UNIVERSITY OF BAHRAIN

College of Engineering **Dept. of Mech. Engineering**

A Baseline Quantitative Risk Assessment (QRA) for the Road Transportation of Hydrogen Vehicle Fuel in Bahrain – A Framework for Future Risk Analyses

Thesis Proposal submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering Management

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September 2025

UNIVERSITY OF BAHRAIN
Deanship of Graduate Studies & Scientific Research

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Dissertation Deposit Form

Form Code: UDNGS025

Author Name:	Hamed Mohammed Hamed Al Nahawi
Thesis Title:	A Baseline Quantitative Risk Assessment (QRA) for the Road Transportation of Hydrogen Vehicle Fuel in Bahrain - A Framework for Future Risk Analysis
Year of Publication:	2025
Department:	Mechanical Engineering
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The Discussion Committee met on 28/6/2025 **in** 31-209 **upon discussing the student whose details are stated above in public. The discussion committee recommends the following:**

The student is awarded the grade pass **in the thesis course** IEN598.

☐ **Without making any changes to the thesis.**

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Discussion Committee Members Approval:

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Abstract

Net zero emissions is a global target which countries are all making commitments towards. Bahrain has committed to a net zero emissions target by the year 2060. To achieve this goal, it is proposed to substitute gasoline and fossil fuels with sustainable and environmentally favorable sources such as green hydrogen powering fuel cell vehicles. This study examines hydrogen fuel cell vehicle technologies by means of an extensive literature review, and outlines Bahrain's targets. Additionally, the study presents the available standards for hazardous material transportation, hydrogen transportation, and quantitative transportation risk assessments. The research establishes the framework for a transportation risk assessment assuming green hydrogen as the main fuel for vehicles in the Kingdom. Furthermore, the study establishes base risk figures assuming the current road network, the current distribution terminal's location, and the existing retail fueling stations.

The research methodology is mainly in line with the methods prescribed in the "Guidelines for Quantitative Risk Assessment 'Purple Book' (CPR 18E)". Statistical analysis of the General Directorate of Traffic's (GDOT) accident statistics is conducted to build a frequency analysis. The results of the frequency analysis are used to predict the probability of future accidents in a likelihood analysis. Subsequently, a consequence analysis is performed to evaluate the severity of loss of containment (LOC) events and their escalations. Finally, the consequence severity and the incident likelihood results are combined to establish the baseline risk figures.

Keywords: Transportation Risk Analysis; Quantitative Risk Analysis; Net-Zero Emissions; Green Hydrogen; Hydrogen Fuel Cell Vehicles; CPR 18E Purple Book

Dedications

All praise and gratitude are due to God.

This study is dedicated to my father, mother, brother, wife, son, beloved family and every person dear to my heart. I also dedicate this work to the martyrs, the wounded, and the proudly steadfast people of Gaza, the bravest souls on this planet.

Acknowledgements

All praise and gratitude are due to God, the most merciful, the beneficent. His blessings on me are infinite and by his mercy and aid I have concluded this work.

“He who does not thank the people does not thank the lord”.

I first and foremost thank Dr. Bassam Al Hamad for his guidance, support, patience, encouragement, and genuine desire for my success.

Secondly, I acknowledge and thank my company – ioMosaic International Consulting – our CEO, managers and my esteemed colleagues for their support and encouragement to complete this thesis. I also specifically acknowledge ioMosaic for allowing me to use SuperChems® to complete this study.

Most of all, I thank my father for pushing me towards enrolling in a Master’s program, my mother for her endless love and care, my brother for his aid, encouragement, and provocation, my wife for her heartfelt support, and my family for being there for me throughout this journey.

I thank my friends who have been there for me through thick and thin.

I thank every person who has helped, guided, advised, or assisted me throughout this journey, and who have contributed towards this work – may God reward you and bless you.

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Chapter One

Introduction

1.1 Background

In light of the pressing environmental concerns of fossil fuel usage, there is an exponentially increasing need for sustainable energy sources that satisfy the ever-growing energy demand. While sustainable energy technologies have already gained traction in different parts of the world, the gap between sustainable energy supply and energy demand remains a matter of concern (International Renewable Energy Agency [IRENA], 2020).

In the past few years, major environmental changes have been encountered across the globe. Countries in all continents have experienced violent and unprecedented climate conditions. For example, flash floods in Pakistan and Australia, violent summers in Europe, and some of the coldest winters in the Americas have repeatedly struck. It is claimed that those major climate changes are primarily due to the excessive emission of greenhouse gases as a result of processing and burning fossil fuels for energy. The most commonly released greenhouse gas is certainly carbon dioxide (MIT Climate Portal, 2023).

Decision makers are pushing towards the adoption of "Low Carbon Economics" to reduce greenhouse gas emissions while also meeting the global energy demand. Decarbonization, carbon-neutral fuels, and carbon capture, storage, and sequestration, are all novel strategies towards the achievement of zero-carbon emissions goals. The concept of zero carbon emissions has been accepted as one method to mitigate environmental calamities such as global warming (Grantham Research Institute, 2023). This novel concept refers to the reduction or elimination of carbon dioxide emission during the processing or combustion of energy sources, as well as the capturing of any unavoidable carbon dioxide productions prior to their release to atmosphere. Accordingly, it is better suited that this concept is referred to as "net-zero caron emissions". Net-zero emissions goals can

hence be thought of as a means to maintaining a functional economy without the emission of greenhouse gases. The postulate is that if more eco-friendly energy sources are used, less fossil fuels are burned, and any inevitable production of greenhouse gases – and primarily carbon dioxide – is either prevented or mitigated by one of the above mentioned techniques, then a net-zero emissions system can be established, whereby environmentally harmful releases can no longer contribute to climate change.

As a result of the international effort to mitigate climate change in global conventions such as the Paris Agreement, Kyoto Protocol, and the UNFCCC, countries have started to commit to tangible targets for achieving net-zero emissions economies. Those efforts to combat climate change have also been aligned with the Sustainable Development Goals. In addition, countries hosting fossil-fuel dependent economies have accelerated their measures to diversify their economies and introduce cleaner energy sources. Bahrain – being one of the Arabian Gulf countries – has been a fossil fuel dependent country since the discovery of oil on its lands in 1936 (Oxford Business Group, 2022). Nonetheless, Bahrain has undertaken a "Nationally Determined Contribution (NDC)" in line with the Paris Agreement ahead of the COP26 Climate Summit to achieve a net-zero emissions target by 2060 (Bahrain News Agency, 2021). For this reason, Bahrain has started investigating alternative energy options to replace a portion of the conventional fuel consumption in the country. Recently, hybrid and electric vehicles have been introduced. Bahrain has also set sight to the introduction of Hydrogen Fuel Cell Vehicles in the future – with potential for making those vehicles the dominant mode of transportation in the country by the year 2060 (Oxford Business Group, 2022).

1.2 Research Problem

In the current years, hydrogen and hydrogen technologies have gained extreme attention and interest globally and in the Gulf region. This is primarily due to the abundance of hydrogen as an element and its ability - in its molecular form – to fulfil the energy demand with little to no compromise on the current energy consumption habits. Nonetheless, and as with combustible fossil fuels, hydrogen needs to be burned to harness its energy – a process involving great risks and high potentials for catastrophic accidents.

As it stands, there have been no studies performed to evaluate the risks of transporting hydrogen in Bahrain via the Kingdom's road network. Additionally, there exists no framework for road transportation risk evaluations in Bahrain.

Accordingly, the risks of road transportation of hydrogen need to be analyzed and quantified prior to introducing it as a transportation fuel requiring transportation by bulk quantities, and a framework for such risk evaluations needs to be established.

1.3 Research Questions

This study primarily investigates the risks associated with the road transportation of hydrogen, considering the existing road network and the locations of existing fuel retail stations. The study also investigates the ideal location for a hydrogen distribution terminal given the current road network.

Throughout the study, other relevant topics and questions are tackled and answered, including a survey of the international frameworks and international benchmarks for fuel transportation risks, a detailed explanation of what green hydrogen is and how it differs from blue or grey hydrogen, an concise summary of hydrogen fuel cell technologies and hydrogen internal

combustion engine vehicles, a survey of the viable methods for green hydrogen production in the case of Bahrain, and lastly an elucidation of the modes of transporting hydrogen fuel be it gaseous or liquid.

1.4 Research Objectives

This research investigates the risks associated with the road transportation of hydrogen in Bahrain. The study considers the properties of hydrogen, the globally available and implemented transportation and storage technologies, the different modes of transporting hydrogen by road, and the local scene for fuel transportation to assess the risk associated with hydrogen transportation as opposed to that of conventional fuels such as gasoline and diesel. The study aims to quantify the outcomes of a catastrophic events following the loss of containment (LOC) of hydrogen on road – for both gaseous hydrogen transporters and liquid hydrogen transporters. The magnitude of the consequence is combined with frequency and probability predictions for such loss of containment events on road, and an overall risk is quantified.

It is not within the scope of this study to analyze, determine, or predict the nature of the hydrogen supply chain in Bahrain by the year 2060 as that is an extensive task beyond the purpose of establishing a quantitative risk evaluation framework. Accordingly, the study assumes hydrogen as the dominant transportation fuel in Bahrain by the year 2060; and considers both Gaseous Hydrogen and Liquid Hydrogen configurations.

1.5 Research Significance

This study offers baseline quantitative risk figures for the road transportation of hydrogen as a fuel in Bahrain. Baseline risk figures presented prior to the actual introduction of hydrogen fuel allows decision makers in Bahrain to implement measures to eliminate or mitigate those identified risks.

Additionally, in the absence of a framework for fuel transportation risk assessments in Bahrain, this study is expected to present a native contribution by establishing such a framework. This also opens the doors for future research by working on implementing accuracies into the framework and refining the model for quantifying risks associated with the transportation of fuels in Bahrain. As such, this research and its authors hope to make a contribution towards safety and risk management in Bahrain which propagates into the future and tangibly enhances the quality of life in the country.

1.6 Research Terminology

Table (1): Research Terminology

Term/Abbreviation	Explanation
H_2	Hydrogen
GH2	Gaseous Hydrogen
LH2	Liquid Hydrogen
T/T Length	Tangent to Tangent Length
LOC	Loss of Containment
CA	Consequence Analysis
IR	Individual Risk
SR	Societal Risk
F-N Curve	Farmer's Diagram
BLEVE	Boiling Liquid Expanding Vapor Explosion
ACOP	Approved Code of Practice
ADR	The European Agreement concerning the International Carriage of Dangerous Goods by Road
GPS	Global Positioning Satellites
DoT	U.S. Department of Transportation

PPE	Personal Protective Equipment
P	Probability
API	American Petroleum Institute
ASME	American Society for Mechanical Engineers
NFPA	National Fire Protection Association
UK HSE	United Kingdom Heath and Safety Executive
UV Radiation	Ultra-Violet Radiation
GHG	Greenhouse Gas

Chapter Two

Literature Review

2.1 History of Hydrogen Technologies

Record of the synthesis of hydrogen gas – although not yet discovered as a discrete substance – date as far back as the sixteenth century, when Paracelsus (Philippus von Hohenheim – Swiss Chemist, Physicist, and Philosopher) unknowingly produced hydrogen gas as a byproduct of the reaction of various metals with sulfuric acid (Encyclopaedia Britannica, 2023).

During the early 17th century, the Genevan physician Theodore de Mayerne picked up and advanced Paracelsus' theories and regenerated the gas which he referred to as "inflammable air".

Later in 1662 the infamous Irish scientist Robert Boyle experimentally established the fundamental relationship between pressure and volume in support of Towneley and Power's observations, and Boyle's Law came about. He then went on to investigate sources of flames and explosions and experimented with what he called "filings of steel" and a "saline spirit [hydrochloric acid]" to observe flammable fumes which produced considerable heat but not much light.

It was not until the middle of the 18th century – specifically the year 1766 – that the British scientist Henry Cavendish identified that this flammable gas produced by the metal/acid reaction was a unique and discrete substance, however. He wrote in his publication "On Factitious Airs" an account of his experiments describing the density of this inflammable air which he deduced was 7 to 11 times lighter than air, and when combusted produced water. In the year 1781, he went on proving that the combustion of this gas produced water (Chemistry LibreTexts, 2023).

Soon after in the year 1783, the French Antoin de Lavoisier recreated Henry Cavendish's experiments and was the first to name Hydrogen based

on the Latin etymology where *hydro* means water and *genes* means producer (Chemistry LibreTexts, 2023).

The discovery of hydrogen as a discrete substance could be recognized as one of the most important scientific and chemical discoveries in history. Coupled with the discovery of oxygen, as well as the shower of chemical discoveries that took place in the late 18th century, scientists were now equipped to study water, its known reactions (such as the water-gas shift reaction discovered in 1780), and the methods to isolate hydrogen and oxygen from water.

The years 1789 and 1800 witnessed the first successful experiments of the electrolysis of water to produce hydrogen and oxygen distinctly. In the year 1789 Jan Deiman and Adriaan van Troostwijk conducted the first experiment for the electrolysis of water. Then in the year 1800 William Nicholson and Anthony Carlisle successfully separated hydrogen and oxygen by electrolysis of water using a different experimental setup altogether. In the same year, Johann Ritter replicated their experiments with modifications to collect those two gases separately (Chemistry LibreTexts, 2023).

Realizing the properties of hydrogen such as it being flammable and lighter than air, scientists used it to fly hot-air balloons. Also due to its notable combustible nature, scientists investigated the use of hydrogen as a fuel as early as the year 1800. In 1801, Humphary Davy brought about the concept of a fuel cells in a report he published. The concept was refined and the working principles of a fuel cell were first discovered by Friedrich Schoenbein in the year 1838. This all materialized into a working fuel cell prototype which was conceived by William Robert Grove in 1839. Based on the notes of Nicholson and Carlisle, Grove investigated how to recompose water using electrodes. He achieved this upon mixing hydrogen with oxygen in the presence of an electrolyte and platinum electrodes connected

in series, to produce electricity and water – he called his invention the "gas battery". The prototype was improved by William Grove by using different electrodes and electrolytes, in what was nicknamed the "Grove cell". At the time, however, his invention did not generate sufficient electricity to be helpful. Nonetheless, his prototypes proved that water could be re-comprised from its constituent atoms and electricity could be generated (Chemistry LibreTexts, 2023).

Following in his footsteps, Fredrich Ostwald – often referred to as the father of physical chemistry – provided further theoretical basis for the functioning of a fuel cell, and in 1893 he backed his theoretical findings with experiments that determined the functions of the different fuel cell components.

During this time, various teams and researchers were exploring the same idea. It was Ludwig Mond and Charles Langer who originally introduced the term "fuel cell" in 1889. They attempted to create a working fuel cell utilizing air and gas derived from coal.

This electrochemical innovation gained recognition as a potential way to produce electricity; however, early researchers faced challenges in generating sufficiently high voltages to demonstrate the viability of their findings. Ongoing research in Germany and the Soviet Union throughout the early 1900s ultimately led to advancements such as the carbonate cycle, Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs), which still exist today.

Research on fuel cells continued to thrive throughout the latter part of the twentieth century and into the early twenty-first century. In the 1930s, engineer Francis T. Bacon initiated important studies on fuel cells. The initial configurations employed porous platinum electrodes and sulfuric acid as

the electrolyte solution. The use of platinum was costly, and sulfuric acid posed corrosive issues. Bacon enhanced the costly platinum catalysts by developing a hydrogen and oxygen cell that utilized a less corrosive alkaline electrolyte and more affordable nickel electrodes. It wasn't until 1959 that Bacon refined his design and showcased a five-kilowatt fuel cell capable of powering a welding machine (Bellis, 2021).

In the early 1960s, General Electric created a fuel-cell-based electrical power system for NASA's Gemini and Apollo space capsules. This design was grounded in the principles of the "Bacon Cell." Currently, the Space Shuttle relies on fuel cells for its electricity, which also produces drinking water for the crew. This decision was reinforced by NASA's findings that nuclear reactors posed too great a risk and that batteries or solar power were too cumbersome for use in space missions. NASA has supported over 200 research contracts focused on fuel-cell technology, advancing it to a stage suitable for private sector applications (Bellis, 2021).

Fuel cells have evolved significantly since their creation. They are now utilized in diverse applications such as transportation, stationary power generation, and portable power devices (Bellis, 2021). Fuel cells represent a promising technology that can help lessen our reliance on fossil fuels and address climate change. In particular, hydrogen fuel cells present substantial potential for sustainably replacing fossil fuels with clean alternatives.

2.2 Hydrogen as a Fuel

a. Properties of hydrogen

Hydrogen is the lightest chemical element, and is a colorless, odorless, tasteless and generally non-toxic chemical. Hydrogen is the most abundant chemical in the universe and can be found in many different forms. When in its pure form, hydrogen exists as a diatomic gas, H_2. On Earth, hydrogen

can be abundantly found in the molecular form in compounds such as water and organic compounds including foods and fuels. Hydrogen is also the main constituent of our Sun and many other stars in the universe; hydrogen undergoes a nuclear fusion reaction at the core of the sun to form helium.

Hydrogen in its most common isotope is made up of 1 proton, 1 electron, and no neutrons. It normally forms covalent bonds as is the case with its bonds in the water molecule and the many organic compounds it forms.

Under normal conditions, hydrogen is nonmetallic – meaning that it does not conduct electricity. However, at extremely high pressures hydrogen becomes metallic in what is called the metallic hydrogen form. In this phase, hydrogen acts as a conductor.

Aside from its versatile nature and combination with carbonaceous molecules to form organic compounds, hydrogen plays an important role in various reactions to form ionic or inorganic compounds. Hydrogen is a crucial player in acid-base type reactions involving the transfer of protons as well as electrons. When a single hydrogen atom combines with one or more non-metallic elements, this is referred to as a covalent hydride reaction. Some of those covalent hydrides are essentially acids or bases being formed. This is because the electron sharing that takes place as a result of the covalent bond allows the compound to become more electro-neutral. Some examples of the formation of covalent hydrides include the formation of hydrochloric acid, ammonia, and borane.

Hydrogen also plays a very important role in metallic hydride reactions with transition metals, as well as ionic hydride reactions with s-block metals (groups 1 and 2 of the periodic table). Metallic hydrides can exhibit unique characteristics in that they may be non-stoichiometric compounds,

with the number of hydrogen atoms not fixed and the composition of the compound variable.

Hydrogen is also known for being an energy carrier, meaning that it allows the usable transport of energy just like electricity. Under the right conditions, hydrogen gas is highly flammable in the presence of oxygen, a combustion reaction which produces water as its product and expenses energy in the form of heat (U.S. Department of Energy, n.d.). Additionally, hydrogen forms explosive mixtures in various environments such as air or chlorine. The combustion or explosion of hydrogen gas or hydrogen mixtures is a spontaneous reaction requiring the presence of an ignition source. At normal conditions, diatomic hydrogen is typically not very reactive, or to be accurate, exhibits very low and nearly negligible rates of reaction. Simply the presence of hydrogen gas along with oxygen or air is not enough to cause it to spontaneously ignite. This is due to the fact that the hydrogen molecule – in the diatomic form – has a very strong H-H bond and a non-polar nature. Nonetheless, when a spark, radiation, or catalyst is present, it becomes possible to overcome the dissociation energy of that bond causing hydrogen to react at a considerable rate.

All in all, it is the fact that hydrogen can expense high amounts of energy when combusted and produce no by-products other than water that makes it a sustainable and environmentally friendly fuel. This in turn accelerates interest in adopting it as an alternative energy source especially when considering that the H_2 gas molecule is – in theory – abundantly available. Refer to Appendix B for the thermo-physical properties of hydrogen

b. Reactivity, Flammability, and Explosibility of Hydrogen

Hydrogen atoms are the smallest among all elements, and they have the smallest covalent radius. The electroneutral hydrogen atom comprises a

nucleus of a single proton (positively charged) and a single valence electron (negatively charged). By virtue of its size and the fact that the valence shell of the atom contains only a single electron, hydrogen atoms tend to bond to one another to form diatomic hydrogen as previously mentioned. This covalent H-H bond is a very strong bond with a considerably large disassociation enthalpy of about 435 kJ/mol (LibreTexts, n.d.). This strong covalent bond provides a thermodynamic basis for why hydrogen tends to be quite stable and unreactive at room temperature.

Neutral hydrogen atoms tend to form strong bonds with other atoms as well. The hydrogen atom can lose its electron to become a cation – or a positively charged proton, or it can gain an additional electron to become an anion – or a negatively charged hydrogen atom. This phenomenon is responsible for a wide range of interesting chemistries such as redox reactions, acid-base reactions, and other inorganic reactions. Hydrogen can also bond with carbonaceous molecules in a very wide range of organic reactions. The fact that hydrogen is very commonly involved in both organic and inorganic chemistries, and considering its presence in almost all organic compounds, a strong argument can be made that more compounds contain hydrogen than any other element. Nonetheless, because the chemistry of hydrogen is not the focus of this research, only a brief introduction of the nature of the hydrogen atom and the various chemistries it is involved in is provided in this section.

Special emphasis is given for the combustion of hydrogen, however, as that is a very important and far more relevant reaction that hydrogen undergoes upon combination with oxygen. Diatomic hydrogen burns in the presence of oxygen to form water and emit a lot of energy. The combustion equation of hydrogen is as follows:

$$2\,H_2\,(g) + O_2\,(g) \longrightarrow 2\,H_2O\,(l) + 286\frac{kJ}{mol}$$ **Equation 1**

While diatomic hydrogen is stable and generally unreactive at room temperature, it is actually easily ignitable in the presence of oxygen and an ignition source. This is because an ignition source brings the hydrogen-oxygen mixture that forms in air to its ignition temperature beyond which the reaction becomes spontaneous. The ignition energy required to initiate the combustion reaction for hydrogen mixtures in air is about 0.017 mJ and is about 0.0012 mJ for mixtures with oxygen.

