted, ideally with the results of the prior two suggested research tasks taken into consideration. Given the incident severity that will be developed from the BLEVE and RPT tests, the overall incident severity can be determined through modeling. When combined with incident frequency analysis, this will enable a full risk analysis for LNG transport risk.

Considerations:

- To address gap 4: Finally, we propose that the previous possible research should be undertaken with the specific goal of providing emergency response guidance suggestions based on whatever results are obtained.
- Additionally, it should be acknowledged that any changes or slight modifications to the ERG can have a downstream impact on fire and dangerous goods / hazardous materials training curriculum and practical exercises. Future research may be needed to perform a gap analysis against the training curriculum to provide the training community insight on what updates may be needed to accurately reflect the differences between LPG and LNG.

Further Suggestions:

The authors support the recommendations made by the National Academy of Sciences LNG by Rail Study to PHMSA and U.S. DOT / FRA to review the DOT-113C120W9 tank car specification to ensure that it adequately accounts for the cryogenic and thermal properties of LNG that could contribute to a tank release and cascading impacts (National Academies of Sciences, Engineering, and Medicine, 2021). In particular, entities should obtain data needed to assess:

- The capacity of the pressure relief devices to vent sufficient LNG when the tank car is engulfed in an LNG fire, taking into account derailment conditions, such as a rollover, that could degrade this capacity.

- The effects of adding more and different types of insulation in the annular space to ensure sufficient performance of the multi-layer insulation system when the tank car is exposed to heat flux and direct flame impingement from an LNG fire; and
- The potential for the outer tank to experience cryogenic brittle failure and loss of vacuum insulation when exposed to an LNG pool.

11. Summary of Key Findings and Recommendations

11.1 Key Findings

[1] Emergency response information sources for an LNG incident should be viewed as a system consisting of the following elements:

- Emergency Response Guidebook, Guide 115 and/or LNG Safety Data Sheet used by Awareness and HazMat Operations personnel.
- Incident Management Field Tools, including Liquefied Natural Gas (LNG) Commodity Preparedness and Incident Management (CPIMRS) Reference Sheet used by HazMat Technicians, HazMat Officers and Incident Commanders and the NFPA On-Scene Commander Field Guides
- Implementation of Emergency Response Assistance Plan (ERAP) by Incident Commanders (used in Canada only).

Additionally, the concept of the Commodity Preparedness and Incident Management Reference Sheet (CPIMRS) or equivalent should be considered as a tool for providing product and container specific information to HazMat Technicians, HazMat Officers and Incident Commanders. The current LNG CPIMRS that was developed for LNG rail transport and provided through HAMMER can be used as a framework for developing CPIMRS for cargo tank truck transportation. The level of information provided through the CPIMRS could also be used to complement the ERAP.

Incident specific decisions should be based upon the use of a risk-based analysis process. *NFPA 470 – Hazardous Materials Standards for Responders* defines Risk Based Response (RBR) as a systematic process, based on the facts, science and circumstances of the incident, by which responders analyze a problem involving HM/WMD to assess the hazards and consequences, develop an incident action plan (IAP), and evaluate the effectiveness of the plan.

[2] Both LNG and LPG are covered under Guide 115 of the Emergency Response Guidebook. The 2020 Edition includes updates that reflect the hazards associated with LNG, including:

- FIRE - For **LNG - Liquefied natural gas (UN 1972)** pool fires, DO NOT USE water. Use dry chemical or high-expansion foam.
- SPILL OR LEAK - For **LNG - Liquefied natural gas (UN 1972)**, DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors.

[3] LNG transportation presents four potential general risk related scenarios:

- Cryogenic Behavior and Effects
- Fire (Pool Fire, Jet Fire, Vapor Cloud Fire, BLEVE)
- Vapor Cloud Explosion (open air vs. confined)
- Rapid Phase Transition (RPT)

[4] While there is substantial incident and research test data on the risk of BLEVE scenarios involving LPG containers, equivalent data on the BLEVE risk of bulk LNG transportation containers could not be found.

- LPG poses a greater risk of a BLEVE scenario and has a more rapid flame spread than LNG when ignited. In comparison LNG has a substantially higher heat flux factor (3 to 5 times) than other commonly transported hydrocarbons, thereby increasing thermal impact distances.
- Most containers used for transportation of LNG have an inner tank and an outer tank, with an insulation space between the two tank shells. The "tank-within a tank design" utilized for LNG transport results in added protection for the inner container due to the annular space. The integrity of the annular space is critical in the fire performance of an LNG container. In contrast, LPG highway containers have a single-shell, non-insulated design and therefore do not have this added protection. LPG rail containers, however, have an outer jacket and thermal protection.
- The majority of incident and research test data involving LNG containers and their behavior in an emergency is based upon marine transportation.
- There are currently no incident reports or research testing of a BLEVE of a cryogenic container constructed to current North American standards (TC/MC-338, T75, TC/DOT-113). No incident experience or research test data was found to support modifying the protective action distances (increase or decrease) for LNG fire scenarios at this time.

[5] The risk of metal embrittlement of an LNG outer tank shell is not commonly encountered by emergency responders, but the hazard is highlighted in the ERG.

[6] A comparative summary of container information, incident types/scenarios, hazards and release effects, and emergency response procedures during transport for both LNG and LPG is provided in **Annex E** of this report.

11.2 Recommendations

[1] At the present time ERG Guide 115 accurately captures the hazards associated with LNG and related flammable cryogens and is consistent with the ERG structure of classifying refrigerated liquids into flammable gases, inert gases and oxidizing gases. At the present there is not a need to develop a separate ERG Guide for LNG. The four-year ERG review cycle should be continued.

[2] The authors of this research study support the recommendations from National Academy of Sciences to review DOT- 113C120W9 tank specifications, specifically to:

- Assess the capacity of pressure relief to sufficiently vent when tank is engulfed in fire, considering derailment conditions
- Study the effects of adding more and different insulations into the annular space

[3] The authors suggest that the recommendation to use CO_2 on LNG fires should be validated. CO_2 is not commonly referenced for LNG fires.

[4] Through this study, a few gaps were identified within ERG Guide 115 where slightly modified language could make the guide more inclusive of LNG. For future updates to the ERG, the authors propose one new addition and other contextual updates (or equivalent language) to be considered, to ensure considerations for LNG are adequately covered in Guide 115 for flammable gases.

ERG Guide 115: POTENTIAL HAZARDS – FIRE OR EXPLOSION

- ERG Guide 115 does not address the Rapid Phase Transition (RPT) phenomena. Thus, a statement on RPT is suggested to be added to ERG Guide 115 – POTENTIAL HAZARDS – FIRE OR EXPLOSION section.
  - Original Statement: None
  - Suggested Addition: ***When an LNG release is on or near water, exercise caution as rapid phase transitions may occur from the liquid to vapor phase with an associated rapid pressure increase.***

ERG Guide 115: POTENTIAL HAZARDS - HEALTH

- Since inhalation issues are more applicable in closed / confined areas versus open air release, the authors suggest the following modification.
  - Original Statement: Vapors may cause dizziness or asphyxiation without warning.
  - Suggested Modification: Vapors may cause dizziness or asphyxiation without warning, ***especially when in closed or confined areas***.
- Incorporate cryogenic liquid
  - Original Statement: Contact with gas or liquefied gas may cause burns, severe injury and/or frostbite.
  - Suggested Modification: Contact with gas, liquefied gas, ***or cryogenic liquids*** may cause burns, severe injury, and/or frostbite.

ERG Guide 115: EMERGENCY RESPONSE - FIRE

- Bullets 2 and 3 (under Fire Involving Tanks) should be combined into one bullet so that the user reads them together and doesn't miss the context of Bullet 3, since the pressure relief device may be temperature or pressure actuated for flammable compressed gas cylinders (e.g., CNG) and pressure actuated for flammable liquefied gas (e.g., LPG) and flammable cryogenic liquid (e.g., LNG) containers. This is not a technical issue, but rather a human factors issue.
  - Original Statement – Two separate bullets (in reference to Bullets 2 and 3)
    - Cool containers with flooding quantities of water until well after fire is out.
    - Do not direct water at source of leak or safety devices; icing may occur.
  - Suggested Modification: "***Avoiding the container's pressure relief device and the source of the leak*****,** cool the container with flooding quantities of water until well after the fire is out. ***Activation of the pressure relief device may be delayed and*** icing may occur."

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13. Annex Materials

Annex A	Co-citation Cluster Plots
Annex B	Butane and Propane Property Comparison
Annex C	Selection of Relevant Equations Supplemental Information
Annex D	Modeling LNG and LPG Releases Supplemental Information
Annex E	Summary of LNG/LPG Emergency Response Considerations by Transport Type
Annex F	Flammable Zone Size Research Comparison
Annex G	Reference to ERG Guide 115
Annex H	TRANSCAER – LNG Safety and Emergency Response Reference
Annex I	Volpentest Hazardous Materials Emergency Response (HAMMER) Federal Training Center - Commodity Preparedness and Incident Management Reference Sheet for Liquefied Natural Gas (LNG)

Annex A – Literature Review: Co-citation Cluster Plots

Cited articles can be seen as the intellectual base of a research field, on which future knowledge seeking activities build. A two-level intellectual base analysis has been performed, using journals and references co-citation analysis as implemented in VOSviewer. From this, the journals, books, incident reports, or other media that are frequently cited in the research of LNG and LPG, have been identified and are summarized in Figures 13, 14, 15, and 16. Highly cited sources reflect the main knowledge carriers that support the research of LNG and LPG and can be regarded as its intellectual base, which has been utilized to complete the literature review for this project.