Due to its highly flammable nature, the National Fire Protection Agency (NFPA) designates the highest flammability rating of 4 to hydrogen. Interestingly, hydrogen not only possesses a high energy density upon its ignition, but it also exhibits a generally larger flammability range than most other fuels in air. The hydrogen gas flammability range in air is from as low as 4% to as high as 76%. As such, hydrogen can form a flammable mixture with air within this wide range and can be easily ignited to result sever consequences.

Table (2): Flammability and Detonation of Hydrogen

Lower Flammability Limit in air (%vol)	4
Upper Flammability Limit in air (%vol)	76
Stoichiometric mixture in air (%vol)	29.5
Lower Detonation Limit in air (%vol)	18.3
Upper Detonation Limit in air (%vol)	59
Minimum Ignition Energy in air mixture (mJ)	0.017
Minimum Ignition Energy in oxygen mixture (mJ)	0.0012

Hydrogen also has a very low energy requirement for spontaneous ignition. Hydrogen leaks can ignite without apparent ignition sources as concluded in the *HSE RR615, Spontaneous ignition of hydrogen – Literature Review.* While the mechanisms behind the ignitions are not fully understood, the review establishes a correlation between the spontaneity of the ignitions and the pressure of the hydrogen source – the higher the pressure of the hydrogen source the easier it becomes for it to spontaneously ignite. This review examined multiple historical incidents in which spontaneous ignition of hydrogen leaks was observed.

From an energy perspective, hydrogen possesses very strong potential to replace natural gas, conventional gasoline, and diesel fuels due to its high

specific energy density (Le, Sharma, Bora, Tran, Truong, Le, & Nguyen, 2024).

c. Abundance and Availability of Hydrogen

Considered to be the most abundant chemical element in the universe, hydrogen is the main fuel for stars, including our solar system's sun (U.S. Energy Information Administration [EIA], n.d.). On Earth, hydrogen is not readily found in the form of a pure gas. It is, however, present in water in the oceans and reservoirs, ice in the glaciers, and in the organic compounds constituting the basic molecules for fossil fuels, plants, and animal cells and tissues. As such, accepting hydrogen as an abundant source of energy on Earth by virtue of it being commonly found in various molecules is potentially misleading. This is because the extraction of hydrogen gas from those various molecules its atoms exist in is not necessarily a feasible task. A detailed understanding of the different methods required for obtaining pure hydrogen is necessary prior to accepting it as a feasible fuel. Additionally, a technical and economic understanding and comparison of hydrogen to other fuels is required.

In the current day in time, the most widely consumed source of energy is fossil fuels; namely, crude oil and natural gas. The discovery of fossil fuels and the incredible potentials they possess has been a vital factor in their widespread use. In their most primary use, the combustion of fossil fuels generates huge amounts of energy which can be cultivated to operate the technologies required to prosper economies. The burning of fossil fuels to produce steam and run turbines to generate electricity is technically as simple as it sounds, and the true complexity lies mainly in scaling this task to the level needed to meet the ever-increasing demands.

Additionally, products of reacting the different fractions of fossil fuels have also allowed for the introduction of new chemical products previously not known to humanity, such as plastics, petrochemicals, chemical fertilizers, and synthetic pharmaceuticals – all at an economically desirable cost. For these reasons and many others, fossil fuels have contributed to the establishment of entire sectors upon which modern economies have been based. For example, the countries of the Arabian Gulf and their economies have become highly dependent on extracting, refining, and selling fossil fuels and their fractions up until now. This is mostly due to the abundance of this resource in unparalleled amounts in this region of the world (Praveen, Keloth, Abo-Khalil, Alghamdi, Eltamaly, & Tlili, 2020).

Despite the many positives that fossil fuels offer, there are extremely harmful and unwanted effects of their extraction, burning, and reaction. Those harmful effects include their high capability of polluting the environment either directly by spillage and loss of containment, or indirectly by means of emission of harmful gaseous byproducts that contribute to the concerning issue of global warming. In general, those emissions are referred to as "greenhouse gases" or GHGs for short. GHGs are gaseous chemical molecules known to trap heat within the Earth's atmosphere. The mechanism by which heat is trapped by GHGs is known as the "greenhouse effect" (Filonchyk, Peterson, Zhang, Hurynovich, & He, 2024).

Naturally, light particles – or photons – are emitted by the Sun, and travel to Earth and enter its atmosphere. sunlight (photons) reaches Earth, passes through the atmosphere, and warms the planet. Earth absorbs some of this energy and re-emits it at longer wavelengths, which are then absorbed by greenhouse gases (GHGs) in the atmosphere, causing them to vibrate and generate heat—a process known as the greenhouse effect. While this effect is essential for maintaining life-supporting temperatures, excessive

GHGs—especially from human activities—intensify it, leading to global warming.

The main GHGs include both naturally occurring ones like water vapor, carbon dioxide, and methane, and human-made ones like chlorofluorocarbons (CFCs). Although CFCs have been largely phased out due to their harmful effects, other GHGs from fossil fuel combustion remain a major concern. Reducing these emissions requires re-engineering industrial processes, shifting to cleaner materials, and transitioning from internal combustion engine vehicles to electric or alternative energy-powered vehicles. With this understood, strong focus has been placed in the past decade on enhancing electric vehicle technologies in order to replace ICE powered vehicles with electric vehicles (EVs). Other alternative sources of energy to power vehicles have also been investigated, including solar energy and hydrogen.

d. Grey, Blue and Green Hydrogen

Due to the rarity of pure hydrogen gas in nature, it must be obtained by means of chemical reactions that convert molecules which contain hydrogen to other products and separate the hydrogen from them. For example, hydrogen is commonly produced via processes such as the steam reforming of natural gas or hydrocarbons or the electrolysis of water. It may also be obtained as a side product from processes such as the hydrolysis of hydroxides, or other reactions of acids with metals. All those processes involve the release or production of compounds other than hydrogen which may classify as greenhouse gases making their release to the atmosphere undesirable.

The term “grey hydrogen” refers to the hydrogen gas produced from a hydrocarbon source with no attempt to recover or capture carbonaceous

greenhouse gases produced alongside. Grey hydrogen is environmentally undesirable; nonetheless, this remains currently the most common method of producing hydrogen.

Alternatively, the term “blue hydrogen” refers to gas produced from a hydrocarbon source through the steam reforming of natural gas as an example, accompanied by capturing and sequestration of carbonaceous greenhouse gases. Blue hydrogen is often referred to as low-carbon hydrogen in reference to the low carbon emissions as a result. Be it high or low, however, carbon emissions are unwanted in light of the net-zero emissions targets; thus, hydrogen production methods involving no production of carbon emissions whatsoever are sought.

“Green hydrogen” is a term used to refer to sustainably produced, environmentally friendly hydrogen, produced via processes that don’t rely on a hydrocarbon source nor produce harmful emissions. Production of green hydrogen relies solely on sources that are available in nature and is not associated with hydrocarbon sources that when reformed or processed may lead to the production of carbon dioxide. For example, hydrogen produced through the electrolysis of water to form hydrogen and oxygen only is inherently environmentally friendly and involves no release of harmful emissions to the atmosphere. The term “green hydrogen” also covers the entire lifecycle of producing hydrogen. This means that no harmful gases are to be produced at any stage leading up to the production of hydrogen. Accordingly, all power required in the production process should also be from renewable sources and should not involve the emission of greenhouse gases.

At the current point in time, production of green hydrogen – for example by electrolysis of water using only renewable energy sources such as solar power – is significantly more technically challenging and far less

economically favorable than producing grey or blue hydrogen. As a result, the amount of green hydrogen produced in comparison with grey and blue hydrogen is very little (Ajanovic, Sayer, & Haas, 2022)

Having distinguished between the designations of "green" and "non-green" hydrogen, it is informative and worthwhile to discuss the different hydrogen production technologies in details in this section. This is because hydrogen gas production is a pivotal step towards "green" economics and the clean, sustainable production of renewable energy. Under standard conditions, hydrogen gas in its diatomic form is not highly reactive; however, it is highly flammable. Hydrogen can also undergo chain reactions with oxygen whereby water is formed in an exothermic reaction. While the electrochemical reaction required to power fuel cells needs hydrogen gas, the gas in its pure form is not abundantly available on earth. Accordingly, industrial synthesis of hydrogen gas is required. Since hydrogen as an element is most commonly available in water and since water is abundantly available on earth, it makes for a good raw material for the production of gaseous pure hydrogen. Other large reservoirs of elemental hydrogen are hydrocarbons such as fossil fuels and natural gas.

As such, the production technologies can be categorized into two main categories – the first is reforming which refers to technologies using hydrocarbon feedstock, and the second is electrochemical which refers to technologies using electrolysis for the production from inorganic feedstocks such as water.

2.3 Hydrogen Fuel Cell Vehicles (HFCVs)

The concept of fuel cell-powered automobiles dates back to the early 1960s when NASA developed the first fuel cell technology for space applications. However, it was not until the late 1990s that the first hydrogen fuel cell

vehicle was introduced to the market. Since then, several automobile manufacturers, have invested in the development of fuel cell vehicles and related technologies.

Hydrogen fuel cell vehicles (FCVs) have emerged as a promising alternative to traditional fossil fuel combustion engine vehicles due to the increasing concerns about the environment and global warming. Hydrogen fuel cell vehicles are vehicles that use hydrogen as the fuel feeding a hydrogen fuel cell where the electrochemical reaction is undertaken to produce electricity and power the vehicle's electric engine/motor. Hydrogen (H_2) as a fuel offers several advantages over conventional fossil fuels such as clean emissions, high efficiency, and potentially unlimited supply. Moreover, hydrogen is a versatile energy carrier that can be produced from a variety of renewable and non-renewable resources, including water, natural gas, and biomass. Hydrogen Fuel Cell Vehicles in turn also have various advantages over conventional fuel cell combustion based vehicles. That is that hydrogen fuel cell vehicles produce no harmful tailpipe emissions and only emit water vapor and heat. They also exhibit high fuel efficiency and have driving ranges reaching as high as 400 miles per tank. Last but not least, hydrogen fuel cell vehicles refueling requires only a few minutes which is as fast or maybe faster than refueling conventional fossil fuel combustion based vehicles.

The fuel cell vehicles – despite their specific challenges – have substantial advantages in that they are relatively simpler in construction and components than conventional vehicles. They require fewer moving parts, a less complicated engine/motor, and can operate at a comparatively high efficiency.

Environmentally, the benefits of hydrogen fuel cell vehicles are also many, starting with the sustainable nature of the hydrogen fuel. The

electrochemical conversion reaction is a clean one with only water (or water vapor) generated as the product. The reaction is deemed a zero-emissions reaction (in reality, it is a zero-adverse emissions reaction since it generates water vapor but no carbonaceous byproducts, soot, or greenhouse gases), thus making the vehicles among the cleanest technologies for transportation. Hydrogen fuel can also be renewably produced from sources such as solar power, wind, or electrolysis; this is especially important as it means that hydrogen fuel cell vehicles can achieve a complete zero-emissions fuel cycle from fuel production to consumption and utilization. They hereby have real potential to contribute to overall reduction of greenhouse gas emissions and improved air quality should they replace conventional fuel cell vehicles on a wide scale.

Evaluating hydrogen fuel cell vehicles from the perspective of energy independence, the hydrogen fuel cell vehicles technology offers an important solution to the problem of dependence on foreign fossil fuel supplies. This is because hydrogen can be produced from various sources including renewable sources, water, biomass, natural gas, or even fossil fuels. The shift towards hydrogen reduces if not eliminates dependance on fossil fuels (usually purchased from foreign oil-rich countries).

In addition to their environmental benefits and energy independence contributions, hydrogen fuel cell vehicles are comparatively of high efficiency – the efficiency of hydrogen fuel cell vehicles can reach up to 60%, which is comparatively higher than that of conventional fossil fuel internal combustion engine vehicles.

Having discussed the benefits and positives of hydrogen fuel cell vehicles, it is important to understand that they also have their disadvantages and associated challenges. One of the most substantial challenges with hydrogen fuel cell vehicles is the high cost of production of hydrogen fuel cells,

the vehicles, and the relatively high cost of producing hydrogen despite the improvements in this specific aspect. The cost of producing hydrogen for the purpose of fueling and refueling hydrogen fuel cell vehicles is still elevated when compared to fossil fuels and internal combustion engine vehicles. Another cost item worth considering is the cost of building, maintaining, and operating refueling stations and the necessary infrastructure required to support the widespread adoption of hydrogen fuel cell vehicles.

Their widespread adoption of hydrogen fuel cell vehicles also faces the challenge of requiring major automobile manufactures to adopt the concept and mass-produce cost-effective and safe vehicles for the market. In the present time, only a handful of major automobile manufacturers have undergone commercial hydrogen vehicle production with a very limited number of produced vehicles.

Since 2015, three hydrogen-powered cars have been offered for sale from three different car companies: the Honda Clarity Fuel Cell, the Hyundai Nexo SUV, and the Toyota Mirai (Voelcker, 2024). However, there are only about 15,000 hydrogen-powered vehicles on U.S. roads right now, and all of them are in California (Voelcker, 2022). While electric cars are getting attention, with major manufacturers focusing on making them dominant by 2030, hydrogen vehicles are less so widespread and gain less traction for now. This limited production of hydrogen fuel cell vehicles makes them expensive and generally out of the reach of many consumers.

Another overwhelming challenge with hydrogen fuel cell vehicles is ensuring the safety of those vehicles and being able to ensure the public that the vehicles are safe to drive and operate. As is well known, hydrogen is highly flammable, which poses concerns at every stage of the hydrogen fuel cell vehicles' operating cycle, starting with its production, transportation, storage, dispensation, and lastly consumption by the vehicles. Despite

the fact that fuel cells are designed taking into consideration the safety concerns, the risk of fire and explosion in the event of a collision, rollover, or other on road accidents remains present and concerning.

With the advantages and disadvantages of hydrogen fuel cell vehicles unraveled, it is important to realize that the vehicles have high potential for becoming widely adopted and even possibly the dominant mode of road transportation. A number of important factors could influence this widespread adoption including lowering production costs, governmental support, and increased awareness.

If the automobile manufacturers are convinced of the profitability of hydrogen fuel cell vehicles over conventional fossil fuel combustion vehicles, then undoubtedly they will shift towards mass production of those vehicles thus leading to lowered production and retail costs. Additionally, as the technology continues to develop and advance, the cost of producing capable and dependable vehicles is likely to drop. Moreover, the cost of producing hydrogen itself continues to actually drop as novel production techniques are adopted and as economies of scales are achieved.

Governments have the ability to support and accelerate the widespread of hydrogen fuel cell vehicles through realizing their benefits and implementing policies which make them attractive for manufacturers to produce and consumers to buy. Governments also have the responsibility of performing all the studies needed to ensure safety, reduced (acceptable) risk levels, and cost effectiveness for the adoption of this solution.

It is not enough for the automobile manufacturers and governments to adopt the technology, but it is also crucial to increase awareness of the advantages of hydrogen fuel cell vehicles within the public. Consumers must become aware of the benefits of the fuel cell vehicles and must be

convinced of their importance to the environment and to the individual in order for demand for those technologies to increase.

2.4 Hydrogen for Internal Combustion Engine Vehicles (ICEs)

Hydrogen as a fuel can be used to power vehicles by employing either electric-cell or internal combustion engines (Durkin et al., 2024). Hydrogen internal combustion engine vehicles are substantially different from hydrogen fuel cell vehicles with regards to the mechanisms that operate the vehicle.

Since the ICE is powered by hydrogen, no carbon dioxide emissions are expected, and the technology is deemed a sustainable and environmentally friendly technology. What makes hydrogen ICEs an interesting prospect is that they require little to no modification to the generally available, accepted, and often times preferred mechanisms and technologies of conventional vehicles.

Hydrogen ICE vehicles may be advantageous over HFCVs in that they meet the liking of car fanatics who are still reluctant to shift to electric vehicles on the expense of the joy, sound, power, and such preferences of driving a conventional car. As such Hydrogen ICE vehicles can allow for an expedited shift to sustainably operated vehicles and away from GHG emitting vehicles.

2.5 Modes of transporting hydrogen fuel and hydrogen fuel retail

a. Pipeline Transportation:

Pipeline transportation of hydrogen fuel is the most common method used for industrial purposes. The risk associated with pipeline transportation of

hydrogen is the potential for pipeline rupture due to corrosion, impact, or overpressure. This could cause hydrogen gas leaks leading to fire, explosion, or asphyxiation.

Pipeline failures can be prevented by regular inspections, routine maintenance, and adequate safety measures. The Pipeline and Hazardous Materials Safety Administration (PHMSA) in the US provides regulations for the safe transportation of hydrogen fuel through pipelines. The PHMSA also requires pipeline operators to maintain a risk management plan that addresses potential accidents, including pipeline rupture.

b. Tanker Truck Transportation:

Transportation of hydrogen fuel by road is another common method used to supply fueling stations. Risks associated with this mode of transportation include vehicle accidents, fuel leakage, and explosions. In the event of an accident, the high flammability of hydrogen fuel can lead to fires and explosions, making it extremely hazardous.

One method to transport hydrogen by road is using tanker trucks similar to the ones that are commonly used to transport fuels in general, whereby the hydrogen is compressed and filled into a pressure vessel towed by the truck.

Truck transportation of hydrogen fuel can be managed by implementing safety measures such as proper vehicle maintenance, training of drivers, and appropriate packaging and labeling of the fuel. The National Fire Protection Association (NFPA) has developed guidelines for the safe transportation of compressed gases in cylinders and cargo tanks, including guidelines for the transportation of hydrogen fuel.

c. Tube Tanker Transportation

On the other hand, hydrogen could be compressed into smaller tubes rather than filling into pressure vessels and transported by trucks similar to how LPG or kitchen gas is transported. Both tanker trucks and tube trailer trucks are two methods known to be used to transport hydrogen by road.

The methods to manage the safety of transporting hydrogen by tube trailers are almost identical to those stated for tanker trucks.

d. Gaseous Hydrogen (GH2) and Liquid Hydrogen (LH2) Fueling Stations

Hydrogen is supplied to vehicles in the gaseous state at high pressures that could reach as high as 700 barg (Teesing, n.d.). Despite that, the fuel may be delivered and stored at retail locations in either the gaseous state or the liquid state. Stored or delivered gaseous hydrogen is referred to using the acronym GH2, while liquid hydrogen is referred to using the acronym LH2.

It is important to understand the difference between those two modes and the implications on safety as a result. Facilities or retailers which produce hydrogen often times store it in the gaseous form (GH2). This GH2 may be produced by electrolysis of water for example, generating low-pressure hydrogen in the gaseous state, which can then be compressed, sent through pipelines to the storage tanks, and stored at pressures near what it will be dispensed at.

On the other hand, liquid hydrogen stations entail cryogenic storage facilities to maintain the fuel in the liquid state. This could mean that hydrogen needs to be stored at temperatures reaching as low as -253 °C, and heavy insulation is required on the storage tanks to prevent heat leakages (Cheng, Zhang, Shi, & Lin, 2024). Liquid hydrogen is then vaporized as it is sent to the dispensers ahead of refueling. Cryogenic storage and pumping

necessitates additional safety considerations and mitigations to ensure safe operation, especially when considering flammable or explosive fluids such as hydrogen.

2.6 Historical road accidents involving fuel transportation

Accidents during the road transportation of fuels are not very common and are referred to as low-probability accidents. Nevertheless, the consequences of such accidents are very severe, and for this reason, the process of road transportation of fuels is considered a high risk process. It is important to understand the magnitude of such events by looking at famous case studies and incidents that are recorded and better yet considered in literature.

a. San Carlos De La Rapita Disaster, Spain (July 11, 1978)

On the afternoon of July 11, 1978, a propylene road tanker caught fire in a camp site Tarragona, Spain, eventually leading to a BLEVE (Boiling Liquid Expanding Vapour Explosion). Although the initiating event for the fire is unclear, it is reported that a large cloud of propylene escaped from the tanker to subsequently ignite and result in a massive fireball. After the initial ignition, the propylene remaining in the tanker BLEVE'd and eventually exploded tearing the body of the tanker and projecting it at different distances. This tragic event lead to more than 200 casualties and about 600 were injured. Investigations revealed multiple shortcomings which came together leading up to the disastrous results of this incident such as the overcrowding of the camp site, the absence of a relief valve on the tanker, the overfilling of the tanker beyond its maximum capacity, and the routing of the tanker through heavily populated areas (Arturson, 1981).

b. LNG Road Tanker Explosion near Tivissa, Spain (June 22, 2002)

On the 22nd of June, 2002, a tanker carrying natural gas overturned as it was moving downhill, and finally came to a stop at a sandy slope. The tanker then caught fire near the cabin and the beginning of the trailer. Soon after the tyres also caught fire resulting in small explosions, and finally a large explosion took place. This incident resulted in the death of the driver and injuries to two bystanders. In this incident as well, the violent explosion led to the fragmentation of the truck and the projection of those fragments at distances from the location. The analysis of the incident revealed that a thermal crack took place in one section of the tanker due to the initial fire causing a temperature gradient along the vessel wall, and subsequent failure of the vessel. It is up to discussion whether the explosion could be categorized as a BLEVE or not; however, the aftermath was catastrophic either way (Planas-Cuchi, Gasulla, Ventosa, & Casal, 2004).

c. LPG Railway Accident in Viareggio, Italy (June 29, 2009)

On the 29th of June. 2009, a train carrying 14 tank-cars of LPG derailed in Viareggio, Italy. The derailment resulted in overturning of the LPG tank-cars thus releasing the contained LPG. Investigations revealed that the first tank car's axle broke due to its mechanical failure, causing it to detach from the locomotive, derail, and drag nine more tank-cars with it. The first tank-car crashed into a structure after derailing thus cracking the vessel wall and releasing its contents. The released LPG cloud drifted into the nearby neighborhood and accumulated in different buildings until it eventually ignited and exploded. As such multiple internal explosions took place within houses and other buildings. Tragically, this accident took place in a congested neighborhood near the Viareggio railway station and resulted in

some thirty two casualties and tens of injuries (Landucci, Tugnoli, Busini, Derudi, Rota, & Cozzani, 2011).

d. LPG Road Tanker Explosion in Kannur, India (August 27, 2012)

In a more recent event, an LPG tanker truck crashed into a divider as it was attempting to overtake a vehicle in Kannur (Kerala), India on August 27, 2012. LPG vapor escaped from the tanker who's 1 cm thick steel wall cracked upon impact. The escaped LPG cloud drifted for about 20 mins before meeting an ignition source and flashed into a fireball. A total of 3 further blasts followed finally projecting missiles from the tanker vessel at varying distances (Kumar, 2013).