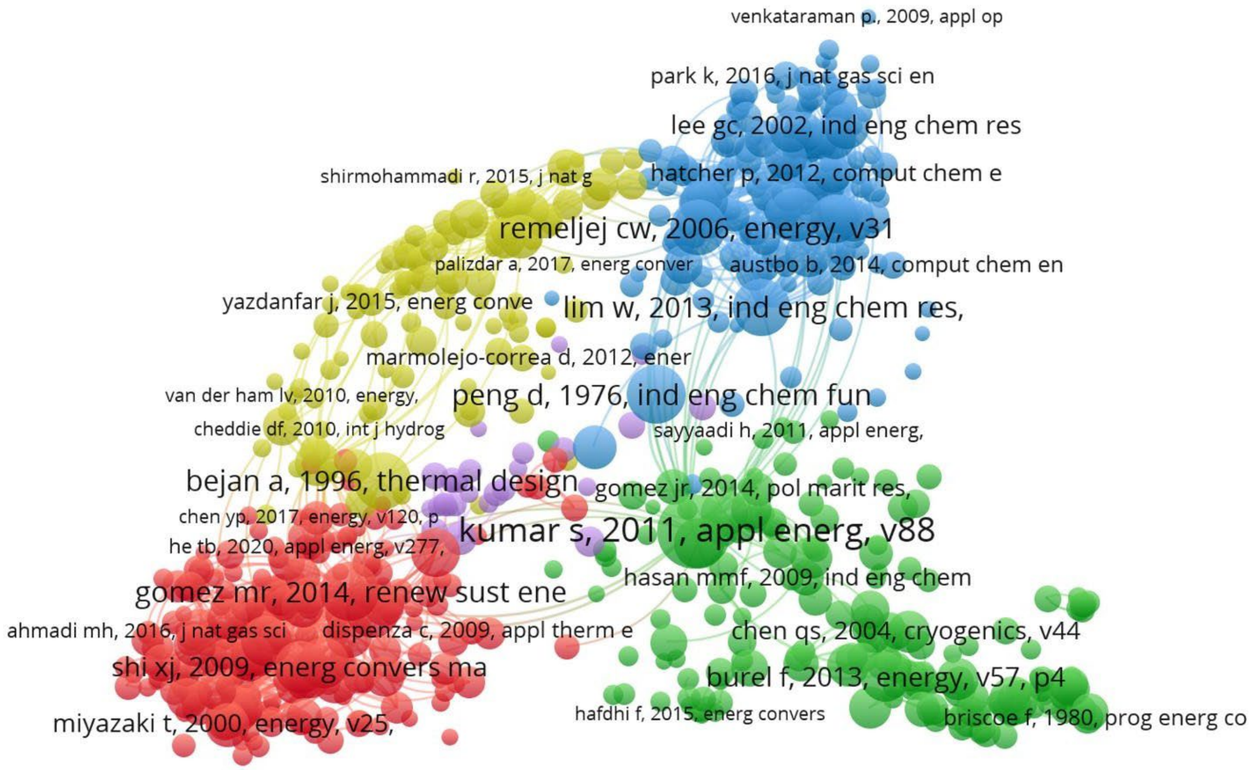

Figure 13: LNG Co-citation Map (10 co-citation minimum)

Top "LNG" Co-citations:

1. LNG: An eco-friendly cryogenic fuel for sustainable development (Kumar et al., 2011)
2. Current status and perspectives of liquefied natural gas (LNG) plant design (Lim et al., 2012)
3. Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process (Gómez et al., 2014)

These articles focus on the potential advantages of using liquefaction for the transport of natural gas and potential of natural gas as a fuel, the current state of LNG production plants as well as the refrigeration cycle, and exploring the thermodynamic cycles involved in LNG regasification, respectively. This implies that research to this point on LNG has found a primary focus on proving its efficacy and benefits, then focusing on how to optimize the supply and production of natural gas. These are the most co-cited articles because they lay the foundation of why natural gas is transported as a liquefied, cryogenic substance. However, it is worth noting that no focus is given to the safety parameters and emergency response aspect of LNG.

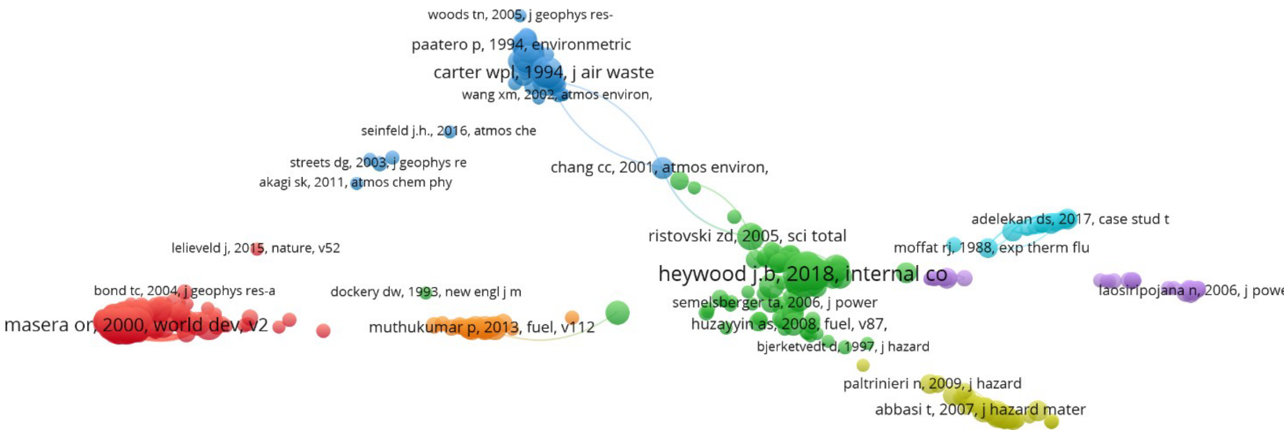

Figure 14: LPG Co-citation Map (10 co-citation minimum)

Top "LPG" Co-citations:

1. Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use (Puzzolo et al., 2016)
2. Who adopts improved fuels and cookstoves? A systematic review (Lewis and Pattanayak, 2012)
3. From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model (Masera et al., 2000)

These papers focus on the use of LPG at a small scale on the consumer level, and the use of LPG as a cleaner burning fuel at the household level. This demonstrates that research in the area has focused on the use and consumer level of LPG rather than the industrial scale and transport. Even more apparent is the lack of safety and emergency response studies that would perhaps accompany the industrial-scale research.

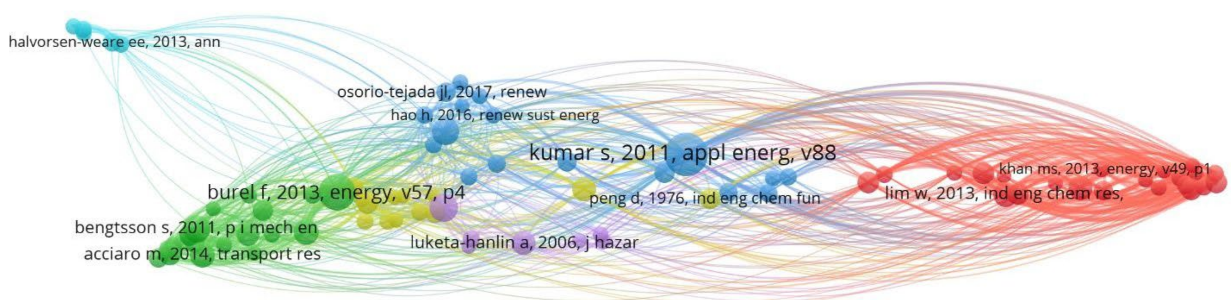

Figure 15: LNG Transport Co-citation Map (10 co-citation minimum)

Top "LNG Transport" Co-citations:

1. LNG: An eco-friendly cryogenic fuel for sustainable development (Kumar et al., 2011)
2. Improving sustainability of maritime transport through utilization of liquefied natural gas (LNG) for propulsion (Burel, 2013)
3. Optimization of propane pre-cooled mixed refrigerant LNG plant (Alabdulkarem et al., 2011)

These papers focus on the potential advantages of using liquefaction for the transport of natural gas and potential of natural gas as a fuel, the potential benefit of LNG as a fuel option for merchant ships and its impact on the environment and optimizing the energy consumption of LNG plants. The focus on the efficacy of LNG makes sense to be the most co-cited, as this research established viability of the product. The focus of legitimate uses of LNG as a fuel also provides more support for the use of LNG, and of course cooling optimization of LNG leads to the guarantee that liquefaction is an efficient mode of transport. However, again the research has not focused on the safety, nor the emergency response involved in LNG transport.