All the above examples involve tragic catastrophic accidents that took place on road during the transportation of fuels of different natures. In all events, a loss of containment takes place to then meet an ignition source and cascade into a fire or explosion. Although seemingly straightforward, this sequence of events involves various factors that complicate the analysis of the accidents and the quantitative modeling of the accidents. One of the most important factors that strongly influence the nature of the accident and the extent of the consequences is the type of fuel involved. For example, a lighter fuel is expected to rapidly release as a jet or flash into a rising cloud. On the other hand, heavier fuels often times linger at lower elevations and spread into a wide cloud near the ground. Moreover, heavier fuels continue to boil inside the ruptured vessel eventually leading to a BLEVE.

The above examples provide a characterization for the severity of the road accidents involving large volumes of flammable or explosive fuels. However, in the context of this study, it is also important to consider case studies

and examples of such accidents involving hydrogen fuel and to draw parallels with accidents involving other fuels.

2.7 Standards and methods for gasoline and fuel transportation

a. The European Agreement Concerning the International Carriage of Dangerous Goods by Road ("ADR")

The European Agreement Concerning the International Carriage of Dangerous Goods by Road referred to as (ADR) for short is an agreement first done in 1957 under the United Nations Economic Commission for Europe (UNECE) – one of the five regional commissions falling under the United Nations Economic and Social Council. The agreement's purpose is to regulate the international transport of goods by road between UNECE member states and ither states that apply ADR (UNECE, n.d.).

ADR is a fundamental reference for road transportation of fuels in general as it captures important considerations to do with the roads, the types of transporting vehicles, various design considerations for the transporting vehicles and their storage shells, among other critical considerations. Despite the fact that ADR is a European agreement under one of the United Nations' European bodies – namely UNECE, it is worth noting that many countries and even transporting companies located outside Europe voluntarily adopt ADR as a guiding reference or standard.

b. UK HSE – Approved Code of Practice and Guidance L133

The UK HSE is the United Kingdom's Health and Safety Executive acting as the "national regulator" for all health and safety related matters in workplace. The UK HSE is to an extent a legislative body which develops and enforces certain legislations. More broadly however, the HSE issues publications and guidance codes varying from leaflets to webpages to whole

books. They additionally issue what is referred to as “Approved Codes of Practice (ACOPs)”, some of which hold a legal status and hold the prefix “L”. In the UK, those codes hold a pseudo-legal status in the sense that complying with their provisions is not compulsory; however, complying will guarantee that you are operating in line with the law.

Over the years, the UK HSE has set forth many standards and regulations pertinent to process safety and process engineering in general. Additionally, the UK HSE has taken strong interest in risk management by establishing risk guidelines and standards.

With relevance to this study, the Approved Code of Practice and Guidance (ACOP) L133 titled “Unloading petrol from road tankers” has been considered. ACOP L133 is specifically intended for and directed towards “people who are involved in the delivery and unloading of petrol at filling stations, including petrol station site operators, road tanker operators, road tanker drivers and authorities who have responsibility for enforcement of the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR) at petrol filling stations.” (Health and Safety Executive [HSE], 2014).

This ACOP and the regulations it pertains to require that the risk associated with the transportation, storage, and use of dangerous substances such as fuels (hydrogen in the context of this study) is eliminated or reduced to **ALARP** – the acronym used by the HSE to indicate risk should be “**A**s **L**ow **A**s **R**easonably **P**racticable”. This requirement was adopted within the context of this study as it provides basis for obtaining risk acceptance criteria (Health and Safety Executive [HSE], n.d.).

Additionally, this ACOP references other resources containing guidance on risk assessment for activities that pose a risk of fire and explosion, including the Energy Institute (EI)'s Red Guide discussed in the next section.

c. Petrol Filling Stations – Guidance on Managing the Risks of Fire and Explosion (The Red Guide) – Energy Institute

Other important engineering bodies in the UK have their share in establishing guidelines and standards for fuel transportation, storage, or dispensation. The Energy Institute (EI) is one prominent body of chartered engineers and companies in the field of energy. The Energy Institute (EI) established "Petrol Filling Stations – Guidance on managing the risks of fire and explosion (The Red Book)". The guidelines discuss applicable legislation in the UK, as well as regulatory inspections and the law related to them. Then the guidelines outline the hazards associated with petrol filling stations, managing the risks at the stations, operational management, commissioning and decommissioning, and lastly some specific activities worthy of highlighting for safe operation of filling stations. The purpose of the red guide is to provide clear guidelines for the operators of fuel stations to comply with the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR). Furthermore, the guidelines provide guidance on necessary measures to reduce and/or mitigate the risks of fire and explosion that could arise from the fuel storage or dispensation activities.

The guidance specifically goes over the most common fire and explosion hazards due to storage, dispensation, and road tanker unloading activities, and provides basis for how to identify, evaluate, and mitigate the risks associated with the said events.

Though based on technical engineering principles, the red book does not delve into technical engineering aspects and only covers the fire and

explosion at filling stations from a risk-based evaluation perspective. Technical engineering aspects are covered in detail in a separate publication titled Design, construction, modification, maintenance and decommissioning of filling stations (The Blue Book) co-published by the Energy Institute and the Association for Petroleum and Explosives Administration (APEA).

An interesting concept covered in the guidelines is that not all fuel stations require taking the same safety precautions. The guidelines recognize that different sites may entail different surrounding conditions, thus the probability of an incident and the severity of its consequences may vary. This said, the guidance for fire and explosion risks management may still be categorized for all locations and situations under the following broad headlines:

A) Physical engineering controls and safeguards
B) Managerial or administrative measures
C) A combination of both physical and administrative measures

The red book guidelines encourage engineering controls for the purpose of risk reduction as they are dependable and effective despite their cost and high maintenance requirements.

d. Guidance on hydrogen delivery systems for refueling of motor vehicles, co-located with petrol fueling stations (Supplement to The Blue Book) – Energy Institute, Association for Petroleum and Explosives Administration, and British Compressed Gases Association (BCGA)

As mentioned in the previous section, the Blue Book provides technical engineering guidelines for fire and explosion risk management and protection. The Energy Institute, Association for Petroleum and Explosives Administration, along with the British Compressed Gases Association

(BCGA) have issued a joint publication focusing specifically on dealing with hydrogen at fueling stations and supplementing the generic provisions of the Blue Book. The publication thus recognizes the use of hydrogen as a motor vehicle fuel and the need to dispense it to customers at retail locations. The guidelines are aimed at the providers of hydrogen fueling services and the authorities in charge of supervising the refueling companies. Though not a guideline or regulatory document per se, this publication is considered a good practice which may very well become the basis for regulatory and legal framework concerning the use and dispensation of hydrogen as motor vehicle fuel in the future. The document provides the technical linkage between the industry code of practice BCGA CoP CP 41 – *The design, construction, maintenance and operation of filling stations dispensing gaseous fuels* and the Blue Book and provides basis for the co-location of petrol filling stations and hydrogen fueling stations.

Many important considerations and concepts are covered in this publication including the importance of regulatory control, the basic principles for hydrogen risk assessment, hazardous area assessment, the layout and design of stations, the delivery and dispensing of the fuels, as well as maintenance and inspection requirements.

There are various important and highly relevant concepts covered in this publication that are relevant to this study in specific. It is hence suitable to cover in detail some of those concepts and provisions. Firstly, the document compares hydrogen to petrol and natural gas in the sense that it is more or less as dangerous as those types of fuels which have for long been used at an acceptable level of risk and in a relatively safe manner. This establishes the notion that hydrogen too can be used safely as a fuel if proper guidelines are established and upheld.

i. Risk Assessment Considerations:

- Hydrogen's penetrative nature and the fact that nitrogen testing and leak-tight designations may not suffice. The document references ASME B31.8, *Gas transmission and distribution systems* for further guidance and suggests helium testing is more suitable for leak-tight testing of hydrogen systems
- Adequate ventilation for storage containing hydrogen to prevent accumulations potentially creating explosive or asphyxiant environments
- The need for careful consideration of vertical separation distances between hydrogen installations and not just horizontal distances (Typically, horizontal distances are more commonly considered when talking about petrol filling stations due to the fact that petrol fuel is mixture of organics that is heavier than air and will tend to spread along the ground levels rather than spreading readily. On the other hand, hydrogen is very light and will spread vertically in a cloud thus necessitating vertical and horizontal separation distance considerations.)
- The need for specific certification of electrical equipment used in hydrogen environments
- The low ignition energy of hydrogen resulting in spontaneous ignition potentials, and the subsequent need for stringent control on static electric discharge potentials.
- The near-invisible nature of hydrogen flames versus highly radiant hydrocarbon combustion flames. Human perception of hydrogen flames is not the same as perception of the radiant hydrocarbon flames and thus requires further caution and awareness.

- Despite the less radiant flames, the ignition of a control mass of hydrogen can release nearly three times as much energy as the same mass of diesel.
- Safe discharge of ventilation lines is needed. Inerting and purging to safe concentrations is also required.
- Cryogenic flammability of liquid hydrogen takes place at very low temperatures. This can result in the condensation of air and generate an oxygen rich liquid.
- Liquid hydrogen must be completely separated from water. Contact between water and liquid hydrogen may result in boiling of the hydrogen which may produce enough energy to cause ignition or explosion.

ii. Hydrogen Spillage Characteristics

Liquid hydrogen spillage is a major concern requiring specific considerations. For liquid hydrogen to be present, cryogenic transport and storage is required. Should liquid hydrogen escape or leak, it will flash immediately in a manner dissimilar to petrol leaks. Additionally, as soon as the cryogenic storage is compromised, the liquid hydrogen stored therein will boil and flash excessively within the storing vessel. The thermophysical nature of the phenomena associated with the flashing of the leaked liquid hydrogen and the boiling of the remaining stored liquid hydrogen gives rise to various sever escalations leading to major consequences.

Computational Fluid Dynamics (CFD) modelling has been performed by researchers at the HySAFER Centre in Ulster University, UK to develop an understanding of the those thermodynamic and physical properties associated with the said phenomena. The research concludes that gaseous phase blast and boiling liquid expanding vapor explosion (BLEVE) take

place back to back upon storage tank rupture under fire (Kangwanpongpan, Makarov, Cirrone, & Molkov, accepted).

All liquid hydrogen during such incidents will ultimately flash into the vapor phase and either burn or disperse. Due to the cryogenic state the liquid hydrogen is initially in, the escaped flashing gas is heavier than air for a short period of time. However, it also needs to be recognized that there are additional thermodynamic phenomena which could arise. For example, the cryogenic cloud released can pocket near the location of the leak and can inhibit the heating up of the cloud and its flashing. This can in turn cause the leaked gas cloud to settle closer to the ground and spread near ground levels for prolonged durations.

The most important concept which the blue book supplement document stresses in this regard is the understanding that the leaking of cryogenic liquid hydrogen can introduce many challenges and risks be it from the cryogenic release, the flashing into a vapor cloud, the boiling and potential explosion of the remaining stored liquid hydrogen in what is known as a BLEVE, or even the displacement of oxygen and the risk of asphyxiation.

e. Delivery Vehicle Unloading

The supplement document discusses important considerations for the layout of refueling facilities, the design of hydrogen dispensation locations, provisions for vehicles being refueled, and considerations for the hoses and canopies at the stations. The document also provides considerations for unloading of delivery vehicles. That is because the terminal point in the process of transporting hydrogen fuel as defined within the context of this study is when the road tanker arrives at the station. Unloading of gaseous or liquid hydrogen from the transporting vehicles – while a critical activity with heightened risk – is not considered part of the risks of transportation

and is rather more relevant for quantitative risk assessments and consequence modeling within the refueling stations. It is worth mentioning nonetheless that the document recognizes that there are various hydrogen transporter types such as tube trailers, tanker trucks, or bulk cryogenic liquid tankers, each requiring specific considerations. The document suggests that site designers are the party responsible for the determination of the classifications of the area and the provisions required for safe unloading of the transporting vehicles.

i. NWCG Standards for Transporting Fuel

There are other standards regulating the transportation of hazmat and fuels in the USA, including the standards put forth by the National Wildfire Coordinating group (NWCG) and the other bodies that fall under it such as the National Interagency Fire Center (NIFC). The NWCG have a published standard (PM 442) which specifically covers the ground transportation of fuels such as gasoline, diesel, mixed gas, or drip torch fuels. The standard provides recommended best practices and is based on the regulations stipulated by the US Department of Transportation (DOT) and the US Department of Labor Occupational Safety and Health Administration (OSHA). The standard focuses primarily on establishing requirements for the transporters based on sizes and volumes transported, the approved containers for the respective fuels, safety provisions such as labeling, placarding, marking and shipping, as well as recommendations for training and emergency response guidance. As such, this standard does not necessarily cover technical considerations related to risk of transportation of the fuels, but rather focuses on administrative recommendations and guidance to complement technical considerations.

2.8 Standards and methods for hydrogen transportation

Many standards are being developed focusing specifically on hydrogen transportation and systems related to the transportation process. Many of those standards are similar in their provisions and stipulations to their LPG or fuel transportation counterparts, with specific attention given to hydrogen as the fuel at hand. Nonetheless, given the developing nature of the hydrogen market, those standards are constantly being updated and revised. Following is a list of relevant standards that should be considered when discussing hydrogen transportation:

Table (3): Summary Descriptions of Standards and Methods for Hydrogen Transportation

Standard	Scope
International Organization for Standardization – Technical Committee 197 – Hydrogen Technologies	
ISO 13984:1999 Liquid Hydrogen – Land Vehicle Fueling System Interface	• Specifies characteristics of liquid hydrogen refueling and dispensing systems on land vehicles of all types in order to reduce risk of fire and explosion during the refueling procedure and thus to provide a reasonable level of protection from loss of life and property • Covers the design and installation of liquid hydrogen (LH2) fueling and dispensing systems. • Describes the system intended for the dispensing of liquid hydrogen to a vehicle, including that portion of the system that handles cold gaseous hydrogen coming from the vehicle tank, that is, the system located between the land vehicle and the storage tank.

ISO 13985:2006 Liquid Hydrogen – Land Vehicle Fuel Tanks	• Specifies the construction requirements for refillable fuel tanks for liquid hydrogen used in land vehicles as well as the testing methods required to ensure that a reasonable level of protection from loss of life and property resulting from fire and explosion.
ISO 19881:2018 Gaseous Hydrogen – Land Vehicle Fuel Containers	• Contains requirements for the material, design, manufacture, marking and testing of serially produced, refillable containers intended only for the storage of compressed hydrogen gas for land vehicle operation. • Containers considered are to be: permanently attached to the vehicles, having a capacity of up to 1000 liters water capacity, and having a nominal working pressure that does not exceed 70 MPa. • Scope is limited to fuel containers containing fuel cell grade hydrogen according to iso 14687 for fuel cell land vehicles and Grade A or better hydrogen as per ISO 14687 for internal combustion engine land vehicles. • Contains requirements for hydrogen fuel containers acceptable for use on board light duty vehicles, heavy duty vehicles and industrial powered trucks such as forklifts and other material vehicles.
ISO 14687:2019 Hydrogen Fuel quality – Product Specifications	• Specifies the minimum quality characteristics of hydrogen fuel as distributed for utilization in vehicular and stationary applications. • Applicable to hydrogen fueling applications listed in Table 1 of the standard.
CSA Group/American National Standards Institute (ANSI)	

CSA/ANSI HGV 2-2023 Compressed Hydrogen Gas Vehicle Fuel Containers	• Covers service conditions, material qualification tests, manufacturing processes, inspection requirements, batch testing, impact testing, stress analysis, container wall thickness, and other considerations relating to the material and integrity of compressed gas containers. • Contains requirements for the material, design, manufacture, marking, and testing of serially produced, refillable TYPE HGV2 containers intended only for the storage of compressed hydrogen gas for on-road vehicle operation. • Containers considered are to be: permanently attached to the vehicle, having a capacity of up to 1000 liters (35.4 cubic foot) water capacity, and having a nominal working pressure that does not exceed 70 MPa.
CSA/ANSI HGV 3.1-2022: Fuel System Components for Compressed Hydrogen Gas Powered Vehicles	• Establishes requirements for newly produced compressed hydrogen gas fuel system components that are intended for use on hydrogen gas powered vehicles. • Applies to devices that have a nominal working pressure of either 25, 35, 50, or 70 MPA referred to in the standard as H25, H35, H50, and H75 respectively. • Applies to components downstream of the first stage of pressure reduction with a maximum operating pressure designated by the manufacturer in MPa or kPa (psi).

CSA B51:19 (R2024) Boiler, pressure vessel, and pressure piping codes – Part 2	• Contains requirements for high-pressure cylinders for the on-board storage of natural gas, blends of natural gas and hydrogen (hydrogen blends), and hydrogen as fuels for automotive vehicles.
CSA HPRD1 Basic Requirements for Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers	• Contains requirements for pressure relief devices intended for use on fuel containers that comply with CSA B51, Part 2 Boiler, Pressure Vessel and Pressure Piping Code, SAE J 2579, Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles or ISO DIS 15869.2, Gaseous hydrogen and hydrogen blends – Land vehicle fuel tanks • Relief device design is intended for fuels complying with SAE J 2719 Information Report on the Development of a Hydrogen Quality Guideline for Fuel Cell Vehicles, or ISO 14687 Hydrogen Fuel – Product Specification.
Society for Automotive Engineers (SAE)	
(Fuel Cell Standards Committee – Safety Working Group) SAE J 2579:2023 – Standard for Fuel Systems in Fuel Cell And Other Hydrogen Vehicles	• Defines design, construction, operational, and maintenance requirements for hydrogen fuel storage and handling systems in on-road vehicles. • Provides performance-based requirements for verification of design prototype and production hydrogen storage and handling systems. • Describes complementary test protocols (for use in type approval or self-certification) to qualify designs

	(and/or production) as meeting the specified performance requirements. • Includes requirements relating to crashworthiness and vehicle integration for fuel vehicles. • Defines recommended practices related to the integration of hydrogen storage and handling systems, fuel cell system, and electrical systems into the overall Fuel Cell Vehicle.
(Fuel Cell Standards Committee – Interface Working Group) SAE J 2601:2020 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles	• Establishes protocols and process limits for hydrogen fueling of vehicles with total volume capacities greater than or equal to 49.7 liters. • Process limits include: fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure. • Considers affecting factors such as ambient temperature, initial pressure in the vehicle's compressed hydrogen storage system. • Sets a performance target of fueling time of 3 minutes and a state of charge (SOC) of 95 to 100% (with communications) achievable at T40 – cold delivery temperature category
SAE 3202 – Hybrid Road Vehicles Fueled by Compressed Gaseous Hydrogen	• Recommended Practice establishes uniform procedures for testing Heavy Duty Fuel Cell Hybrid Vehicles, Classes 4 to 8, designed primarily for operation on the public streets, roads and highways. • Addresses vehicles with compressed on-board storages or vehicles supplied by an off-board source.

Compressed Gas Association (CGA)	
CGA H-4 Terminology Associated with Hydrogen Fuel Technologies	• Provides a comprehensive overview of terminology and technologies related to hydrogen fuel. • Discusses Hydrogen production methods including: Steam Reformation, Partial Oxidation, Autothermal Reformation, Gasification, Electrolysis, Photoelectrolysis. • Discusses Hydrogen storage and transportation with emphasis on compressed gas, cryogenic liquid reversible metal hydride, chemical hydride, and adsorption based technologies. • Overviews the uses of hydrogen fuel in fuel cells and for combustion.
CGA C-6.4 Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Vehicle (HV) Fuel Containers and Their Installation	• Outlines methods for external visual inspection of Natural Gas Vehicle (NGV) and Hydrogen Vehicle (HV) fuel containers and their installation. • The inspection scope outlined includes periodic visual examination provisions and Canadian applicable standards such as ANSI NGV2, DOT FMVSS 304, and CSA B51 • Provides detailed inspection procedures such as damage identification, mounting and installation, labelling and markings, and leak detection. • Lastly, it provides safety and compliance guidance including documentation and inspector qualifications

National Fire Protection Agency (NFPA)	
NFPA 2 – Hydrogen Technologies Code	• Provides fundamental safeguards for the production, storage, piping, installation, handling, and use of hydrogen in compressed gaseous and cryogenic liquid states • The code applies to various hydrogen applications including vehicular, portable, and stationary ones • The code includes the measures needed to reduce likelihood and magnitude of hydrogen incidents
NFPA 55 – Compressed Gases and Cryogenic Fluids Code	• More generic than NFPA 2 in that it covers compressed gases and cryogenic fluids in general – also provides considerations relating to installation, storage, use, and handling of the fluids • Provides the guidance to safeguard and prevent accidents and ensure safe handling of fluids covered • Applies to the industrial, medical, and research facilities among other settings
UN Recommendations on the Transportation of Dangerous Goods	• Includes a classifications for systems and a listing of dangerous goods to ensure correct identification and handling during the different transportation modes • Sets standards for the packaging of portable tanks, their construction, safety, inspection, and uses • Outlines the procedures for signage, placarding and documentation for effective communication of the hazards and safe transport of the chemicals

2.9 International applications of Hydrogen Fuel Cell Vehicles (HFCV)s

As research advances, and in light of the strong push for sustainable and greener solutions for vehicular transportation at no environmental cost, Hydrogen Fuel Cell Vehicles (HFCVs) have started to gain popularity considering their promising potentials, despite challenges with high cost of fuel cell technology and the lack of suitable infrastructure (Wang, Li, & Li, 2024).

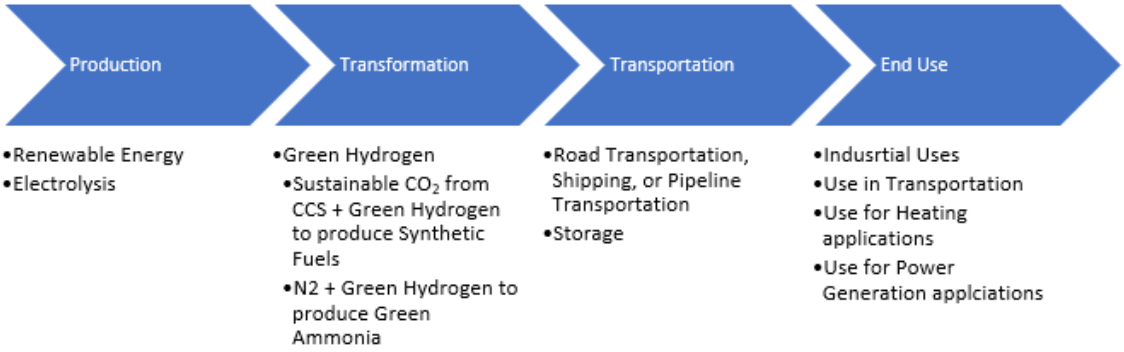


Fig. 1: Green Hydrogen Chain (Soleimani, Hosseini Dolatabadi, Heidari, et al., 2024)

This section explores and demonstrates some of the international applications of HFCVs which are gaining traction. In the context of this section, hydrogen fuel is assumed to be "green" and sustainably produced using renewable energy, water electrolysis or similar. It is worth noting that the applications of hydrogen fuel cells extend beyond Hydrogen Fuel Cell Vehicles (HFCV). Soleimani et al. represent the "green" hydrogen chain in their review summarized in Fig. 1.

Specific international applications of HFCVs include the following:

1. Long Haul Trucking and Local Distribution – Nikola, Hyundai, Toyota, Kenworth, and UPS all already manufacture hydrogen powered semi-trucks and vans.
2. Buses – Public transportation applications including hydrogen fuel cell powered electric buses.
3. Trains – Hydrogen fuel cell trains are now being operated in countries such as Germany, the UK, Japan, and South Korea (Sierra Northern Railway and WHA)
4. Personal Vehicles – There are various auto manufacturers who have undertaken production of hydrogen fuel cell electric vehicles such as Toyota, Honda, Hyundai, and BMW to name a few. This specific application has been discussed in previous sections of this study.
5. Aviation – long range unmanned aircraft powering and commercial aviation powering using hydrogen fuel cells are being investigated in experimental projects.
6. Unmanned Arial Vehicles – powering of UAVs (drones) for military and non-military applications such as search and rescue missions, package delivery and similar.
7. Boats and Submarines – marine applications whereby solar panels are used to power electrolysis and generate hydrogen, and the consumption of hydrogen on board in hydrogen fuel cells is a reality. The use of hydrogen fuel cells to power long range submarines offers a substitute to nuclear power.
8. Mobile Power Generation – this is perhaps one of the oldest applications of hydrogen fuel cells as NASA employed hydrogen fuel cells to power rockets and shuttles in space. While not necessarily a hydrogen fuel cell "vehicle" application, it is important to recognize this application due to its historic use and promising potentials.

2.10 Road Transportation Risks

Road Transportation Risk is the term used to describe all the hazards and associated consequences that impact vehicular transportation of goods, commodities, or people via roads (iFluids, n.d.). There are many risks which can be encountered by a vehicle on the road, some of which may not be as trivial and obvious as others. Within this section, road transportation risks are seen from the perspective of vehicles transporting goods, commodities, or fuels thereby relating to the context of the study.

Intuitively, the most pronounced risk on road is the risk of traffic accidents, which can have fatal consequences on the parties involved. Furthermore, should they involve hazardous materials, flammables, or explosives the consequences may extend to the general public even beyond the network of roads. A collision involving a fuel transporting vehicle – irrespective of the responsible party – is likely to result in a loss of containment event endangering the parties involved, the users of the road, and the general public within the vicinity of the location of the accident.

Another source of risk to the vehicles on the roads is the weather. Adverse conditions may result in loss of control over the vehicles or compromised road visibility thus resulting in further escalations like traffic accidents or turnovers. Vehicles transporting bulk liquids are particularly subject to increased risk of turnovers due to inertial reactions of their contents. Baffles introduced within the tankers attempt to mitigate this risk but do not entirely eliminate it.

Similarly, irrational driver behavior non-compliant with traffic regulations and good driving consensus may lead to loss of control or similar upon reaction to those actions. The same risk encountered by bulk liquid transporters due to inertia may arise due to sporadic movements or sudden

changes in speed initiated by driver behavior. Looking from all perspectives, it is important to also consider the condition of the driver of the fuel or goods transporter. Fatigue, drowsiness, or impairment can compromise the performance or judgement of the driver resulting in accidents or consequences.

The condition of the driven vehicles, their safety, and the integrity of trailers or tankers connected to them is another very important source of risk. Should the integrity – be it mechanical or administrative – of the vehicles and any associated ancillaries be compromised, the risk of loss of control or loss of containment of the vehicles transported goods, fuels or similar may materialize into a high-consequence event. Vehicle condition in how it is defined within this study includes both the condition of the vehicle itself as well as the condition of locks, harnesses, casings, refrigeration, or any other auxiliary precautions required for "safe" transportation of any carried goods or fuels.

One other major source of additional risk is the condition of the road infrastructure. Defects, collapses, poor design, or inadequate signage are but a few contributors to the overall risk to vehicles on the roads.

All mentioned risks and many more emphasize the dangers associated with road transportation of hazardous materials making it imperative to study, minimize, or mitigate the risks for safe transportation.

2.11 Safety Challenges with Hydrogen

In addition to its flammable and energy dense nature as discussed in earlier sections, there are various safety considerations and challenges that need to be taken into account when opting for one mode of transportation over the other.

For instance, hydrogen is known to cause hydrogen embrittlement in metals, a phenomenon that can be linked to the small size of the hydrogen molecule relative to metal molecules. Hydrogen Embrittlement (HE) – also known as hydrogen assisted or hydrogen induced cracking – is the phenomenon in which the hydrogen molecule gets absorbed into the metallic matrix, causing the metal to lose some of its ductility and eventually cracking. This is because small hydrogen molecules can permeate through the solid metal matrix, thus reducing the magnitude of the stress required to initiate or propagate a crack through the solid structure. Hydrogen Embrittlement (HE) is the result of various complex micro-mechanisms that may occur separately or jointly. The phenomenon is common with various metals including steel, copper, iron, nickel, cobalt, or their alloys. It is less of an issue with some other metals resistant to the phenomenon such as copper, aluminum, and stainless steel.

Hydrogen Embrittlement (HE) is especially concerning for road transportation of hydrogen, as it potentially compromises the integrity of the pressure vessel or tube within which pressurized gaseous or liquid hydrogen is contained. Hydrogen could thus escape and leak through the structure's wall if the structure has already started cracking, or could make the rupture of the structure upon impact a more probable outcome overall.

- Hydrogen Embrittlement in metals which can weaken the shell or the tubes
- Leakages, proper leak detection and handling protocols are crucial to prevent hydrogen leaks from igniting
- Cryogenic hazards, proper insulation and safety measures are important during transport – liquid hydrogen is normally at temperatures as low as -253 °C

- High pressure, hydrogen is compressed for transportation, pressure relief valves need to be provided and adequately sized, emptying and filling tanks and tube trailers are safety critical activities, and over-pressurizing the vessels must be avoided

Refer back to section 2.8 where many of the safety concerns are covered in the context of supplementary technical guidance by the EI/APEA/BCGA.

2.12 QRAs and Transportation Risk Assessments

Having discussed the importance of hydrogen and the potentials of its use as a fuel, and having addressed the challenges relating to its sustainable production, its transportations, the safety challenges with hydrogen storage and transportations, and the general risks associated with road transportation, it is important to understand that safe and successful transportation of the fuel is only possible in light of this detailed understanding of its behavior and actual evaluation of the risks in both the qualitative and quantitative manner.

This study will analyze the risks associated with the transportation of hydrogen fuel, including the risk of fire and explosion. It will also explore risk management strategies and regulatory frameworks that can be put in place to mitigate these risks.

An in-depth understanding of the concept of risk and how to analyze and quantify it is required in order to assess the probability of those risks materializing and estimate the consequences of their occurrence.

A Quantitative Risk Assessment (QRA) is a systematic methodology to identify, quantify, and map the risks associated with chemical, petrochemical, and process industries for the evaluation of the safety of a process and all activities associated with it. QRA studies often times compliment other

process safety studies and are extensively used by process safety engineers to provide solid basis for recommendations and decision-making facility. A typical QRA study can involve many sub-studies including a Process Hazard Analysis (PHA), HAZard and OPerability (HAZOP) study, a Safety Integrity Level (SIL) Determination study, Fault Tree Analysis (FTA), Event Tree Analysis (ETA), consequence analysis studies, and more. Generically speaking, however, the main constituents of a QRA study are a probability and likelihood analysis, a consequence analysis, and an overall risk estimation.

In the chemical and process industries, the consequences of an event often times involve loss of containment events and their escalations. That is, they involve the releasee of dangerous chemicals to the atmosphere which have the potential to ignite, burn, or explode, or which may otherwise be toxic or asphyxiating. In this context, the types of consequence analysis studies may involve dispersion analysis, radiation analysis, jet fire, flash fire, vapor cloud fire estimations, Boiling Liquid Evaporating Vapor (BLEVE) explosion estimations, Vapor Cloud Explosion (VCE) estimations, deflagration and detonation analysis and similar.

All of the QRA constituents are extensive studies in their own right, which thus makes the QRA study a very extensive one requiring plenty of input data, lots of resources, and prolonged analysis efforts. Nonetheless, it remains one of the most robust and informative methods in the industry and is highly reliable for the determination of risk reduction measures and even potentially development of lifecycle cost estimations. The outcomes of a QRA study can also inform the Cost Benefit Analysis (CBA) for different risk mitigation measures.

Additionally, QRAs are instrumental precursors to facility siting studies. QRAs are also often times performed to identify and quantify the risks

associated with construction of new buildings within chemical and petrochemical complexes – this is often referred to as a Building Risk Assessment (BRA).

It is due to its broad yet involved and extensive nature that QRA studies are perceived as specialized and difficult studies, however, and it is for this same reason that those studies are only normally performed by process safety engineers and consultants who are equipped with the tools and experience to perform the analyses.

As mentioned, QRA studies cover the processes and any related activities. In the context of the transportation of dangerous materials and chemicals, some additional considerations are introduced. For this reason, a QRA performed specifically for the transportation process is sometimes referred to as a Transportation Risk Analysis (TRA) indicating the additional scope. Some of the additional studies required are statistical analysis of past (historic) data to provide probability estimations. Other additional considerations include the consideration of transportation routes and the evaluation of road transportation risks and their potential in conjunction with the risks posed by the transported chemicals.

Chapter Three

Methods and Procedures

3.1 Methodology and Model Development

Recalling the purpose of this study, the aim is to establish a framework for conducting a road transportation risk analysis which can be extended to the transportation of any hazardous material. Additionally, the study aims to present this framework through a baseline study performed for the transportation of hydrogen fuel using Bahrain's road network.

Ideally, evaluating the risk of handling or transporting any hazardous material entails an understanding of the properties of this material and how it behaves in its different states and under different conditions. The properties of hydrogen as the main fuel being analyzed in this study have been thoroughly discussed in the earlier sections.

The properties of the subject fuel are important as they govern the nature of the consequences arising from a deviation, a mishandling, or an accident involving the chemical. Those consequences and their magnitudes are analyzed in a consequence analysis, which is the first step in the framework being suggested.

Once the consequences and their magnitudes are understood, a second step would be to understand how often those consequences may occur. This is achieved in two stages, the first being a statistical analysis of the frequency of occurrence of similar events based on historical data, also referred to within this suggested framework as a frequency analysis.

It must be understood that since hydrogen fuel is not the fuel of choice yet in Bahrain, and given that it is not generally transported by road throughout the Kingdom, there are no readily available statistical or historical data that exist per se. This does not impair the frequency analysis however, as this analysis is not limited to considering accident statistics that strictly involve hydrogen fuel tanker trucks and a loss of containment event. This is

because it is both more realistic and more conservative to run the frequency analysis considering statistics for all accidents that involve heavy transportation vehicles irrespective of their contents. This is because it is generally the movement of tanker trucks on road and their interaction with other road users that results in accidents and not the transporting vehicle's contents.

The stage following the frequency analysis would be the development of statistical inference for the probability of occurrence of a similar event in the future. This is referred to within this framework as a likelihood analysis. There are well established methods for statistical inference. Nonetheless, there are some intricacies that must be carefully considered in order to accurately estimate the probability of accidents in the future.

Within this research, and given the limited information currently available, many assumptions were made in order to establish baseline risk and put together the framework which will allow for honing and tuning of baseline risk as decisions are made and information is established. The assumptions are listed and explained in detail in the next section.

Lastly, the results of the consequence (magnitude) analysis and the likelihood (probability) analysis are combined to provide risk figures which are benchmarked against tolerable risk figures set by the stakeholders or suggested in internationally recognized standards and guidelines.

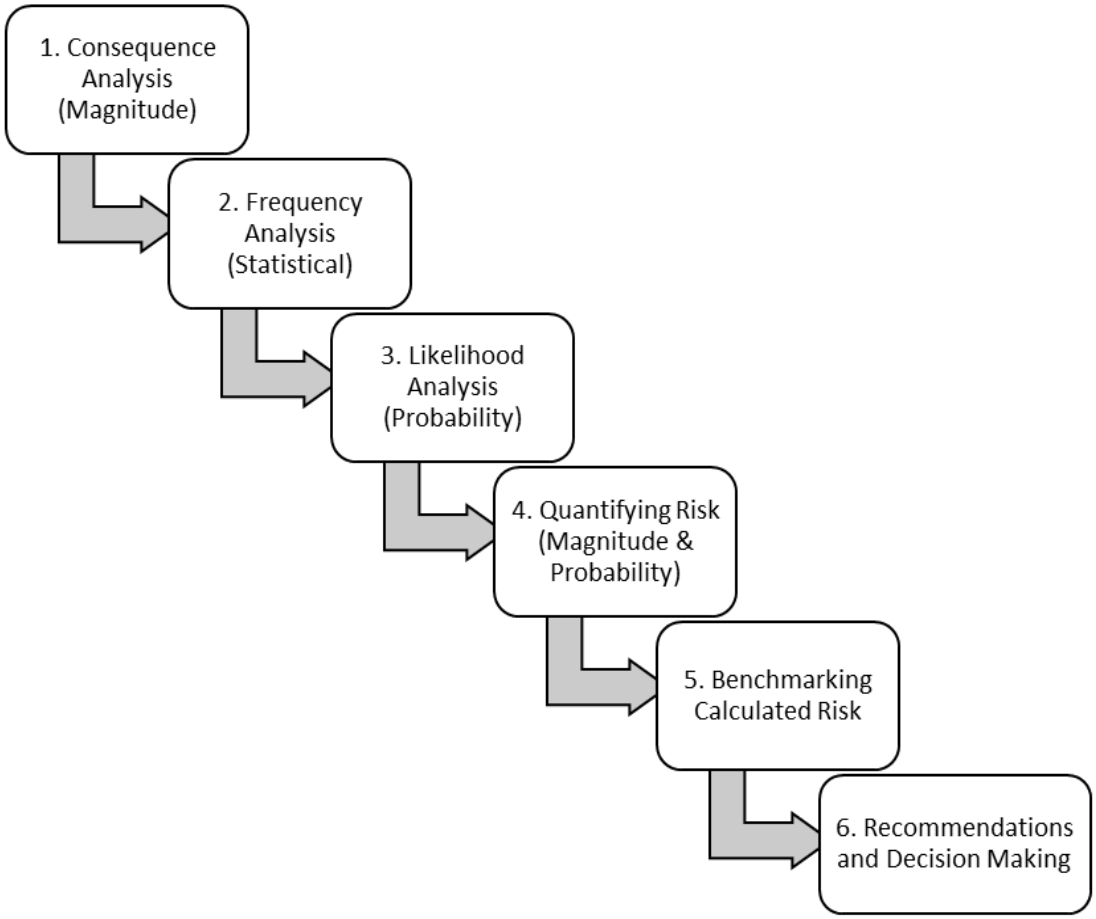


Fig. 2: Generic QRA Study Workflow

The following sections dwell into the definitions and details of each stage in the suggested framework, and breakdown the procedure followed in this study.

a. Consequence Analysis

A consequence is an outcome of an event or series of events, and generally carries a negative connotation eluding to it being undesirable. In the context of technical safety evaluations, a consequence is the ultimate result of an incident or accident on people, property, and the environment. For example, the consequences of the infamous loss of containment of methyl isocyanate (MIC) from the Union Carbide India Limited plant in the city of Bhopal included:

- Immediate Consequence
    - The escape of approximately 40 tonnes of MIC to the atmosphere within a duration of 2 hour
- Consequences to people and lives
    - Acute exposure of plant employees and surrounding citizens to high concentrations of MIC
    - Subsequent death of thousands of exposed individuals
    - The development of long term chronic illnesses and permanently disabling injuries in the population exposed to relatively lower concentrations
    - Potential genetic mutations in the surviving exposed population
- Consequences to property and economy
    - The closure of the Union Carbide plant in Bhopal, India
    - Incident investigation and subsequent legal action against Union Carbide
    - Overload of the Indian health care sector
- Consequences to environment
    - The contamination of certain commodities such as fish
    - Contamination of drinking water in areas within the vicinity of the UCIL MIC Plant
    - Soil pollution in areas within the vicinity of the UCIL MIC Plant

A consequence analysis involves the quantification and qualification of the severity of primary events that can lead to undesirable outcomes (API, 2014). Potential process upsets have to be anticipated or predicted as part of the consequence analysis for a given process. This exercise is called scenario identification. Subsequently, the outcomes resulting from the

scenarios identified must be evaluated. Finally, those outcomes are quantified using the most suitable approaches, theoretically sound and applicable equations, and industry accepted methods pertaining to each failure scenario.

Since a consequence analysis offers a quantification and qualification of the effects of process deviations, it is an integral part of any risk assessment. This is because the evaluation of risk is subject to both its severity and its likelihood. In the coming sections, a discussion of how likelihood is calculated, and what comprises a risk assessment is described.

In the context of this study, a consequence analysis is performed in order to quantify scenarios involving the loss of containment of high pressure (compressed) hydrogen from fuel transport tankers – mainly due to accidents that these tankers can experience on route or at terminal points – leading to the ignition of the escaped material or an explosion. The focus of this consequence analysis is hence aimed towards evaluating the following:

- Fire
    - The potential for formation of a liquids pool that can ignite and burn
    - The size of the potential liquids pool
    - The duration for which this pool will burn
    - The magnitude of thermal radiation resulting from the burning of the liquids and the distance up to which the thermal radiation can impact
- Flash Fires
    - The potential for rapid ignition of escaped hydrogen gas due to rupture of the vessel
    - The velocity of the flame front

    - The time and intensity of the flash fire
    - The radiative (instantaneous) impact of the flash fire
- Jet Fire
    - The potential for a jet stream leak from a rupture in the vessel
    - The velocity and duration of the jet
    - The severity of a jet fire resulting from the ignition of the jet stream
- Explosion
    - The potential for an explosion upon loss of containment
    - The type of such an explosion (deflagration, detonation, condensed phase explosions)
    - The magnitude of the explosion and the area that can be impacted by the resulting shockwave or projectiles
- Boiling Liquid Expanding Vapor Explosion (BLEVE)
    - The potential for a BLEVE, which is a specific type of explosions associated with partially filled vessels containing flashing liquids
    - The magnitude of such an explosion and the area that can be impacted by the resulting shockwave or projectiles

The loss of containment event is superimposed onto a specific segment of road at a given geographical location. This allows for plotting the identified consequences and their magnitudes as contours on a map.