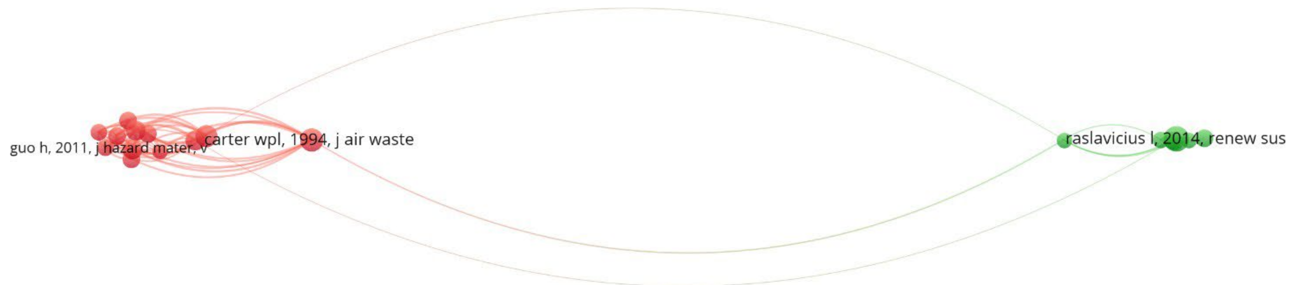

Figure 16: LPG Transport Co-citation Map (10 co-citation minimum)

Top "LPG Transport" Co-citations:

1. Development of ozone reactivity scales for volatile organic compounds (Carter, 2012)
2. Sources of ambient volatile organic compounds and their contributions to photochemical ozone formation at a site in the Pearl River Delta, southern China (Ling et al., 2011)
3. Concentration and distribution of 17 organochlorine pesticides (OCPs) in seawater from the Japan Sea northward to the Arctic Ocean (Cai et al., 2010)

The most cited papers on LPG transport focus on emissions and source apportionment. Therefore, it can be determined that the research for LPG transport has focused more on the effects from its burning, and how this effects the environment. Again, we see that the most prevalent research within the transport of LPG has not focused on safety or emergency response.

Annex B – Butane and Propane Property Comparison

Since LPG can be composed of many different compositions (primarily butane-rich and propane-rich), it is important to establish the range of properties that LPG can exhibit. Therefore, a property comparison of the relevant properties of Butane and Propane is given in Table 18.

Table 18: Key Property Comparison of Butane and Propane

Property	Butane	Propane
Molecular Weight (g/mol)	58.12	44.1
Liquid Density (kg/m^3) (at 25°C)	604	580
Gas Density (kg/m^3) (at 25°C)	2.489	1.882
Vapor Viscosity ($Pa \cdot s$)	$7.0 \cdot 10^{-6}$	$7.4 \cdot 10^{-6}$
Liquid Surface Tension (N/m)	0.023	0.007
Specific Gravity (at 25°C)	0.601	0.495
Heat of Combustion (MJ/kg)	45.82	46.43
Boiling Point (°C)	-1 (30 °F)	-42.2 (-44 °F)
Flash Point (°C)	-60 (-76 °F)	-104 (-155 °F)
Auto Ignition Temperature (°C)	287 (549 °F)	470-550 (878-1022 °F)
Lower Flammability Limit (Volume % in air)	1.86	2.1
Upper Flammability Limit (Volume % in air)	8.41	10.1
Combustion Flame Temperature (°C)	1970 (3578 °F)	1980 (3596 °F)

Annex C – Selection of Relevant Equations Supplemental Information

While Table 7 encompasses the fundamental equations most vital to understand LNG and LPG releases and their differences in an emergency response context, there are many aspects of releases and incidents that can be quantified through more equations. Below are equations that provide variables that are utilized in Table 7, provide deeper understanding of the phenomena involved in release, or provide better understanding of the risk involved in a release.

When calculating the radiant heat flux equation provided in Table 7, it is necessary to calculate both the transmissivity and view factor, therefore the equations to calculate these parameters are below:
The atmospheric transmissivity, τ, is computed with:

$$\tau = 2.02 \cdot \left[\frac{P_{water}}{x}\right]^{-0.09}$$

where P_{water} is the partial pressure of water vapor in air [Pa] and x is the line-of-sight distance from point on flame to receptor [m].

The view factor, F, is found using the following formula:

$$F = \int\int_S \left[\frac{\cos(\beta_1) \cdot \cos(\beta_2)}{\pi \cdot d^2}\right] dA_1$$

where β1 and β2 are the angles between line joining flame and receptor and line normal to flame surface or receptor surface, and d is the distance between flame surface element and receptor, [m].

Modeling the consequence of an LNG spill requires source term modeling and dispersion modeling. Heat transfer mechanisms are very applicable in the source term modeling. Equations that model liquid pool evaporation and provide further understanding of the dynamics involved in pool formation are as follows (Nawaz et al., 2014):

$$Q_{cond} = \frac{\pi r^2 \chi_s k_s (T_s - T)}{1000 t^{0.5} (\pi \alpha_s)^{0.5}}$$

Where Xs is the surface roughness factor, ks is the thermal conductivity of the surface, Ts is the temperature of the substrate at infinite depth, t is time, α_s is the thermal diffusivity of the surface, T is the temperature of the pool, r is the radius of the pool, and Q_{cond} is the heat flow rate from conduction.

$$Q_{conv} = \frac{\lambda_a N_u \pi r^2 (T_a - T)}{1000 L}$$

Where λ_a is the thermal conductivity of air, N_u is the Nusselt number, Ta is the atmospheric temperature, L is the diameter of the pool, T is the temperature of the pool, r is the radius of the pool, and Q_{conv} is the heat flow rate from convection.