The loss of containment event is evaluated for each one of the above possible modes using the following specific procedure:

1. Determining whether the mode is applicable in the case of a hydrogen release from
    a. Liquid Hydrogen Tanker
    b. Gaseous Hydrogen Tanker

c. Tube Trailer

2. Evaluating the mode deemed applicable for multiple rupture (orifice) sizes, and at different initial conditions depending on the tanker contents
3. Superimposing the event onto a road segment for visual depiction of the severity of the consequence and the extent of impact

To perform the consequence analysis per the above procedure, certain assumptions are made and summarized in table:

Table (4): Consequence Analysis Assumptions and Setup

Parameter Description	**Value**	**Reference**
Cryogenic Liquid Tanker Truck (50 m^3 – 3500 kg)		
Inside Diameter	2.6 m	(Cryolor, 2024)
Tangent to Tangent (T/T) Length	16.2 m	(Cryolor, 2024)
Shell Wall Thickness	0.0127 m	SuperChems® Default Value
Type of Vessel Heads	Elliptical 2:1	Assumed
Head Wall Thickness	0.0127 m	SuperChems® Default Value
Volume Transported	30-60 m^3	(Aziz, 2021)
Vessel Fill Level	85%	(Aziz, 2021)
Mass Transported	2100-4200 kg	(Aziz, 2021)
Design Pressure	10.7 barg	(H2tools, n.d.)

Vacuum Rating (minimum design pressure)	-1 barg (full vacuum)	Assumed
Normal Operating Pressure	0.14 barg	(Cryolor, 2024)
Design Temperature	100 °C	Assumed
Minimum Design Temperature	-253 °C	Assumed
Normal Operating Temperature	-253 °C	Assumed
Vapor Tanker Truck (3500 kg @ 500 barg)		
Inside Diameter	1.5 m – 2.6 m	Calculated
Tangent to Tangent (T/T) Length	12 m – 16.2 m	Calculated
Shel Wall Thickness	0.0127 m	SuperChems® Default Value
Type of Vessel Heads	Elliptical 2:1	Assumed
Head Wall Thickness	0.0127 m	SuperChems® Default Value
Volume Transported	26 m^3	Calculated in SuperChems®
Mass Transported	3500 kg	Assumed
Design Pressure	800 - 1000 barg	(Deng et al., 2022)
Vacuum Rating (minimum design pressure)	-1 barg (full vacuum)	Assumed
Normal Operating Pressure	500 barg	Assumed
Design Temperature	650 °C	Assumed

Minimum Design Temperature	-40 °C	Assumed
Normal Operating Temperature	50 °C	Assumed

b. Frequency Analysis

Frequency is the rate at which an event or occurrence takes place. For instance, the frequency of lease payments made by a tenant to his leaser is monthly. This means that the tenant pays the leaser on a monthly basis during the period of his contract. A more relevant example to this study would be the rate at which an accident takes place on a specific highway – King Faisal Highway for example. This would be described as the frequency of accidents on King Faisal Highway.

In addition to understanding the consequences of certain deviations and their respective magnitude, it is important to understand the rate at which such deviations take place. In other words, it is important to understand the frequency at which consequences occur. A frequency analysis can be performed based on data collected pertaining to an event or pool of events that are of interest. A frequency analysis is hence based on historic data which is statistically analyzed to provide categorical statistical understanding of trends and patterns concerning the events of interest. A frequency analysis returns important statistics for a sample such as its mean, median, mode, among other fundamental statistics. Ultimately, the purpose of such an analysis in research is to allow for statistical inference into the future.

Based on the principles of statistical inference, when trends are established for a specific sample taken from a set, multiple statistical inference models can be applied to extend the trends to the rest of the set. This concept can be used to substantiate the claim that future events of that are of the same

nature as past events will ‘very likely’ follow the same trend that past events follow. Hence, an assumption is made that the probability of future events can be inferred based on the trends of past events. As a result, it is important to establish a distinction between frequency and likelihood in the context of this study. Frequency is the rate of occurrence of past events, while likelihood is the probability of occurrence of this event in the future.

A frequency analysis is performed as part of this study based on official national statistics for the rates of accidents occurring on different highways of the kingdom. The types of vehicles involved in the accidents is also considered for a more accurate representation of the frequency of accidents that can cause a loss of containment event.

Available accident statistics are carefully analyzed in order to establish an annual rate of accidents involving heavy goods vehicles on any given segment of highway in the country. This is done by first categorizing the data available on a yearly basis. Subsequently, the statistics on heavy goods vehicles is isolated. Highways of interest are segmented and the data on frequency of accidents on a given highway is assumed to apply equally at all highway segments. The frequency of heavy goods vehicles accidents on a segment of a given highway is then calculated and normalized to apply for all highway segments.

The detailed procedure for the analysis is listed in this section. Relevant Excel screenshots are provided to clearly depict the development of the model:

1. Obtain accident statistics for the accidents on the roads of the Kingdom of Bahrain. Within this study, the statistics obtained for accidents on the roads of the Kingdom of Bahrain cover a total of 5 years from 2018 till 2022 (which was the latest publication at the time of

writing this report). This period provides sufficient data for the purpose of statistical inference (data.gov.bh, 2024). It is encouraged, nonetheless, to obtain a larger set of statistics, and include the most recent data to obtain more accurate estimates given the ongoing modifications to the roads network in Bahrain.

2. Capture the major highways, avenues, and roads, and determine the total length of each of those roads. The main highways and avenues considered are summarized in Table (5) below.

Table (5): Approximate Lengths of Considered Highways and Their Designated Symbols

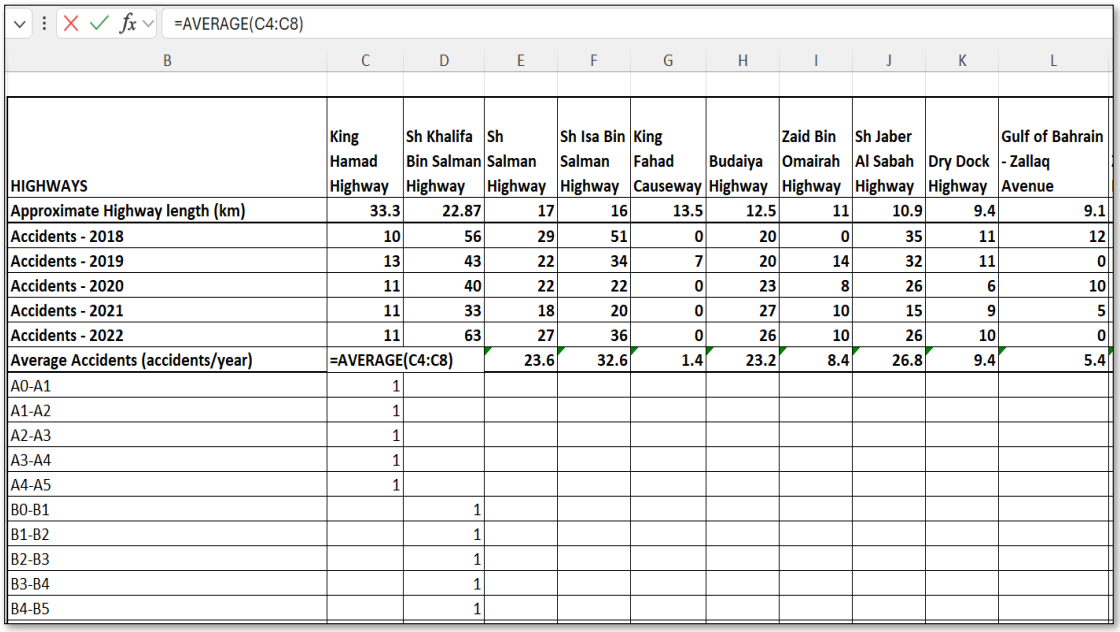
Highway or Avenue	**Symbol**	**Approximate Highway Length (km)**
King Hamad Highway	A	33.30
Sh. Khalifah Bin Salman Highway	B	22.87
Sh. Salman Highway	C	17.00
Sh. Isa Bin Salman Highway	D	16.00
King Fahad Causeway	E	13.50
Budaiya Highway	F	12.50
Zaid Bin Omairah Highway	G	11.00
Sh. Jaber Al Sabah Highway	H	10.90
Dry Dock Highway	I	9.40
Gulf of Bahrain – Zallaq Avenue	J	9.10
Zallaq Highway	K	9.10
Wali Al Ahd Highway	L	8.89

Al Estiglal Highway	M	7.80
Sh. Hamad Avenue (Hamad Town)	N	10.90
Amwaj Highway (Avenue 59)	O	6.85
Sh. Khalifah Bin Salman Causeway	P	6.00
Al Fatih Highway	Q	5.60
Al Muaskar Highway	R	5.50
Khalifah Al Kabeer Highway	S	5.70
Janabiyah Highway	T	5.00
Riffa Avenue	U	4.90
Um Al Nassan Avenue	V	4.73
Quds Avenue	W	4.00
Arad Highway	X	4.00
King Faisal Highway	Y	3.60
Avenue 13 (Tubli)	Z	3.60
Ajwad Al Jabri Avenue	AA	3.60
Sh. Isa Avenue (Manama)	BB	2.90
Saar Avenue	CC	2.40
Sh. Hamad Causeway	DD	2.40
Airport Avenue	EE	2.30
Salmaniyah Avenue	FF	2.20
Sh. Isa Bin Salman Cause-way	GG	2.20
Palace Avenue	HH	2.10

Awal Avenue	II	1.90
Isa Al Kabeer Avenue	JJ	1.90
Lulu Avenue	KK	1.60
Other Roads	-	4265.76
Total Length of Surfaced Roads Per Meter Run for the Year 2022*	4543.00	

3. Divide each highway, avenue, or road into multiple segments having the same length. For the purpose of this study, each road was divided into five segments (N = 5) and a total of six nodes (N+1 = 6).
4. Create a nodal map for the expected route from the distribution terminal to each retail station. Note that a single distribution terminal location was considered for the baseline study. Where segments intersect at the beginning, ending, or at traffic signals and/or junctions, a single node with the symbol of both highways is placed (the complete nodal map is shown in Appendix A).
5. After subdividing the roads into equal length segments, a matrix is constructed to correlate the equal length segments to the roads they pertain to. All other segments of road required to connect the main highway nodes to the stations are measured and listed in a single array under "Other Roads" (see **Error! Reference source not found.**). This is with the exception of two segments connecting Um Al Saad Avenue (exit of the marketing terminal) to the Sh. Jaber Al Sabah Highway in the northern and the southern direction; both those segments were truncated to the Sh. Jaber Al Sabah highway instead.

6. Filter the accident statistics for each highway, avenue, or road considered. The accident statistics considered are based on "Injury Accidents" tabulated by location in the general directorate of traffic's statistics. Those statistics include injuries of all degrees up to fatality. Statistics available for roads other than the ones considered in Table (5) have been truncated into "Other Roads". Using the data for all five years from 2018 to 2022, an average rate of accidents for each highway is calculated as shown in Table (6). **Error! Reference source not found.** has a screenshot of the Excel model depicting the steps summarized up to this point.



=AVERAGE(C4:C8)

	B	C	D	E	F	G	H	I	J	K	L
	HIGHWAYS	King Hamad Highway	Sh Khalifa Bin Salman Highway	Sh Salman Highway	Sh Isa Bin Salman Highway	King Fahad Causeway	Budaiya Highway	Zaid Bin Omairah Highway	Sh Jaber Al Sabah Highway	Dry Dock Highway	Gulf of Bahrain - Zallaq Avenue
	Approximate Highway length (km)	33.3	22.87	17	16	13.5	12.5	11	10.9	9.4	9.1
	Accidents - 2018	10	56	29	51	0	20	0	35	11	12
	Accidents - 2019	13	43	22	34	7	20	14	32	11	0
	Accidents - 2020	11	40	22	22	0	23	8	26	6	10
	Accidents - 2021	11	33	18	20	0	27	10	15	9	5
	Accidents - 2022	11	63	27	36	0	26	10	26	10	0
	Average Accidents (accidents/year)	=AVERAGE(C4:C8)		23.6	32.6	1.4	23.2	8.4	26.8	9.4	5.4
	A0-A1	1									
	A1-A2	1									
	A2-A3	1									
	A3-A4	1									
	A4-A5	1									
	B0-B1		1								
	B1-B2		1								
	B2-B3		1								
	B3-B4		1								
	B4-B5		1								

Fig. 3: Highway segments matrix and highway average accident rate (accidents/year)

HIGHWAYS	Other Roads	Total
Approximate Highway length (km)	4265.76	4543
Accidents - 2018	592	1024
Accidents - 2019	490	890
Accidents - 2020	321	613
Accidents - 2021	415	678
Accidents - 2022	473	819
Average Accidents (accidents/year)	458.2	-
B2 to Rawdah Station (3.66 KM)	1	
D3 to Rumaihi Station (3.14 KM)	1	
D2 to B4 (5.03 KM)	1	
B4 to Seef station (3.29 KM)	1	
H1 to Al Shorooq station (1.05 KM)	1	
H5 to Mahooz Petrol Station (1.95 KM)	1	

Fig. 4: Truncating to segments to "Other Roads"

Table (6): Average Accidents Per Highway for the years 2018 to 2022

Highway or Avenue	Symbol	Average Rate of Accidents Per Highway for years 2018-2022 (accidents/year)
King Hamad Highway	A	11.20
Sh. Khalifah Bin Salman Highway	B	47.00
Sh. Salman Highway	C	23.60
Sh. Isa Bin Salman Highway	D	32.60
King Fahad Causeway	E	1.40
Budaiya Highway	F	23.20

Zaid Bin Omairah Highway	G	8.40
Sh. Jaber Al Sabah Highway	H	26.80
Dry Dock Highway	I	9.40
Gulf of Bahrain – Zallaq Avenue	J	5.40
Zallaq Highway	K	9.80
Wali Al Ahd Highway	L	17.20
Al Estiglal Highway	M	7.80
Sh. Hamad Avenue (Hamad Town)	N	14.00
Amwaj Highway (Avenue 59)	O	9.80
Sh. Khalifah Bin Salman Causeway	P	10.80
Al Fatih Highway	Q	4.00
Al Muaskar Highway	R	5.80
Khalifah Al Kabeer Highway	S	6.0
Janabiyah Highway	T	12.80
Riffa Avenue	U	5.80
Um Al Nassan Avenue	V	1.20
Quds Avenue	W	8.60
Arad Highway	X	17.00
King Faisal Highway	Y	2.80
Avenue 13 (Tubli)	Z	0.00
Ajwad Al Jabri Avenue	AA	0.00
Sh. Isa Avenue (Manama)	BB	3.40

Saar Avenue	CC	1.40
Sh. Hamad Causeway	DD	4.60
Airport Avenue	EE	1.20
Salmaniyah Avenue	FF	0.80
Sh. Isa Bin Salman Cause-way	GG	3.20
Palace Avenue	HH	4.60
Awal Avenue	II	1.40
Isa Al Kabeer Avenue	JJ	1.20
Lulu Avenue	KK	2.80
Other Roads	-	458.20

7. Another sheet is created and an average rate of incidents per segment is calculated using the arithmetic in equation 4: Fig. 5 show this step as performed in Excel.

$$\frac{\textit{Segment Length (km)}}{\textit{Approx. Length of Highway (km)}} \; x \; \textit{Avg. Rate of Acc. per Highway} \left(\frac{acc.}{year}\right) \qquad \textbf{Equation 2}$$

		King Hamad Highway	Sh Khalifa Bin Salman Highway	Sh Salman Highway	Sh Isa Bin Salman Highway	King Fahad Causeway
Symbol		A	B	C	D	E
Approximate Highway length (km)		33.3	22.87	17	16	13.5
Accidents - 2018		10	56	29	51	0
Accidents - 2019		13	43	22	34	7
Accidents - 2020		11	40	22	22	0
Accidents - 2021		11	33	18	20	0
Accidents - 2022		11	63	27	36	0
Average		11.2	47	23.6	32.6	1.4
Segments	Segment Length (kM)					
A0-A1	6.66	=IF(Highways!C10,($C12/D$4)*D$10,"")				
A1-A2	6.66	2.24				
A2-A3	6.66	2.24				

Fig. 5: Average rate of accidents per highway segment per year

8. The average incident rate is then adjusted to an average annual rate per kilometer of road for each highway, avenue, or road. To perform this adjustment, the level of use of a segment is taken into consideration.

    a. The level of use of a segment is considered by accounting for the number of times the segment is used to transport hydrogen from the terminal to a delivery location. For instance, the **D1-D2** segment needs to be traversed to deliver to Madinat Salman Petrol Station, Oil Kingdom (Hamala) Petrol Station, and Benzena Petrol Station, making its level of use equal 3. A screenshot from the excel model representing this stage of the model is provided in **Error! Reference source not found.**.

Fig. 6: Level of use of segments

9. An "average vehicle kilometers" travelled per segment (i.e. the total kilometers a vehicle would cover crossing a given segment for the purpose of transporting the product from the distribution location to an assigned retail location) is calculated considering the ratio of the length of the segment to the total length of the network multiplied by the annual total heavy vehicle kilometers travelled of 120,000 km.

Name Of Road/Highway		Segment Length (km)	Typical vehicle km per segment	A'ALI PETROL STATION	A P S
Other Roads	Terminal 0 - Terminal 1	0.514	=$D4/	1	
Other Roads	Terminal 1 - Terminal 2	0.514	SUM(	1	
Other Roads	Terminal 2 - Terminal 3	0.514	$D$4:	1	
Other Roads	Terminal 3 - Terminal 4	0.514	$D$264)*	1	
Other Roads	Terminal 4 - Terminal 5	0.514	120000	1	
Sh Jaber Al Sabah Highway	Terminal 5 - H1	1.89	532.99	1	

Fig. 7: Average kilometers travelled per segment

10. The average vehicle kilometers travelled per segment is then adjusted to account for the level of use of the segment. This means that the average vehicle kilometers travelled per segment is adjusted to account for the use of the segment in delivery to all retail locations, which serves the purpose of converting the level of use into a meaningful kilometer rate or contribution to the annual total average kilometers travelled by a heavy vehicle.

Name Of Road/Highway		Segment Length (km)	Typical vehicle km per segment	Benzena Petrol Station	Level of Use of Segment	Adjusted veh km level of use per segment
Other Roads	Terminal 0 - Terminal 1	0.514	144.951	1	51	=BE4*E4
Other Roads	Terminal 1 - Terminal 2	0.514	144.951	1	51	7392.4855
Other Roads	Terminal 2 - Terminal 3	0.514	144.951	1	51	7392.4855

Fig. 8: Adjusted average vehicle kilometers travelled per segment

11. The calculated average kilometers travelled per segment is normalized into a typical rate of kilometers travelled by a transporting vehicle
12. The typical rate of incidents per segment per year (calculated in steps 7 and 8) is then adjusted using the normalized level of use. This step allows us to filter for the segments with highest rate – 10 segments are selected for the completion of the likelihood analysis.

Name Of Road/Highway		Segment Length (km)	Typical vehicle km per segment	Benzena Petrol Station	Level of Use of Segment	Adjusted veh km level of use per segment	Normalized to 120,000 km	Difference Ration between typical and adjusted	Typical incidents segment year
Other Roads	Terminal 0 - Terminal 1	0.514	144.951	1	51	7392.4855	=BF4/SUM($BF$4:$BF$264)*120000		
Other Roads	Terminal 1 - Terminal 2	0.514	144.951	1	51	7392.4855	3596.06811	24.8089054	0.05521
Other Roads	Terminal 2 - Terminal 3	0.514	144.951	1	51	7392.4855	3596.06811	24.8089054	0.05521
Other Roads	Terminal 3 - Terminal 4	0.514	144.951	1	51	7392.4855	3596.06811	24.8089054	0.05521
Other Roads	Terminal 4 - Terminal 5	0.514	144.951	1	51	7392.4855	3596.06811	24.8089054	0.05521
Sh Jaber Al Sabah Highway	Terminal 5 - H1	1.89	532.99		20	10659.7983	5185.44956	9.72898252	4.64697
Sh Jaber Al Sabah Highway	Terminal 5 - H2	0.294	82.9095	1	30	2487.28626	1209.93823	14.5934738	0.72286
King Hamad Highway	A0-A1	6.66	1878.15		1	1878.15493	913.626826	0.48644913	
King Hamad Highway	A1-A2	6.66	1878.15		1	1878.15493	913.626826	0.48644913	

Fig. 9: Adjusted average kilometers travelled per segment normalized to 120,000 km

Name Of Road/Highway		Segment Length (km)	Typical vehicle km per segment	Normalized to 120,000 km	Difference Ration between typical and adjusted	Typical incidents by segment per year	Typical incidents by segment per year in percentage	Adjusted incidents by segment per year	Adj inci segi yea per
Other Roads	Terminal 0 - Terminal 1	0.514	144.951	3596.06811	24.8089054	0.05521051	0.01501661	=BI4*(BG4/E4)	
Other Roads	Terminal 1 - Terminal 2	0.514	144.951	3596.06811	24.8089054	0.05521051	0.01501661	1.36971241	0.
Other Roads	Terminal 2 - Terminal 3	0.514	144.951	3596.06811	24.8089054	0.05521051	0.01501661	1.36971241	0.
Other Roads	Terminal 3 - Terminal 4	0.514	144.951	3596.06811	24.8089054	0.05521051	0.01501661	1.36971241	0.
Other Roads	Terminal 4 - Terminal 5	0.514	144.951	3596.06811	24.8089054	0.05521051	0.01501661	1.36971241	0.
Sh Jaber Al Sabah Highway	Terminal 5 - H1	1.89	532.99	5185.44956	9.72898252	4.64697248	1.26392192	45.210314	8.
Sh Jaber Al Sabah Highway	Terminal 5 - H2	0.294	82.9095	1209.93823	14.5934738	0.72286239	0.19661008	10.5490733	1.

Fig. 10: Adjusted average kilometers travelled per segment per year

c. Likelihood Analysis

After understanding what the frequency analysis provides and establishing trends based on data for past events, the trend is extrapolated into the future as a probability within the works of a likelihood analysis. Likelihood analysis is supplemented by guidance that is available in the current time and the knowledge of imminent legislation that is expected to impact the trends either positively or negatively. Additionally, the likelihood analysis is supplemented by international standards which may be to an extent applicable in the Kingdom of Bahrain.

The likelihood analysis also takes into consideration the level of use of a certain segment of highway over the level of use of a different segment on a different highway. This is an important consideration to account for the fact that the geographical location impacts the probability of an event. For example, an accident is more likely to take place on a segment of highway with inadequate or inexistant lighting as opposed to a well-lit segment of highway.

1. After selecting the segments with the highest adjusted incident rate per year, the Loss of Containment likelihood per incident per year is calculated based on an assumed frequency of incidents

Typical incidents by segment per year in percentage	Adjusted incidents by segment per year	Adjusted incidents by segment per year in percentage	Notes	Ranking	Highway Segment	Segment	Adjusted incidents by segment per year in percentage			
1.457857	75.61365	14.29981		1	Sh Jaber Al Sabah Highway (H2-H3)	H2-H3	14.30	=(1/$CB$16)*(CC4/100)		
1.457857	73.00628	13.80671		2	Sh Jaber Al Sabah Highway (H3-H4)	H3-H4	13.81	0.0197	51	0.0
1.457857	73.00628	13.80671	H4-H5	3	Sh Jaber Al Sabah Highway (H3-H4)	H4-H5	13.81	0.0197	51	0.0
1.457857	49.53998	9.36884	61.8271	4	Sh Jaber Al Sabah Highway (H0-H1)	H0-H1	9.37	0.0134	75	0.0
1.263922	45.21031	8.550027		5	Sh Jaber Al Sabah Highway (Terminal 5 - H1)	Terminal 5 - H1	8.55	0.0122	82	0.0
1.773363	38.05978	7.197742		6	Sh Isa Bin Salman Highway (D3-D4)	D3-D4	7.20	0.0103	97	0.0
1.773363	22.20154	4.198683		7	Sh Isa Bin Salman Highway (D2-D3)	D2-D3	4.20	0.0060	167	0.0
0.19661	10.54907	1.995006		8	Sh Jaber Al Sabah Highway (Terminal 5 - H2)	Terminal 5 - H2	2.00	0.0029	351	0.0
1.773363	9.514945	1.799435		9	Sh Isa Bin Salman Highway (D1-D2)	D1-D2	1.80	0.0026	389	0.0
0.93564	5.020155	0.949395		10	Wali Al Ahd Highway (L4-L5)	L4-L5	0.95	0.0014	737	0.0
0.424302	4.553164	0.86108	Not Used				75.97			
0.587495	4.20292	0.794843	Not Used							
0.587495	4.20292	0.794843	Not Used		Assumed Frequency of incidents (1 incident in X year)	7				

Fig. 11: Likelihood of LOC per incident per year for selected segments with highest adjusted incidents rate per year

2. The likelihood of an LOC leading to fire per incident per year is calculated using a probability of direct ignition as reported in Table 4.6 of the Purple Book (Road Tanker Instantaneous) and Table 4.A.1 (Point Source Motor Vehicle)

Typical incidents by segment per year in percentage	Adjusted incidents by segment per year	Adjusted incidents by segment per year in percentage	Notes	Ranking	Highway Segment	Segment	Adjusted incidents by segment per year in percentage	LOC Likelihood per incident per year	LOC per incident per year (1 LOC in X years)		
1.457857	75.61365	14.29981		1	Sh Jaber Al Sabah Highway (H2-H3)	H2-H3	14.30	0.0204	49	=$CD4*$CB$17	
1.457857	73.00628	13.80671		2	Sh Jaber Al Sabah Highway (H3-H4)	H3-H4	13.81	0.0197	51	0.009862	101
1.457857	73.00628	13.80671	H4-H5	3	Sh Jaber Al Sabah Highway (H3-H4)	H4-H5	13.81	0.0197	51	0.009862	101
1.457857	49.53998	9.36884	61.8271	4	Sh Jaber Al Sabah Highway (H0-H1)	H0-H1	9.37	0.0134	75	0.006692	149
1.263922	45.21031	8.550027		5	Sh Jaber Al Sabah Highway (Terminal 5 - H1)	Terminal 5 - H1	8.55	0.0122	82	0.006107	164
1.773363	38.05978	7.197742		6	Sh Isa Bin Salman Highway (D3-D4)	D3-D4	7.20	0.0103	97	0.005141	195
1.773363	22.20154	4.198683		7	Sh Isa Bin Salman Highway (D2-D3)	D2-D3	4.20	0.0060	167	0.002999	333
0.19661	10.54907	1.995006		8	Sh Jaber Al Sabah Highway (Terminal 5 - H2)	Terminal 5 - H2	2.00	0.0029	351	0.001425	702
1.773363	9.514945	1.799435		9	Sh Isa Bin Salman Highway (D1-D2)	D1-D2	1.80	0.0026	389	0.001285	778
0.93564	5.020155	0.949395		10	Wali Al Ahd Highway (L4-L5)	L4-L5	0.95	0.0014	737	0.000678	1475
0.424302	4.553164	0.86108	Not Used				75.97				
0.587495	4.20292	0.794843	Not Used								
0.587495	4.20292	0.794843	Not Used		Assumed Frequency of incidents (1 incident in X year)	7					
0.587495	4.20292	0.794843	Not Used		Prob of delayed ignition	0.5					

Fig. 12: Likelihood of LOC leading to fire per incident per year for segments with highest adjusted incidents rate per year

d. Fault tree analysis (FTA)

Fault Tree Analysis (FTA) is a deductive and systematic process used to analyze the reasons of system failures. The FTA workflow was first developed in the aerospace industry in the 1960s to enhance the safety and reliability of complex systems. The FTA methodology has become a widely utilized tool across many industries and has been combined with various other useful techniques to aid risk evaluation studies. The FTA tool is commonly used in chemical processing, nuclear power, automotive manufacturing, and various other industries.

The main purpose of FTA is to identify possible failure points within a system and understand the different ways these failures can occur. Engineers and safety professionals can implement measures to prevent or mitigate system failures by using FTA workflows to map out possible failure paths. Accordingly, FTA not only helps in enhancing the safety of the system or design, but also contributes to improving the system reliability, reducing the risks associated with design or operation, and providing basis for inherently safer designs.

The fault tree analysis is based around the construction of a fault tree, which is a visual representation of the pathways to system failure using logical gates and symbols. The fault tree primarily contains:

1. **Top Event**: This is the undesired event or system failure that the analysis aims to prevent. It is typically placed at the top of the fault tree schematic.
2. **Intermediate Events**: These are events that occur as a result of one or more basic events. They represent the progression of failures leading up to the top event.

3. **Basic Events**: These are the fundamental causes of system failure, usually depicted as circles at the bottom of the faut tree. Basic events can be hardware failures, human errors, or any other primary causes.
4. Logical Gates: These are used to connect events and illustrate the relationships between them. The most common logical gates are **AND** gates and **OR** gates.
    - **AND Gate**: This gate indicates that all input events must occur for the output event to happen
    - **OR Gate**: This gate indicates that any of the input events can cause the output event to occur

To construct a fault tree and develop a fault tree analysis, the basic process is as follows:

1. Defining the Top Event – in the context of this study the top event is the loss of containment event leading to a fire or explosion
2. Identifying Causes – the potential causes of a loss of containment event leading to fire or explosion are the loss of containment event along with the probability of the presence of an ignition source.
3. Constructing the Fault Tree – the main top event would be the LOC leading to fire or explosion while the sub-top event can be the LOC event itself. Conditional events such as the presence of ignition sources, the phase of transported hydrogen, or the fill level of the transporting vehicle are all taken into consideration. Basic and intermediate events such as the occurrence of an accident involving a hydrogen fuel transporter is also considered.
4. Quantitative Analysis – with the fault tree constructed including the top events, intermediate events, conditional and basic events, quantitative analysis is performed by assigning probabilities to basic events leading up to the top event and calculating overall probability.

5. Identify Mitigation Measures – the fault tree provides basis for the identification of mitigation measures which is beyond the scope of this research but is mentioned here to indicate what future efforts during actual (non-baseline) risk studies should involve.

Fig. 2 shown earlier can be taken as a generic representation of a fault tree which can be associated with this QRA study workflow.

e. Incident/Overall Risk

The calculation of risk can be complex and require detailed analysis. Nonetheless, the results of a QRA study should be the arrival at overall risk based on the frequency, likelihood, and consequence analyses performed. Risk can be broken down to two main categories – individual risk and societal risk.

Individual Risk can be defined as the risk of fatality to an individual due to a loss of containment event. Individual risk calculation involves some assumptions regarding the state of the individual during the time of his exposure to the consequences of the loss of containment, such that he is assumed to be unprotected (consequences are unmitigated) during the time of his exposure. Individual risk is represented on the geospatial map as a contour line.

On the other hand, Societal Risk can be defined as the risk of an accident resulting in N or more simultaneous fatalities. With Societal Risk, the population exposed is assumed to be protected to a certain extent. Societal Risk looks at the number of deaths represented by N and the cumulative frequency of accidents having N or more fatalities represented by F. Societal Risk is hence represented using F-N curves.

To calculate individual and societal risk, the scope of the calculations must be set by constructing what the purple book refers to as a “grid”. The grid

is simply the area of interest over which risk will be calculated. At the center of the grid are points at which the individual risk is calculated, whereas the societal risk is calculated over the grid cell which has a representation of the impacted population attached to it. Lastly, a probability of ignition is also assigned to each grid cell.

Individual risk is calculated at grid points by combining the contributions due to the different risk factors such as frequency of LOCs, weather conditions, wind direction, and probability of ignition. More specifically, the procedure to calculate individual risk is the following:

1. Select an LOC event and estimate its frequency (f) in yr^{-1}.
2. Select the weather class and determine its probability (P_w).
3. Select a wind direction and determine its probability (P_r).
4. Calculate the conditional probability of wind direction given a weather class. The conditional probability (P_c) is hence P_w x P_d
5. For flammable releases, estimate the probability of ignition (P_i).
6. Calculate the probability of fatality (P_d) given the LOC, the weather class, the wind direction, and the probability of ignition.

$$\boldsymbol{IR_{LOC,w,c,i} = f \, x \, P_w \, x \, P_c \, x \, P_i \, x \, P_d \; (yr^{-1})} \qquad \textbf{Equation 3}$$

7. Lastly, calculate individual risk at a grid point given the LOC, weather class, wind direction, and probability of ignition
8. Repeat this process for all ignition events, weather classes, wind directions, and LOC events to calculate the total individual risk

$$\boldsymbol{IR_{total} = \sum_{LOC} \sum_{w} \sum_{c} \sum_{i} IR_{LOC,w,c,i}} \qquad \textbf{Equation 4}$$

f. Purple Book CPR-18E Guidelines for Quantitative Risk Assessment

The CPR-18E Guidelines, officially known as the “Guidelines for Quantitative Risk Assessment” and referred to as the “Purple Book” is a comprehensive document published by the Committee for the Prevention of Disasters (CPR) in the Netherlands. It provides methodologies for calculating risk associated with dangerous substances, and is widely used in the chemical, environmental, and process industries for guidance on environmental permits, labor safety, fire safety, and transport safety. The Purple Book is divided into two main parts. Part 1 focuses on provisions for stationary installations and details methodologies for calculations and risk estimations in fixed facilities. On the other hand, Part 2 focusses on transport of dangerous goods, and provides risk calculation and estimation methods for transportation activities. The guidelines are mainly intended to ensure the safety and integrity installations and transport operations involving hazardous substances.

The purple book is part of a series of publications including the Red Book, Yellow Book, and Green Book collectively covering probabilities, effects, and damage respectively. Those publications provide a comprehensive standard for risk analysis works. Despite some of the guidelines in those documents getting replaced by newer methods, they remain an invaluable source of historical reference and guidelines for risk assessment practices.

With relevance to this research, part 2 is considered in more detail. Part 2 outlines methods for calculating risks associated with the transport of hazardous goods and substances as mentioned above. It provides key information for risk assessment including:

1. ***Risk Calculation Methods*** for assessing risks during the transportation of dangerous goods. This includes identifying potential hazards, evaluating the probability of incidents, and estimating the potential impact on people and the environment.

2. ***Transportation Scenarios*** for the various transportation modes including road, rail, sea, and air transportation. Each mode of transport has its own specific risk factors, mitigation measures, and incident scenarios.

3. ***Safety Measures*** covering the importance of the implementation of safety measures to minimize risks. This includes proper packaging, labeling, and handling procedures for dangerous goods.

4. ***Regulatory Compliance*** guidance to ensure compliance with national and international regulations for the transportation of hazardous materials. This includes adherence to the standards set by organizations such as the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO).

5. ***Emergency Response*** guidelines to cover emergency response planning and preparedness. This includes procedures for dealing with accidents and incidents involving dangerous goods during transport.

The guidelines are designed to help transportation operators and authorities manage the risks effectively and provide direction for safety engineers to develop studies for risk estimations. A very important reference from the CRP-18E which will be utilized in this study is the loss of containment scenario frequencies for road tankers and tank wagons in an establishment. Given that hydrogen is transported under pressurized conditions, pressurized tank frequencies are considered.

3.2 Assumptions

As explained in the previous section, the limited availability of information and data directly relating to hydrogen transportation in Bahrain necessitated the development of assumptions that allow for the establishment of a working framework and help to arrive at baseline risk figures. In this section, all the assumptions made are listed and explained. The purpose of listing all assumptions thoroughly is to allow for critical evaluation of the assumptions and future improvement of the framework.

i. General Assumptions

1. *Hydrogen is assumed to become the dominant fuel used for the purpose of transportation in the year 2060, completely replacing gasoline. Hydrogen fuel is assumed to be predominantly green hydrogen, which is in line with the 'net-zero emissions' target Bahrain has committed to by 2060.*
2. *Hydrogen is assumed to be transported by road to retail dispensation locations throughout Bahrain.*
3. *Baseline risk is established for the current time assuming the information available for gasoline production, transportation, and retail dispensation are applicable to hydrogen. To simplify this assumption further, it is assumed that hydrogen is produced by a single producer and transported from a single location. Extrapolating the assumption of the validity of current gasoline infrastructure, hydrogen is assumed to be produced in the Sitra Refinery, transported from the Refining Marketing Terminal to the existing refueling stations at the time of performance of this analysis.*
4. *The mode of transportation of hydrogen by road uses tanker trucks or tube trailers or similar.*

5. *Baseline Risk Analysis assumes the current road network (at the time this study was prepared) and does not consider ongoing civil works to modify or expand certain roads.*

ii. Consequence Analysis

1. *The consequence analysis is restricted to the fire or explosion arising from the loss of containment of hydrogen due to an accident. Further potential consequences such as blast waves, structural damages, or similar are not considered.*
2. *All road segments and delivery routes are assumed to be open – no confined release is considered.*
3. *Meteorological data is based on data from Bahrain Meteorological Directorate (Bahrain Meteorological Directorate, n.d.).*
4. *Thermal radiation limits are based on the API 521 Standard titled" Pressure-relieving and Depressuring Systems" (API, 2014).*
5. *Instantaneous release of the complete inventory is assumed upon accident occurrence (i.e. complete failure of the shell of the tanker truck).*
    a. *A continuous steady state release is assumed to consider the potential for a BLEVE.*

iii. Frequency Analysis

1. *Incident frequency is well represented by General Directorate of Traffic Statistics, and the likelihood of an incidents can be modeled as a function of incident frequency.*
2. *The frequency analysis is primarily based on 5 years of published GDOT Statistics from the years 2018 until 2022 (latest publication).*
3. *Heinrich's Theory of Accident Causation is applicable to road transportation of fuels. The theory entails that accidents are caused by a combination of unsafe conditions and unsafe acts, and that the number of major accidents is proportional to the number of minor accidents or no-consequence accidents (DeCamp & Herskovitz, 2015).*

4. *Highways are subdivided into 5 equal segments and 6 equally distanced nodes.*
5. *Existing road features such as traffic lights, exits, or similar – despite their effect on accident frequency or likelihood in reality – are not considered in the analysis as their contributions to the frequency is not calculable or quantifiable.*
6. *All minor roads extending from the highways and avenues to the refueling stations are considered under "Other Roads".*
7. *Unreported road accidents are assumed to be inconsequential with no effect on the frequency analysis performed in this study. This assumption is logical as unreported road accidents are typically minor in nature with no consequences and such accidents poses little to no potential for an LOC*
8. *The total number of incidents was averaged over the selected 5 year period (2018-2022)*
9. *The total average annual vehicle kilometers for "Light Vehicles" – aka "private registered vehicles" is assumed to be 20,000 km/year.*
10. *The total average annual vehicle kilometers for "Heavy Vehicles" is assumed to be 6 times that of "Light Vehicles" (Australian Bureau of Statistics, 2020) which amounts to 120,000 km/year.*
11. *Tanker Trucks or Tube Trailers are assumed to use the same route from and back to the distribution terminal.*
12. *Fuel Tanker Trucks or Tube Trailers are assumed to be loaded with fuel as they travel from the terminal to the station. Conversely, they are assumed to be empty/unloaded on their way back from the stations to the terminal.*
13. *An accident involving the tanker truck or the tube trailer on its way back while empty is assumed to lead to no consequences and hence is not considered in the frequency analysis. Thus, the trucks and trailers are*

assumed to make a single trip per segment and its return using the same segment is irrelevant to the study.

14. *Delivery routes are constructed based on the feature of suggested routes by Google Maps. Only minor modifications were made to the suggested routes by Google Maps when an unusable or unsuitable road was qualified.*

iv. Likelihood Analysis

1. *The likelihood of an incident is based on the incidence rate (frequency) per segment*
2. *The likelihood is normalized and adjusted to a per year percentage (probability)*

v. Risk (individual and societal)

1. *Road segment and surroundings overall occupancy is assumed to be 500 persons (400 daytime occupancy and 100 nighttime occupancy)*
2. *Number of vehicles at any given point in time per segment is considered to be 100 vehicles at most*
3. *All loss of containment events and their escalations are assumed to take place in the center of the road segment. The clearance between the point of loss of containment (i.e. center of the segment) and the surrounding population is taken to be 10 meters on either side of the road.*
4. *Individual risk threshold for hydrogen transportation is assumed to be 10^{-6} in line with "Purple Book" guidelines*
5. *Societal risk threshold for annual frequency of hydrogen transport movements is taken to be 500 movements/year for motorways as per table 1.3 of the "Purple Book" Part 2.*

3.3 Research Tools

a. Google Maps

A major task in the study following the establishment of the study objectives and assumptions was to analyze the road maps of Bahrain and to construct delivery routes for the transporting vehicles and to further subdivide the roads into segments and nodes. The nodal delivery routes map was constructed using Google Maps as previously mentioned in the assumptions section. Various important features were utilized allowing for the construction of this map in an efficient and helpful manner for this study.

Google maps is essentially a geographic information system (GIS) with basic features such as superimposition of multiple layers, construction of GPS based road maps, fastest route suggestions, dropping of multiple pins to mark locations, as well as the ability to measure distances and manipulate routes.

Multiple nodal maps were constructed using this tool which provided basic information needed to complete the frequency and likelihood analysis. The information extracted from Google Maps such as segment lengths and total highways lengths was entered into the spreadsheets for the statistical inference calculations as described in the next section.

b. Microsoft Excel

To perform the first sections of the study consisting of frequency and likelihood analysis, basic statistical manipulation and inference was required. For this purpose, Microsoft excel was utilized as it allows for the construction of spreadsheets with embedded statistical formulae. Primarily, a spreadsheet was constructed wherein the relevant accident statistics from the General Directorate of Traffic (GDOT) were tabulated. This allowed for the use of those statistics directly in the analysis in other spreadsheets.

The statistics provided basic inputs for the frequency analysis after some manipulation using Excel formulas. Next, nodal maps constructed in google maps were summarized into tables detailing node locations, highway total lengths, and segment lengths. This information combined with the frequency figures also provided the basic inputs for the likelihood analysis as detailed previously.

c. SuperChems®

SuperChems® is a software tool falling under the Process Safety Office® (PSO) suite created by ioMosaic Corporation. The software is an integrated tool for evaluation and design of pressure relief and flare systems (PRFS), consequence modelling, risk analysis, facility siting, and other process safety activities. The software is recognized in the industry and widely accepted by major companies and by bodies involved in the industry of process safety such as the American Institute of Chemical Engineers (AIChE) and the Design Institute for Emergency Relief Systems (DIERS). SuperChems® is capable of simulating complex releases, dispersions, fire, and explosion scenarios involving hazardous chemicals, including hydrogen. The use of SuperChems® adds technical rigor to this study and provides credible estimates for consequences and risks.

SuperChems® was selected as the main tool for analysis for this study due to various advantages it proposes. This includes the robust and industry recognized consequence modeling capabilities. Moreover, SuperChems® includes risk modeling and QRA features in the software and combines with other software tools in the PSO suite which allow for enhanced and expanded study scopes in the future. Another advantageous feature is that the software includes both the consequence modelling features and the QRA features in one interface making the process of performing the analysis more convenient.

The main consequence models captured in the study and computed in SuperChems® are summarized along with the main equations which the models are based on.

Ideal Nozzle Model

The Ideal Nozzle model is used to compute flowrates through orifices assumed due to the ruptures. In engineering applications, the ideal nozzle model is a simple theoretical representation for how a nozzle behaves under limiting assumptions such as the assumption of an isentropic flow, steady developed flow, one-dimensional flow, and ideal gas behavior. In the context of flow through an orifice, the model represents a theoretical framework to simplify the analysis of fluid flow through a restriction. The key assumptions for the ideal nozzle model for flow through an orifice are that the flow is inviscid and that there is no heat transfer (i.e. adiabatic conditions). The assumption of steady state one dimensional flow remains applicable as well. The model is essentially an adaptation of the Bernoulli Equation under the assumptions of ideality as stated above.