Further, to find the heat flow rate from evaporation, first the evaporation rate must be calculated, as shown below:

$$E_{vap} = \frac{\pi r^2 K_m M_w}{RT} P_v$$

Or, using film theory to add a correction term for high mass transfer rate:

$$E_{vap} = \frac{\pi r^2 K_m M_w}{RT} P_a \ln \left\{\frac{P_a}{P_a - P_v}\right\}$$

Therefore, the heat flow rate from evaporation can now be calculated as follows:

$$Q_{evap} = E_{vap} H_v$$

Where Q_{evap} is the heat flow rate from evaporation, E_{vap} is the evaporation rate, r is the radius of the pool, K_m is the mass transfer coefficient, M_w is the molecular weight of spilled liquid, H_v is the heat of vaporization of the spilled liquid, P_v is the saturated vapor pressure of the spilled liquid, R is the gas constant, T is the temperature of the pool, and P_a is the atmospheric pressure.

Finally, when addressing consequence modeling, it is important to model the fireball resulting from any explosions. Therefore, the maximum diameter and duration of fireballs is included below (Bubbico & Marchini, 2008):

$$D_{max} = \alpha \cdot m_f^{\beta}$$

$$t_c = \gamma \cdot m_f^{\delta}$$

Where D_{max} is the maximum diameter of the fireball, t_c is the duration of the fireball, and the other parameters are constants that are determined as shown in the publication by Bubbico and Marchini.

Annex D – Modeling LNG and LPG Releases Supplemental Information

In recent studies, there have been limited experimental investigations into the formation of LNG pools. Instead, the studies are focused more on the modeling of the pool formation process. Numerical models for LNG pool formation are mainly addressed by the integral model or the Navier−Stokes model (Ikealumba & Wu, 2014).

Integral models originated in the 1980s and are the simpler of the two techniques. These models use algebraic equations to obtain solutions and are usually limited to the modeling of circular pools, flat substrates, and heat transfer only from the substrates. Navier−Stokes models are more complex and the most complete models. Modeling pool formation with Navier−Stokes models can be time-consuming because of their complexity. As a result, researchers prefer to model pool formation with integral models and then transfer the data over to Navier−Stokes models for further analysis.

Various numerical models have been developed to study LNG vapor dispersion. The main differences among the models are in the completeness of simulation for the dispersion process, the capabilities in different release processes, the ability of the model to describe processes, the completeness in fields and data used, and the complexity of the terrain for which the model is situated. Since the 1980s, various numerical models have been developed for the study of atmospheric dispersion of denser than air clouds. These mathematical models that have been used are either box/top-hat models or Navier−Stokes models.

There are two types of box or top hat models: modified Gaussian models and similarity-profile models, and the choice between models depends upon the complexity of conservation equations that must be solved. The modified Gaussian models are the simplest because the Gaussian equation is used for the conservation of species while neglecting or simplifying those for momentum and energy. The similarity-profile models use simplified conservation equations with a mathematical complexity of one dimension. Such simplicity is achieved via averaging the LNG cloud properties across the surface of the entire cloud or over the cross-wind plane. To regain the structural loss because of averaging, similarity profiles are used, therefore leading to quasi-three-dimensional solutions.

The Navier−Stokes models contain the most physically complete description of the LNG dispersion process and are constructed from three-dimensional and time-dependent conservation equations of momentum, mass, energy, and species. Although giving a more complete description of the physical processes available and performing better than box or top-hat models, the Navier−Stokes models are more computationally expensive.

Annex E – Summary of LNG/LPG Emergency Response Considerations by Transport Type

In order to establish emergency response recommendations for a given process or scenario, information pertaining to the substance container, potential incident scenarios, hazards and release effects, and current emergency response procedures is necessary. This Annex provides a summary of this information that has informed the recommendations made within the report.

Table 19: Summary of Container Information for LNG/LPG Transport by Transport Type

Container Information		
Mode of Transportation	**LNG Container Info**	**LPG Container Info**
Road Cargo Tank Truck Specification	TC/MC-338 (Vacuum insulation design with outer jacket)	TC/MC-331 (Single-shell, non-insulated)
Road/Rail/Marine ISO Portable Tank Container Specification	UN T75 (Cryogenic Liquid – refrigerated liquefied gases)	UN T50 (Pressure – used for non-refrigerated liquefied compressed gases)
Rail Rail Car Specification	TC/DOT-113	TC/DOT- 105, 112, 114, 120
Rail Inner Tank Construction	3/16-inch 304 Stainless Steel	Greater of 9/16-inch to 11/16-inch minimum or by formula
Rail Outer Tank Construction	9/16-inch T128 Carbon Steel (for DOT-113C120W9 and anticipated TC-113C120W9)	Thermal insulation and jacketing
Rail Thermal Insulation	Approximate 6-inch vacuum insulation	Meet 100 min. pool fire and 30 min. torch fire requirement
Marine	Membrane or Moss-Rosenberg Design	ISO containers 1CC, 1BB, 1AA