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 \qquad \textit{Equation 5}$$

where

P = Pressure

ρ = Density

V = Velocity

The equation is correlated to the ideal mass continuity equation

$$\dot{m}_{ideal} = \rho A V_2 = A\sqrt{2\rho(P_1 - P_2)} \qquad \textit{Equation 6}$$

where

$\dot{\mathbf{m}}_{\mathbf{ideal}} = \mathbf{Ideal\ mass\ flow\ rate}$

$\boldsymbol{\rho} = \mathbf{Density}$

$\mathbf{A} = \mathbf{Flow\ area}$

$\mathbf{V} = \mathbf{Flow\ velocity}$

$\mathbf{P} = \mathbf{Pressure}$

To enhance the accuracy of the model, real behavior is – to an extent – accounted for by introducing the discharge coefficient to the equation. Under complete ideal behavior, the discharge coefficient (Cd) would equate to 1 thus eliminating entrance losses. However, for valves and orifices, the discharge coefficient can vary from 0.62 for incompressible fluids to 0.975 for compressible flow.

$$\dot{m}_{real} = C_d A\sqrt{2\rho(P_1 - P_2)} \qquad \textit{Equation 7}$$

where

$\dot{\mathbf{m}}_{\mathbf{real}} = \mathbf{Real\ mass\ flow\ rate}$

$\mathbf{C_d} = \mathbf{Orifice\ discharge\ coefficient}$

$\mathbf{A} = \mathbf{Flow\ area}$

$\boldsymbol{\rho} = \mathbf{Density}$

$\mathbf{P = Pressure}$

For choked flow of compressible fluids, the equation is adjusted to include the critical pressure ratio. The choked flow is hence represented by the following equation

$$\dot{m}_{choked} = C_d A P_1 \sqrt{\frac{\Upsilon}{RT_1}\left(\frac{2}{\Upsilon+1}\right)^{\frac{\Upsilon+1}{\Upsilon-1}}} \qquad \textbf{Equation 8}$$

where

$\mathbf{\dot{m}_{choked} = Choked\ mass\ flow\ rate}$

$\mathbf{C_d = Orifice\ discharge\ coefficient}$

$\mathbf{A = Flow\ area}$

$\boldsymbol{\rho} \mathbf{= Density}$

$\mathbf{P = Pressure}$

$\boldsymbol{\gamma} \mathbf{= Specific\ heats\ ratio}$

$\mathbf{R = Specific\ gas\ constant}$

$\mathbf{T = Temperature}$

Gas Flame Jet Model

A gas flame jet model is typically used to model high-temperature ignited jets from a nozzle or an orifice into an ambient environment, its propulsion, ignition, and thermal impacts. The model is complicated and includes essential principles from fluid dynamics, thermal transport, and reactive modeling for reactive flame jets. For simplicity, jets may be assumed to be

axisymmetric and non-reactive, whereby the main equations to develop the model will be:

- The mass continuity equations for axisymmetric, steady state incompressible flow

$$\frac{1}{r}\frac{\vartheta}{\vartheta_r}(r\rho u_r) + \frac{\vartheta}{\vartheta_z}(\rho u_z) = 0 \qquad \textit{Equation 9}$$

where

$\mathbf{r = Radial\ coordinate}$

$\boldsymbol{\rho} \mathbf{= Density}$

$\mathbf{u_r = Radial\ velocity\ component}$

$\mathbf{z = Axial\ coordinate}$

$\mathbf{u_z = Axial\ velocity\ component}$

- The Navier-Stokes Equations to calculate momentum of the jets

$$\rho\left(\frac{\vartheta\vec{u}}{\vartheta t} + \vec{u}\cdot\nabla\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \rho\vec{g} \qquad \textit{Equation 10}$$

where

$\boldsymbol{\rho} \mathbf{= Density}$

$\vec{\mathbf{u}} \mathbf{= Velocity\ vector}$

$\frac{\vartheta\vec{\mathbf{u}}}{\vartheta \mathbf{t}} \mathbf{= Local\ (unsteady)\ acceleration}$

$\vec{\mathbf{u}} \cdot \nabla \vec{\mathbf{u}}$

$=$ **Convective acceleration (nonlinear term)**

$-\nabla \mathbf{p} =$ **Pressure gradient**

$\mu \nabla^2 \vec{\mathbf{u}}$

$=$ **Viscous diffusion (Laplacian of velocity)**

$\rho \vec{\mathbf{g}} =$ **Body force**

- Energy equations to calculate the thermal effects of the flame jet

$$\rho c_p \left(\frac{\vartheta T}{\vartheta t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + \dot{q}_{comb} \qquad \textit{Equation 11}$$

where

$\rho =$ **Density**

$c_p =$ **Specifc heat at constant pressure**

$T =$ **Temperature**

$\vec{\mathbf{u}} =$ **Velocity vector**

$\frac{\vartheta T}{\vartheta t} =$ **Local (unsteady) temperature change**

$\vec{\mathbf{u}} \cdot \nabla T =$ **Convective heat transfer**

$\nabla \cdot (k \nabla T) =$ **Thermal conduction (Fourier's law)**

$k =$ **Thermal conductivity**

$\dot{q}_{comb}$
$=$ **Volumetric heat release rate due to combustion**

Fireball Model

A fireball model focuses on modeling the transient, spherical, ignited, dispersant propagation of a volume of hot gases. Basic characteristics of the fireball model revolve around combustion, air mixing of rapidly released fuels, and thermal radiation and combustion. Principle equations include:

- Energy Balance for released fuel

$$E = m_f \cdot \Delta H_c \qquad \textit{Equation 12}$$

where

E $=$ **Total energy released by combustion**

m_f $=$ **Mass of fuel burned**

ΔH_c
$=$ **Heat of combustion or enthalpy of combustion**

Attenuated with fireball efficiency factors

$$E_{fireball} = \eta \cdot E \qquad \textit{Equation 13}$$

where

$E_{fireball}$
$=$ **Energy that goes into forming the fireball**

η $=$ **Efficiency factor**

$\mathbf{E}$ = Total energy released by combustion

- Thermal Radiation from the ignited cloud based on heat flux equations such as the Stephan Boltzmann equation

$$q^{\eta} = \varepsilon \cdot \sigma \cdot T^4 \qquad \textit{Equation 14}$$

where

$\mathbf{q^{\eta}}$ = Radiative heat flux

$\boldsymbol{\varepsilon}$ = Emissivity of the surface

$\boldsymbol{\sigma}$ = Stefan − Boltzmann constant

$\mathbf{T}$ = Absolute temperature

- Buoyant rise and expansion of the fireball
- Duration and Diameter modeling of the fireball

Chapter Four

Results, Discussion, Recommendations, and Conclusions

4.1 The Study's Results

a. Statistical Analysis

The statistical analysis focused on generating meaningful inputs to the transportation risk analysis based on published General Directorate of Traffic (GDOT) statistics for road accidents for the years 2018-2022.

The average number of accidents by vehicle type was calculated for the period between 2018 and 2022. This was primarily done to inform the study on the relative contribution of heavy vehicle accidents to the overall accident rate in the Kingdom of Bahrain. The average number of heavy vehicle accidents over the selected 5 year period is 115.33 accidents per year. Average number of incidents involving heavy vehicles make up approximately 7.7% of the total average rate of incidents.

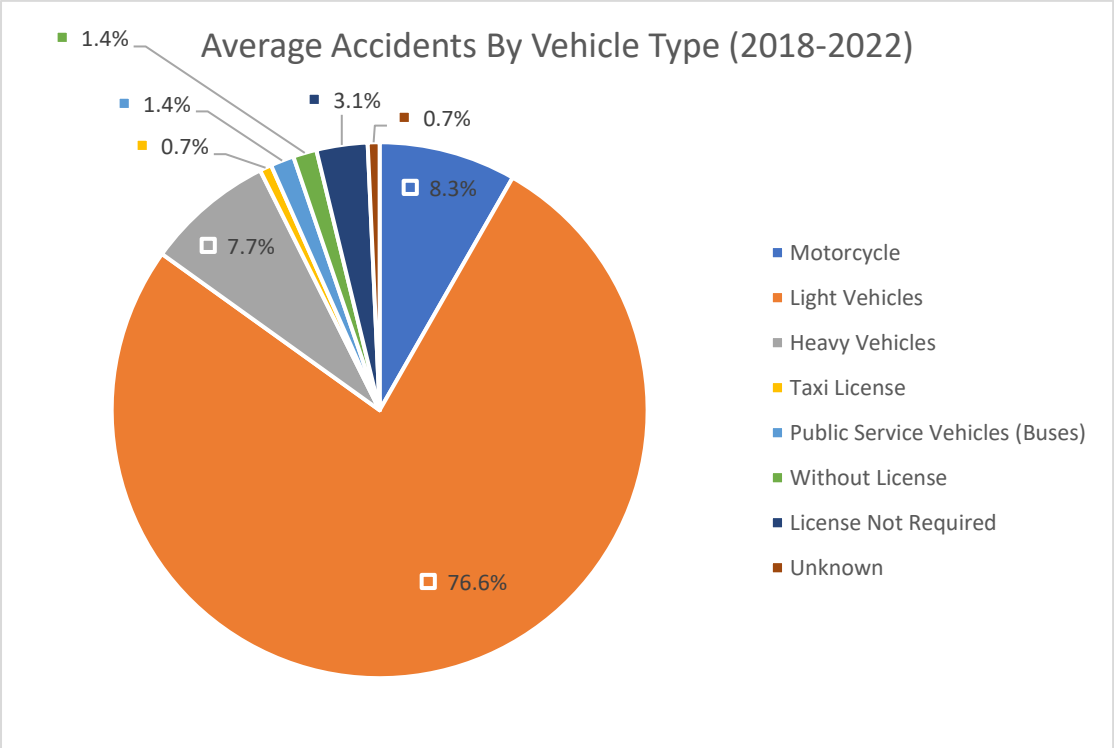


Fig. 13: Average Accidents By Vehicle Type (2018-2022)

After selection of the highways to be considered in the analysis and measuring their lengths and the lengths of the segments pertaining to them as

shown in Table (5), the average rate of accidents per highway was calculated based on the GDOT statistics. Consequently, the average rate of accidents per segment was calculated. Those accident rates per highway and per segment can be considered the main outcomes of the frequency analysis. The average rate of accidents per highway is summarized in the bar diagram shown in Figure 15. To note that the average rate of accidents for the "Other Roads" category has been excluded from the diagram as it is significantly larger than all other highways. This is understandable considering the much larger overall length of the "Other Roads" category.

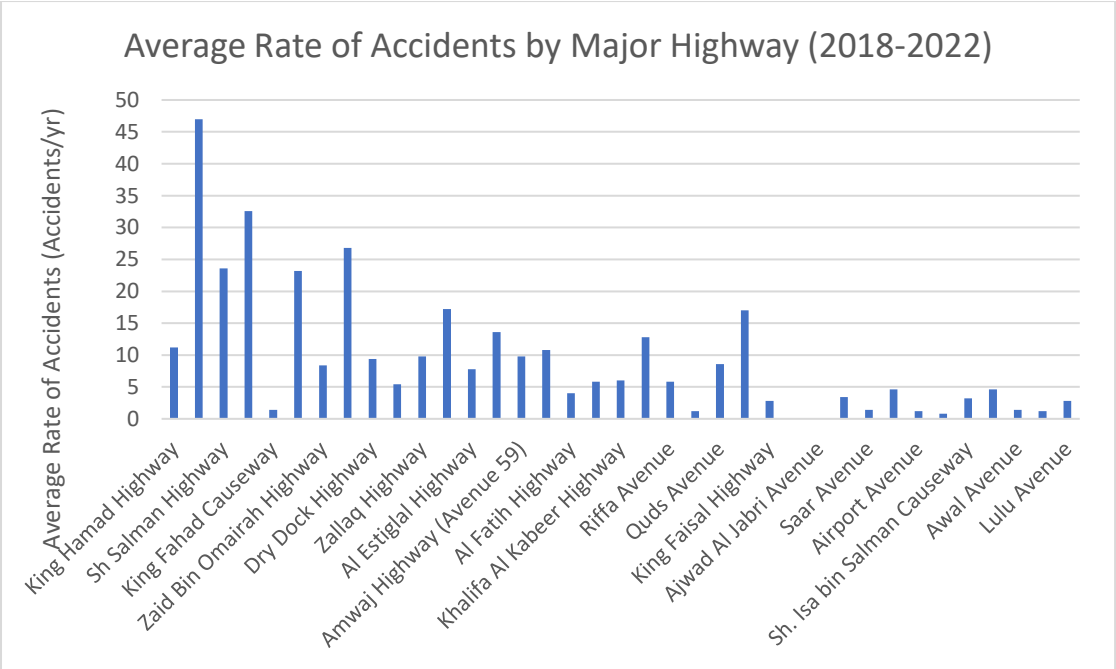


Fig. 14: Average Rate of Accidents by Major Highway (2018-2022)

The total length of highways was measured and summarized as in Fig. 15.

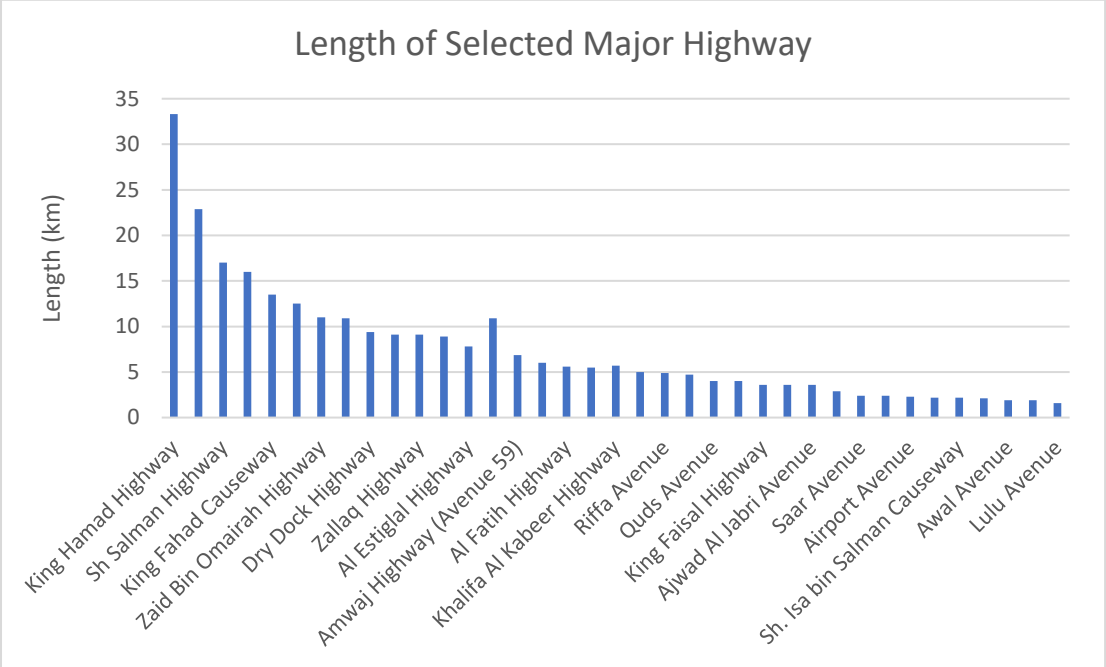


Fig. 15: Length of Selected Major Highways

Early observations can be made at this stage of the frequency analysis upon overlaying the length of the highways and the average rate of accidents as in Fig. 16. It is noted that – in general – longer highways exhibit higher average accident frequencies. Clear exceptions to this observation are “King Fahad Causeway” and “King Hamad Highway”.

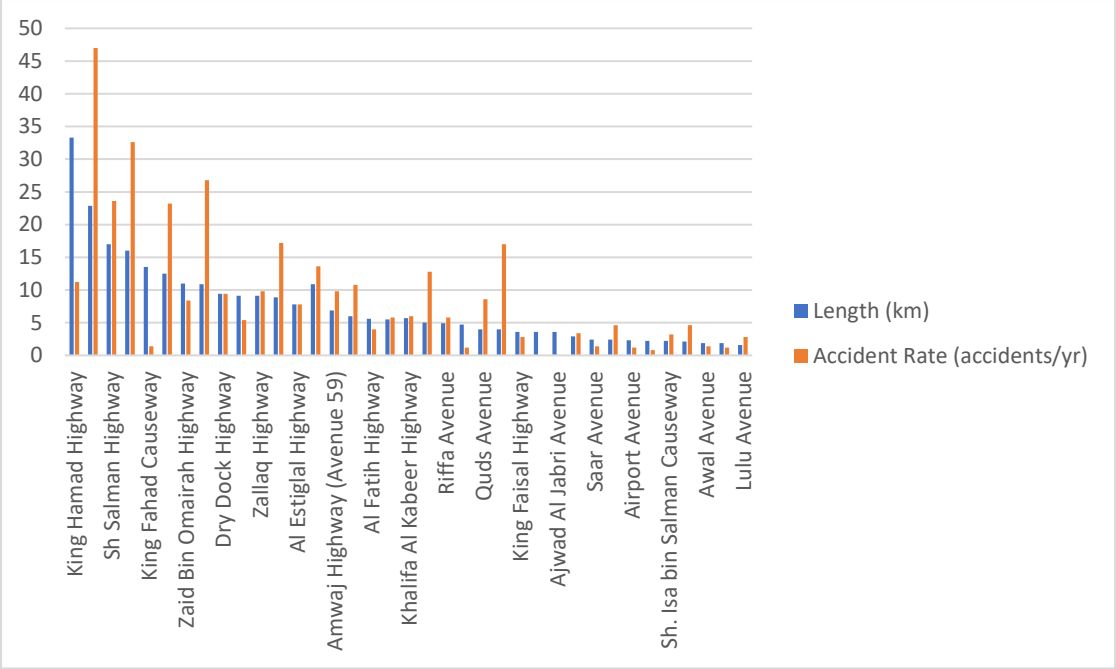


Fig. 16: Length vs. Accident Rate for Selected Major Highways

Highways were subdivided into equal length segments; the list of nodes and segments was displayed. A matrix was constructed to correlate each segment to the highway it belongs to. A horizontal array was added to include the total length of the highway, and a vertical array was added to include the length of each segment.

It was important to calculate a level of use per segment considering the number of times the segment is traversed by a transporting vehicle for delivery to the different locations. This was performed by tallying the number of times a segment is comprised in a route starting at the terminal and ending at the station. Obviously, the segments closest to the distribution terminal (the single source of distribution) showed the highest level of use. Further to the level of use per segment, a typical vehicle kilometers was calculated per segment using an assumed typical annual kilometer rate traveled by a heavy vehicle (120,000 km/yr) multiplied by the normalized length of the segment. Those calculations are the foundations of the likelihood analysis. The calculated level of use and the typical kilometer rate per

segment were multiplied to adjust the kilometer rate to the segments level of use. At this point, each segment has a meaningful level of use calculated for it considering its length and the typical kilometer rate for that segment. To bring the calculations to the same scale, the vehicle kilometer level of use was normalized to the same rate of annual typical kilometer rate of a heavy vehicle (120,000 km/annum). The likelihood analysis was finalized by calculating an annual rate of incidents per segment which is simply the product of the normalized vehicle kilometer level of use per segment and the

Estimating the level of use per segment and normalizing the estimates provides conservative and relatively accurate incident likelihood estimates. The calculated level of use per segment also provides an understanding of which highways and segments are more frequently traversed by fuel transporting vehicles, which in turn provides insight on which segments may be expected to pose higher accident risk. Hence, the incident likelihood by segment shows that incident likelihood is far more pronounced for a small number of segments. By invoking the Pareto Principle, it can be demonstrated that this small number of segments disproportionately contributes to incident likelihood and to overall risk by extension. The top 10 contributing segments to incident likelihood were selected as basis to demonstrate the overall risk. Segment contribution to incident likelihood for the 10 highest contributing segments is shown in Fig. 17.