Table 20: Summary of Incident Types and LNG/LPG Scenarios by Transport Type

Incident Type / Scenarios (Summary of Section 7)		
Mode of Transportation	**LNG Scenarios**	**LPG Scenarios**
All	• Cryogenic Behaviors & Effects • Pool Fire Scenario • Jet Fire Scenario • BLEVE (lower probability) • Vapor Cloud Release • Rapid Phase Transition	• Liquefied Gas Behaviors – not cryogenic • Pool Fire Scenario (Propane-heavy LPG - lower probability) • Jet Fire Scenarios • BLEVE • Vapor Cloud Release
Road	• No additional considerations	• No additional considerations
Rail	• No additional considerations	• No additional considerations
Marine	• LNG may undergo rapid phase transition when released on or near water	• Flammability and asphyxiation risks increase when released in a confined environment such as during maritime transport. • LPG will float on water

Table 21: Summary of LNG/LPG Hazards and Release Effects by Transport Type

Hazards and Release Effects (Summary of Section 4)		
Mode of Transportation	**LNG Hazards**	**LPG Hazards**
All	• Non-odorized • Flammability – pressure fires and pool-fed fires • Higher radiant heat flux (3-5 times) than other commonly transported hydrocarbons • Cryogenic vapors are initially heavier than air and then rise	• Odorized • Flammability – pressure fires • More rapid vapor cloud flame spread than LNG when ignited • Higher probability of BLEVE than LNG • Vapors are heavier than air
Road	• No additional hazards	• No additional hazards
Rail	• No additional hazards	• No additional hazards
Marine	• No additional hazards	• Flammability and asphyxiation risks increase when released in a confined environment such as during maritime transport. • LPG will float on water

Table 22: Summary of LNG/LPG Emergency Response Procedures by Transport Type

Emergency Response Procedures during Transport (Summary of Section 8)		
Mode of Transportation	**LNG Emergency Response Procedures**	**LPG Emergency Response Procedures**
All	• Do not extinguish a leaking LNG vapor fire unless the leak can be stopped. • When ignited, LNG will flash back to its source. • LNG will vaporize rapidly forming a cold vapor cloud that is initially heavier than air, spreading and carrying downwind until it reaches neutral buoyancy as it warms up. • Water fog streams will be critical for fire control and exposure protection. • Do not direct water at spill or source of leak. Do not apply water to pooled LNG as it will heat up and increase rate of LNG vaporization and intensity of the fire. • Water may have limited effectiveness in cooling exposed LNG or cryogenic liquid containers that have maintained their integrity due to the "tank within a tank" design. • Dry chemical (e.g., Purple K) or CO_2 are suitable extinguishing agents for small fires.	• Do not extinguish a leaking vapor release fire unless the leak can be stopped. • When ignited, LPG will flash back to its source. • Water fog streams will be critical for fire control and exposure protection. • Do not direct water at spill or source of leak. • Cooling of any exposed containers will be critical in minimizing growth of the fire problem. • Jet fires can only be controlled by isolating the source of product flow, while protecting exposures. • Dry chemical (e.g., Purple K) or CO_2 are suitable extinguishing agents for small fires. • Significant incident history involving BLEVEs for both bulk and non-bulk containers. • Requires thermal protective clothing.

	• Pressure relief devices used on compressed gas cylinders (e.g., CNG) may be temperature or pressure actuated, while those found on flammable liquefied gas (e.g., LPG) and flammable cryogenic liquid containers (e.g., LNG) are pressure actuated and therefore care must be taken to not direct water towards the valve. • Currently no incident reports or testing of a BLEVE in cryogenic containers (TC/MC-338, UN T75, or TC/DOT-113). • Requires specialized thermal protective clothing suitable for cryogenic materials.	
Road	• No additional unique emergency response considerations for road transport, beyond general guidance above.	• No additional unique emergency response considerations for road transport, beyond general guidance above.
Rail	• LNG fuel tenders - Verify if LNG sensors were activated in the locomotive if unsure about whether there was a leak.	• No additional unique emergency response considerations for rail transport, beyond general guidance above.
Maritime	• No additional unique emergency response considerations for marine transport, beyond general guidance above.	• No additional unique emergency response considerations for marine transport, beyond general guidance above.

Annex F – Flammable Zone Size Research Comparison

When LNG is spilled into the environment, there will be a specific zone that is filled with enough LNG to lie within the flammability limits of LNG in air and therefore can be ignited. The radius outward from the leak source to the boundary where the lower flammability limit is reached is classified as the flammable zone size. Table 23 presents multiple studies that were performed by separate entities each with the goal of determining the flammable zone size for particular LNG spill zone sizes. While there are more accurate measurements of flammable zones for LNG spills, this serves to display the lack of a knowledge base within LNG research. As can be seen in Table 23, these different entities had widely varying results when attempting to address the same spill size, demonstrating the disagreement within scientific research towards, and therefore difficulty in establishing, the risk of LNG transport.

Table 23: LNG Studies of Flammable Zone Size for Various Spill Sizes

Spill Size (m^3)	Massachusetts Institute of Technology (ft)	United States Bureau of Mines (ft)	American Petroleum Institute (ft)	United States Environmental Protection Agency (ft)
100,000	670,000	>400,000	(74,000)	17,000
25,000	300,000	>200,000	37,000	---
5,000	120,000	>90,000	(17,000)	4,500
1,000	53,000	>40,000	(7,400)	---
100	13,000	2,600	(2,300)	---
10	3,000	>4,000	---	---

i. Table is a representative sample of flammable zones for various spill sizes, from past literature and tests. This table has been recreated from Murray et al., 1976.

ii. Values in parentheses represent values that were regarded as crude extrapolations from the collected dataset.

Annex G – Reference to ERG Guide 115

As this project was developed with the goal of establishing emergency response guidance in the field of LNG transport, the relevant section of the ERG is provided below, as reference.

GUIDE 115 Gases - Flammable (Including Refrigerated Liquids)

POTENTIAL HAZARDS

FIRE OR EXPLOSION

- **EXTREMELY FLAMMABLE.**
- Will be easily ignited by heat, sparks or flames.
- Will form explosive mixtures with air.
- Vapors from liquefied gas are initially heavier than air and spread along ground.

CAUTION: Hydrogen (UN1049), Deuterium (UN1957), Hydrogen, refrigerated liquid (UN1966), Methane (UN1971) and Hydrogen and Methane mixture, compressed (UN2034) are lighter than air and will rise. Hydrogen and Deuterium fires are difficult to detect since they burn with an invisible flame. Use an alternate method of detection (thermal camera, broom handle, etc.)

- Vapors may travel to source of ignition and flash back.
- Cylinders exposed to fire may vent and release flammable gas through pressure relief devices.
- Containers may explode when heated.
- Ruptured cylinders may rocket.

HEALTH

- Vapors may cause dizziness or asphyxiation without warning.
- Some may be irritating if inhaled at high concentrations.
- Contact with gas or liquefied gas may cause burns, severe injury and/or frostbite.
- Fire may produce irritating and/or toxic gases.

PUBLIC SAFETY

- **CALL 911. Then call emergency response telephone number on shipping paper.** If shipping paper not available or no answer, refer to appropriate telephone number listed on the inside back cover.
- Keep unauthorized personnel away.
- Stay upwind, uphill and/or upstream.
- Many gases are heavier than air and will spread along the ground and collect in low or confined areas (sewers, basements, tanks, etc.).

PROTECTIVE CLOTHING

- Wear positive pressure self-contained breathing apparatus (SCBA).
- Structural firefighters' protective clothing provides thermal protection **but only limited chemical protection**.
- Always wear thermal protective clothing when handling refrigerated/cryogenic liquids.

EVACUATION

Immediate precautionary measure

- Isolate spill or leak area for at least 100 meters (330 feet) in all directions.

Large Spill

- Consider initial downwind evacuation for at least 800 meters (1/2 mile).

Fire

- If tank, rail car or tank truck is involved in a fire, ISOLATE for 1600 meters (1 mile) in all directions; also, consider initial evacuation for 1600 meters (1 mile) in all directions.
- In fires involving Liquefied Petroleum Gases (LPG) (UN1075), Butane (UN1011), Butylene (UN1012), Isobutylene (UN1055), Propylene (UN1077), Isobutane (UN1969), and Propane (UN1978), also refer to BLEVE – SAFETY PRECAUTIONS (Page 366).

In Canada, an Emergency Response Assistance Plan (ERAP) may be required for this product. Please consult the shipping paper and/or the ERAP Program Section (page 390).

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Figure 17: ERG Guide 115 - Gases - Flammable - Page 166

GASES - FLAMMABLE (INCLUDING REFRIGERATED LIQUIDS) GUIDE 115

EMERGENCY RESPONSE

FIRE

- **DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED.**

CAUTION: Hydrogen (UN1049), Deuterium (UN1957), Hydrogen, refrigerated liquid (UN1966) and Hydrogen and Methane mixture, compressed (UN2034) will burn with an invisible flame. Use an alternate method of detection (thermal camera, broom handle, etc.)

Small Fire

- Dry chemical or CO_2.

Large Fire

- Water spray or fog.
- If it can be done safely, move undamaged containers away from the area around the fire.

CAUTION: For **LNG - Liquefied natural gas (UN1972)** pool fires, DO NOT USE water. Use dry chemical or high-expansion foam.

Fire Involving Tanks

- Fight fire from maximum distance or use unmanned master stream devices or monitor nozzles.
- Cool containers with flooding quantities of water until well after fire is out.
- Do not direct water at source of leak or safety devices; icing may occur.
- Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank.
- ALWAYS stay away from tanks engulfed in fire.
- For massive fire, use unmanned master stream devices or monitor nozzles; if this is impossible, withdraw from area and let fire burn.

SPILL OR LEAK

- ELIMINATE all ignition sources (no smoking, flares, sparks or flames) from immediate area.
- All equipment used when handling the product must be grounded.
- Do not touch or walk through spilled material.
- Stop leak if you can do it without risk.
- If possible, turn leaking containers so that gas escapes rather than liquid.
- Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material.
- Do not direct water at spill or source of leak.

CAUTION: For **LNG - Liquefied natural gas (UN1972)**, DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors.

- Prevent spreading of vapors through sewers, ventilation systems and confined areas.
- Isolate area until gas has dispersed.

CAUTION: When in contact with refrigerated/cryogenic liquids, many materials become brittle and are likely to break without warning.

FIRST AID

- Call 911 or emergency medical service.
- Ensure that medical personnel are aware of the material(s) involved and take precautions to protect themselves.
- Move victim to fresh air if it can be done safely.
- Give artificial respiration if victim is not breathing.
- Administer oxygen if breathing is difficult.
- Remove and isolate contaminated clothing and shoes.
- Clothing frozen to the skin should be thawed before being removed.
- In case of contact with liquefied gas, thaw frosted parts with lukewarm water.
- In case of burns, immediately cool affected skin for as long as possible with cold water. Do not remove clothing if adhering to skin.
- Keep victim calm and warm.

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Figure 18: ERG Guide 115 - Gases - Flammable - Page 167

Annex H – TRANSCAER – LNG Safety and Emergency Response Reference

LNG Safety and Emergency Response

"Liquefied Natural Gas, refrigerated liquid", UN 1972, Hazard Class 2.1 "Flammable Gas"
Emergency Response Guide No. 115

FLAMMABILITY	
Flash Point	-306°F (-188°C)
Boiling Point	-260°F (-160°C)
Explosive Range	5% (LEL) to 15% (UEL)
Autoignition Temperature	1,004°F (540°C)
DISPERSION / EXPANSION RATIO	
Expansion Ratio	600:1 @ 1 Atmosphere
Vapor Pressure	258,574 mm Hg @ 100°F (38°C)
Vapor Density at -166° relative to Ambient Air	1
Vapor Density at -260° relative to Ambient Air	1.4
Liquid Density (Weight per Volume) - Dependent upon methane volume	3.56 - 4 lbs./gallon
CRYOGENICS	
Specific Gravity	0.422 @ -260°F (-160°C)
Solubility in Water	Negligible (below 0.01%)
Critical Temperature	-232°F (-147°C)
Heat of Vaporization	220 BTU/lb.

GUIDE 115 GASES - FLAMMABLE (INCLUDING REFRIGERATED LIQUIDS)

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- Wear positive pressure self-contained breathing apparatus (SCBA).
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Fire

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GASES - FLAMMABLE (INCLUDING REFRIGERATED LIQUIDS) GUIDE 115

EMERGENCY RESPONSE

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- Water spray or fog.
- If it can be done safely, move undamaged containers away from the area around the fire.

CAUTION: For **LNG - Liquefied natural gas (UN1972)** pool fires, DO NOT USE water. Use dry chemical or high-expansion foam.

Fire Involving Tanks

- Fight fire from maximum distance or use unmanned master stream devices or monitor nozzles.
- Cool containers with flooding quantities of water until well after fire is out.
- Do not direct water at source of leak or safety devices; icing may occur.
- Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank.
- ALWAYS stay away from tanks engulfed in fire.
- For massive fire, use unmanned master stream devices or monitor nozzles; if this is impossible, withdraw from area and let fire burn.

SPILL OR LEAK

- ELIMINATE all ignition sources (no smoking, flares, sparks or flames) from immediate area.
- All equipment used when handling the product must be grounded.
- Do not touch or walk through spilled material.
- Stop leak if you can do it without risk.
- If possible, turn leaking containers so that gas escapes rather than liquid.
- Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material.
- Do not direct water at spill or source of leak.

CAUTION: For **LNG - Liquefied natural gas (UN1972)**, DO NOT apply water, regular or alcohol-resistant foam directly on spill. Use a high-expansion foam if available to reduce vapors.

- Prevent spreading of vapors through sewers, ventilation systems and confined areas.
- Isolate area until gas has dispersed.

CAUTION: When in contact with refrigerated/cryogenic liquids, many materials become brittle and are likely to break without warning.

FIRST AID

- Call 911 or emergency medical service.
- Ensure that medical personnel are aware of the material(s) involved and take precautions to protect themselves.
- Move victim to fresh air if it can be done safely.
- Give artificial respiration if victim is not breathing.
- Administer oxygen if breathing is difficult.
- Remove and isolate contaminated clothing and shoes.
- Clothing frozen to the skin should be thawed before being removed.
- In case of contact with liquefied gas, thaw frosted parts with lukewarm water.
- In case of burns, immediately cool affected skin for as long as possible with cold water. Do not remove clothing if adhering to skin.
- Keep victim calm and warm.

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Source: PHMSA COMMODITY PREPAREDNESS AND INCIDENT MANAGEMENT REFERENCE SHEET – Liquefied Natural Gas

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LNG Safety and Emergency Response

"Liquefied Natural Gas, refrigerated liquid", UN 1972, Hazard Class 2.1 "Flammable Gas"
Emergency Response Guide No. 115

EMERGENCY RESPONSE CONSIDERATIONS

KEY INCIDENT OBJECTIVES

Δ **Establish command**

- Incident commander
- Implement ICS
- Safety officer
- Site access control
- Others as needed
- Based upon incident size, consider need for All-Hazard Incident Management Team (AHIMTs)

Δ **Determine Incident Priorities**

- Life safety
- Incident stabilization
- Protection of property/environment

Δ **Isolate**

- Follow ERG guide number 115
- Isolate spill/leak 100 meters (330 feet) all directions
- Large spill initial evacuation 800 meters (0.5 miles)
- Fire – if tank car involved in fire, isolate 1,600 meters (1 mile) in all directions and consider initial evacuation for 1,600 meters (1 mile in all directions)
- Verify with detection equipment
- Control zones & personnel accountability

Δ **Notifications**

- Additional resources as needed
- Local emergency management
- CHEMTREC 1-800-424-9300
- NRC 1-800-424-8802

Δ **Hazard analysis & risk assessment**

- Product hazard analysis & quantity
- Type of container damage
  - Mechanical or thermal stress
  - Container breach
  - Status of annular vacuum
- Environment
  - People, property, environment
- Other materials/containers involved
- Consider impacts of non-intervention

Δ **Life Safety**

- Proper PPE & avoid liquid contact
- Firefighter PPE will not protect from direct contact with cryogenic liquids
- Rescue of Viable Patients
- Medical support/rehab

Δ **Spill control**

- Liquid phase: reduce surface area
  - Pooling or vapor release
- Vapor: support upward dispersion

Δ **Leak control**

- Remote shutdowns if accessible
- Obtain expert assistance

Δ **Fire control**

- If no fire, control ignition sources
- Safety lines
- Adequate water supply
- Consider potential for Confined or Unconfined Vapor Explosion (CVE or UCVE)
- Potential for BLEVE is low due to insulation, maintain awareness of relief valve operation
- If on fire, type of fire
  - Pool fire, jet fire or vapor cloud fire
- DO NOT apply water to liquid spill, points of leak or relief valves
- Protect exposures

Δ **Recovery and termination**

- Evaluate equipment contact with liquid
- Document exposures
- Critique & post incident analysis

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Annex I – Volpentest Hazardous Materials Emergency Response (HAMMER) Federal Training Center – Commodity Preparedness and Incident Management Reference Sheet for Liquefied Natural Gas

In addition to the information provided throughout this report (Validation of recommended emergency actions for liquefied natural gas (LNG) in the Emergency Response Guidebook (ERG)), the authors would like to provide this additional reference: the Commodity Preparedness and Incident Management Reference Sheet (CPIMRS) for Liquefied Natural Gas (LNG), which was released through HAMMER, a Federal Training Center owned by the US Department of Energy (DOE). One of the co-authors of the current report was also the architect of the HAMMER CPIMRS reference sheet and report. The CPIMRS document was developed to serve as a resource tool for emergency preparedness personnel in planning, training, and responding to rail incidents involving the transportation of Liquefied Natural Gas (LNG).