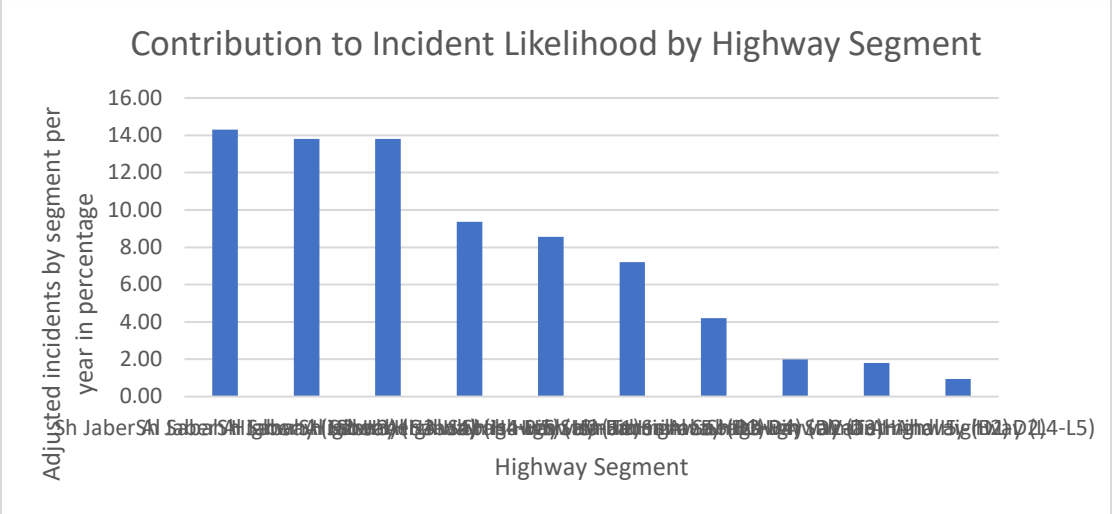


Fig. 17: Contribution to Incident Likelihood by Highway Segment

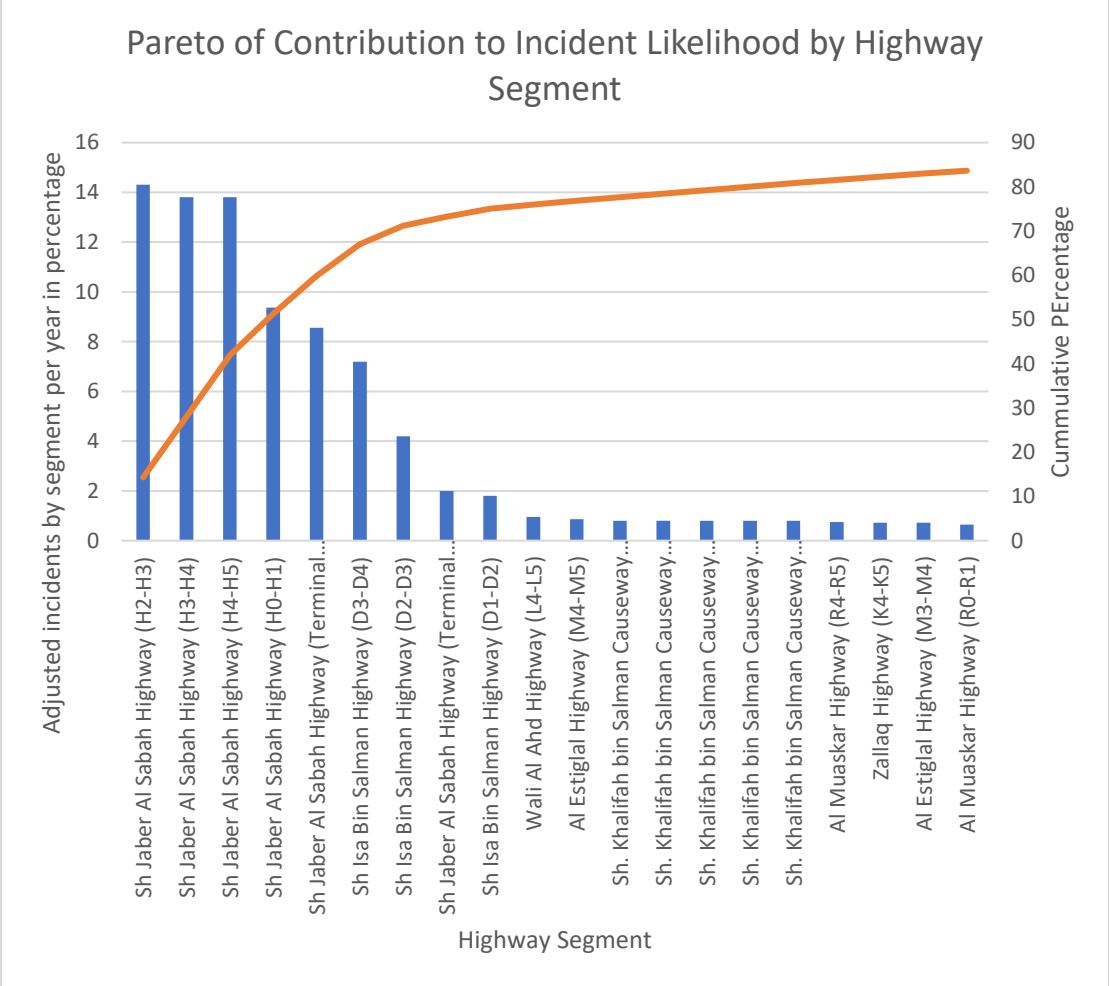


Fig. 18: Pareto of Contribution to Incident Likelihood by highway Segment

Based on the analysis performed, the total contribution to incident likelihood for the top 10 contributing segments accounts for roughly 76% of the total likelihood. The contribution considering the top 20 contributing segments accounts for roughly 83.6% of the total likelihood. Considering the 10 additional segments – though important in its own merit – does not necessarily add value to this study and hence the top 10 contributing segments were found to suffice. Additionally, it is noted that the top 10 contributing segments pertain to only a few highways; namely, Shaikh Jaber Al Sabah Highway, Shaikh Isa Bin Salman Highway, and Wali Al Ahd Highway. Shaikh Jaber Al Sabah Highway segments represent 61.8% of total incident likelihood and 81.4% of the top 10 segments likelihood. This further indicates that Shaikh Jaber Al Sabah Highway is likely the highest risk highway based on the fact that incident likelihood is highest on this highway.

The likelihood of an incident by segment is shown in Fig. 19. The likelihood for an incident on Shaikh Jaber Al Sabah segments was found to be the highest. To also note that all segments comprising the Shaikh Jaber Al Sabah highway are among the top 10 contributing segments and therefore have the highest likelihood of incidents.

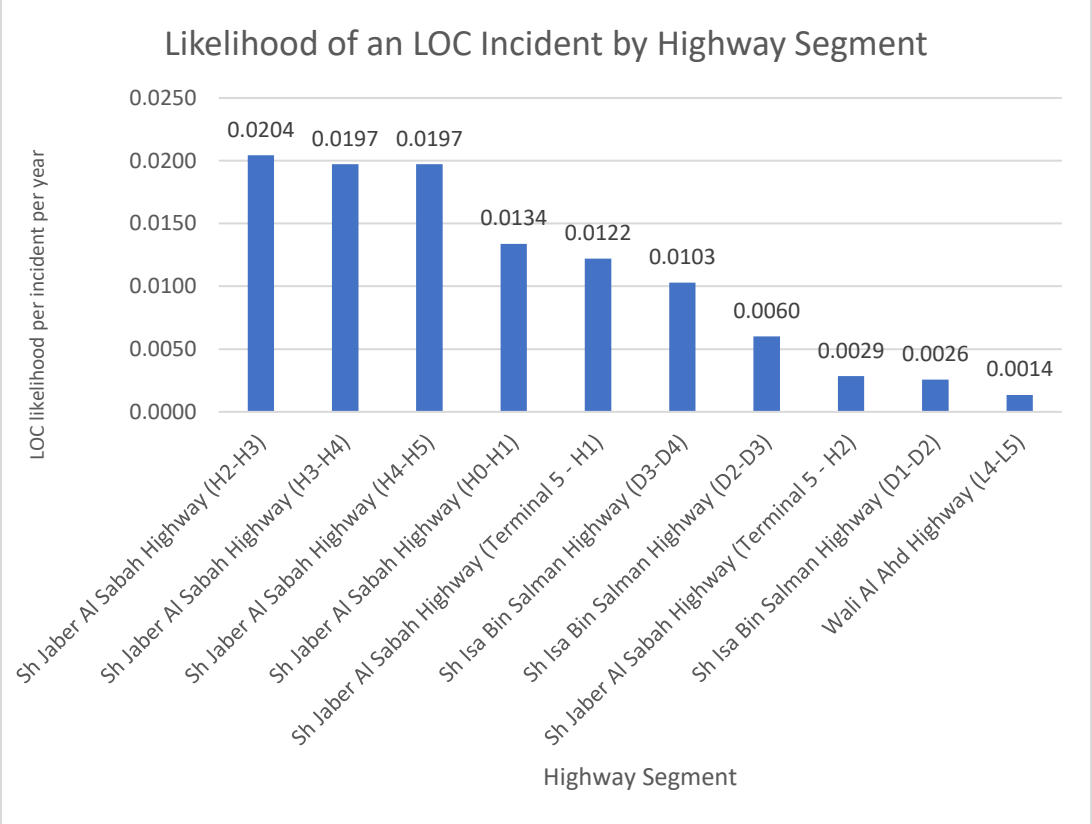


Fig. 19: Likelihood of an LOC Incident by Highway Segment

b. Frequency considering the probability of LOC

Incident likelihood predicts the rate at which future accidents may occur. Not all LOCs lead by necessity to fire or explosion. The likelihood of an incident leading to an LOC was quantified using an assumed frequency of LOC incidents (1 LOC incident in 7 years). The incident likelihood was further adjusted to determine the likelihood of LOCs leading to fire, by combining with the probability of ignition. The probability for direct ignition given an LOC from a road tanker in an instantaneous release event is taken to be P=0.4 in accordance with guidance from the “Purple Book”. Note that this probability is also the probability for delayed ignition from a motor vehicle point source as per the “Purple Book” as well. Guidance in the purple book is provided for calculating the probability of ignition for a road or transportation route by considering the length of the road, the average velocity of vehicles on the road, and the number of vehicles

traversing it per hour. Given that this data was not available, only the direct and delayed ignition probabilities of 0.4 were considered in the analysis. The computed likelihood for LOC leading to fire are shown in Fig. 20. The results of the likelihood of LOC leading to fire are similar and consistent with the results of incident likelihood shown previously. This is of course understandable given that the probability of ignition considered for all segments is the same. To point out, however, that the results could differ should the probability of ignition be calculated based on segment length, rate of use, and average velocity of vehicles on that segment.

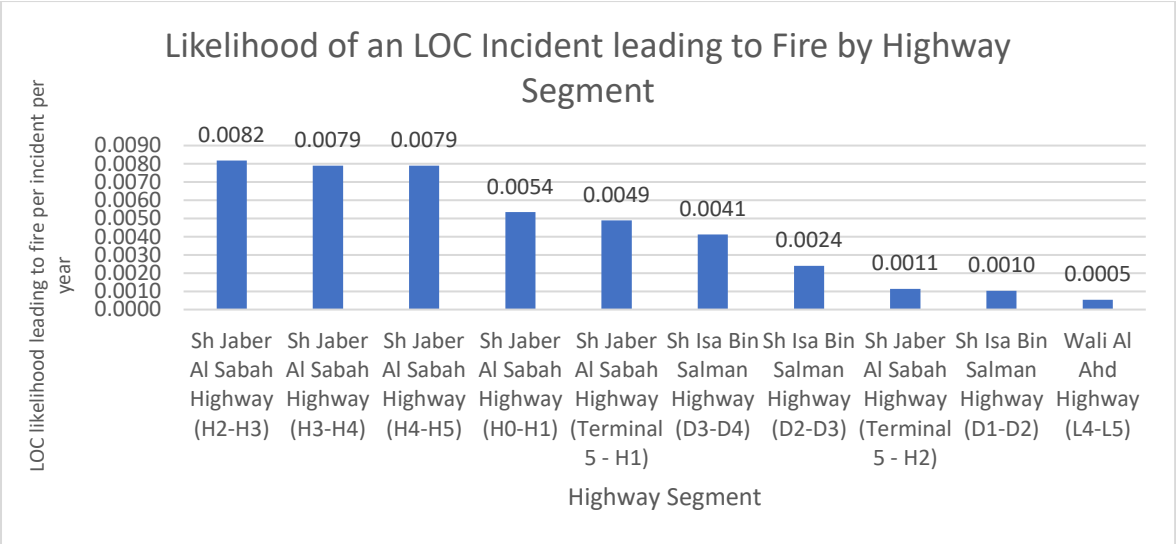


Fig. 20: Likelihood of an LOC Incident leading to Fire by Highway Segment

c. Consequence Results

Receptor height was taken to be 1.72 m which is the average male height in Bahrain for the year 2024 according to world population review (World Population Review, 2024). The consequence analysis results consider the LOC event on the identified top 10 contributing segments to incident likelihood. Sensitivity cases were considered by assuming different release orifice radii (100 mm and 25 mm) as mentioned earlier in this study.

Scenarios were created to study the release form both a gaseous hydrogen transport tanker and a liquid hydrogen transport tanker. Different initial conditions impact the phase of the release and thus impact the development of the consequence.

The iterations performed for each segment are summarized in the following table:

Table (7): Consequence Analysis Scenarios

Sr.	**Scenario Iteration Per Segment**
1	*TANKER TRUCK – 100 MM – GH2*
2	*TANKER TRUCK – 25 MM – GH2*
3	*TANKER TRUCK – 100 MM – LH2*
4	*TANKER TRUCK – 25 MM – LH2*

Additionally, different release angles from said orifices were studied in models where the angle impacts the progression of a release in order to consider the different modalities of rupturing of the transport vehicle's shell. A release angle of 45° was assumed to cover cases where the rupture (orifice) exists in the upper half of the cylindrical vessel. Such a release angle could be due to collision with another heavy vehicle that is as high or higher than the hydrogen fuel transporter, collision against stationary objects such as crossing bridges or other objects, or due to flying debris as a result of other incidents or inclement weather conditions. A release angle of 0° was considered to capture cases in which the rupture is approximately at the equator of the shell. Such ruptures can occur due to approximately the same reasons as the ones listed for ruptures in the upper half of the shell. Last but not least, a release angle of -45° was considered to capture ruptures in the lower half of the transporter's shell. Such ruptures can occur

due to collision with light vehicles or other smaller users of the road. Additionally, they may occur due to rollover or self-inflicted incidents.

The results of the consequence analysis are hereby displayed by model and for the different sensitivity cases considered.

i. Gaseous Hydrogen Release Scenarios

For models involving the release of gaseous hydrogen, the ideal nozzle model was used to calculate the release conditions from either a 100 mm or a 25 mm orifice. The ideal nozzle model models the isentropic flow of a fluid through an orifice or an ideal nozzle. The results show that the release is choked for either orifice size, and the release conditions aside from the flowrate are identical for both orifices. The results are summarized in Table (8) for the 100 mm orifice followed by the results of the consequence models performed assuming the results of this ideal nozzle calculation.

Ideal Nozzle Model: Gaseous Hydrogen, 100 mm orifice

Table (8): Ideal Nozzle Model Inputs and Outputs – 100 mm Orifice

Model Input	**Value**
Initial Temperature (°C)	50.00
Intital Pressure (barg)	500.00
Initial Flow Velocity (m/s)	0.00
Ambient Pressure (barg)	0.00
Flow Area (m^2)	0.007854
Flow diameter (m)	0.10
Overall discharge coefficient	0.62
Model Output (Results)	**Value**
Discharge Temperature (°C)	-12.19
Discharge Pressure (barg)	237.50 (Flow is Choked)

Mass Flow Rate (kg/s)	136.51
V/F Molar Ratio	1.00

Assuming the tanker contains 3500 kg of hydrogen, and given the release rate of 136.51 kg/s, the duration of the release is calculated to be 26.5 seconds and was rounded up to 30 seconds in the following models. A very fast release of the entire tanker inventory can be expected as such.

Ideal Nozzle Model: Gaseous Hydrogen, 25 mm orifice

The results are summarized in Table (9) for the 25 mm orifice followed by the results of the consequence models performed assuming the results of this ideal nozzle calculation.

Table (9): Ideal Nozzle Model Inputs and Outputs - 25 mm Orifice

Model Input	**Value**
Initial Temperature (°C)	50.00
Intital Pressure (barg)	500.00
Initial Flow Velocity (m/s)	0.00
Ambient Pressure (barg)	0.00
Flow Area (m^2)	0.00049087
Flow diameter (m)	0.025
Overall discharge coefficient	0.62
Model Output (Results)	**Value**
Discharge Temperature (°C)	-12.19
Discharge Pressure (barg)	237.50 (Flow is Choked)
Mass Flow Rate (kg/s)	8.53
V/F Molar Ratio	1.00

Assuming the tanker contains 3500 kg of hydrogen, and given the release rate of 8.53 kg/s, the duration of the release is calculated to be 410.3 seconds and was rounded up to 415 seconds in the following models.

Vapor Jet Model: Gaseous Hydrogen

The vapor jet model was used to analyze both the ignited and unignited release of pressurized gaseous hydrogen fuel. This model is used to simulate the dispersion of a gaseous release resulting in the formation of a jet. The model is typically used to model releases from high pressure sources. The model uses the gas expansion model given that the release pressure is higher than ambient pressure. Depending on the release angle, the model depicts the direction of the jet. The vapor jet model is based on the Ooms formulae.

Multiple sensitivities were performed at 45°, 0°, and -45° release angles. This was done for both a 100 mm orifice and 25 mm orifice. Model inputs and outputs are provided in Appendix C. Note that the vapor jet model switches to the gaussian model as soon as the dispersion jet hits the ground.

Fireball Model: Gaseous Hydrogen

Another model considered was the Fireball model, whereby the mass of a cloud developed due to the release is taken as the total mass of the inventory as per guidance from the “Purple Book”. The model provides an understanding of the thermal radiation effects considering thermal damage criteria for hydrogen. The Fireball model simulates the effects of a fireball arising from the immediate ignition of an instantaneous release of a pressurized and flammable material from a failed vessel. Fireballs often follow BLEVEs and are a time dependent consequence. Thermal radiation

distances and dosages are main outputs of the model and ae compared against thermal damage criteria defined for the model as previously mentioned.

Model inputs and outputs are provided in Appendix C.

Gas Flame Jet: Gaseous Hydrogen

Next the Gas Flame Jet model was considered. This model differs from the vapor flame jet model in that it immediately considers the effects of an initially ignited flare or jet. This model is thus more depictive of the direct ignition possibility. SuperChems® considers its own built in probit functions to estimate the probability of fatality for the protected and unprotected observers, as well as the probability of first or second degree burns as a result of exposure to the flame jet. SuperChems® also considers the supplied thermal damage criteria for hydrogen to analyze heat flux at different sampling distances. The model inputs and results are displayed here considering a 45° release angle.

Model inputs and outputs are provided in Appendix C.

ii. Liquid Hydrogen Release Scenarios

The ideal nozzle model is not preferred to quantify flow of a cryogenic liquid through an orifice. This is because the release of a cryogenic liquid is expected to instantly flash as it leaves the orifice. To more accurately model the release of the flashing cryogenic liquid hydrogen, the "Pipes Containing Two Phase" model was utilized. The release orifice was modeled as a stub of pipe with a very miniscule length. The release flowrate is constant irrespective of the orifice diameter; and as such, scenarios 3 and 4 in Table (7) were truncated and only one iteration of consequence models was performed.

Pipes Containing Two-Phase model

The flow model produces the maximum capacity flow of a two-phase fluid through a piping element or a piping isometric.

Table (10): Pipes Containing Two-Phase Model Inputs and Outputs - 100 mm Orifice or 25 mm Orifice

Model Input	Value
Initial Temperature (°C)	-253
Intital Pressure (barg)	0.14
Flow diameter (m)	0.10 and 0.025
Model Output (Results)	**Value**
Discharge Temperature (°C)	-253
Discharge Pressure (barg)	0.14
Mass Flow Rate (kg/s)	1.41

The mass flow rate through this exit stub was used as input for the further consequence models. Assuming this flow rate as the steady state flow rate from the orifice, the inventory of 3,500 kg is expected to take 2,482 seconds to completely empty. Conservatively, model durations is taken to be 2,500 seconds.

Two Phase Jet model: Liquid Hydrogen,

The two phase jet model was used to analyze both the ignited and unignited release of liquid hydrogen fuel. This model is used to simulate the dispersion of a two phase release resulting in the formation of a jet. While the model is normally used to simulate release from high pressure sources, and despite the source having a near atmospheric pressure, the flashing of hydrogen upon release may be expected to result in a jet and thus the model was performed.

Multiple sensitivities were performed at 45°, 0°, and -45° release angles.

Model inputs and outputs are provided in Appendix D.

Heavy Gas: Instantaneous

Given the cryogenic condition of liquid hydrogen at the start of the LOC event, the released hydrogen – be it two phase or all vapor – may be extremely cold and thus denser than air. To entertain this possibility, the "Heavy Gas: Instantaneous" model was performed. This model evaluates an instantaneous release of a gas that is heavier than air and models low momentum releases assuming the total cloud mass is known. As with previous models, the total cloud mass is taken to be the total initial mass of hydrogen contained in the tanker, namely, 3500 kg. Model inputs and outputs are provided in Appendix D.

Fireball Model: Liquid Hydrogen

The fireball model was used to model a BLEVE arising from an LOC involving liquid hydrogen inventory.

Model inputs and outputs are provided in Appendix D.

Two Phase Flame Jet model: Liquid Hydrogen

Multiple sensitivities were performed at 45°, 0°, and -45° release angles.

Model inputs and outputs are provided in Appendix D.

d. Risk Results

i. Individual risk

An assumed incident frequency of 1 in 7 years (Peris-Sayol et al., 2016) was used to complete the risk assessment. The likelihood of LOC per incident per year was calculated for the top 10 ranking segments. Furthermore, the likelihood was multiplied by the probability of ignition to quantify the probability of an LOC leading to an ignited event of fire. The probability of ignition was based on the Purple Book for instantaneous events involving road tankers.

The results of the individual risk calculations are summarized in Table (11).

Table (11): Likelihood of LOC per Incident Per Year

Segment	**LOC Likelihood Per Incident Per Year**	**Likelihood of LOC Leading to Fire Per Incident Per Year**
H2-H3	0.0204	0.0082
H3-H4	0.0197	0.0079
H4-H5	0.0197	0.0079
H0-H1	0.0134	0.0054
Terminal 5 – H1	0.0122	0.0049
D3-D4	0.0103	0.0041
D2-D3	0.0060	0.0024
Terminal 5 – H2	0.0029	0.0011
D1-D2	0.0026	0.0010
L4-L5	0.0014	0.0005

Individual Risk contours were plotted and compared to the selected risk acceptance criteria of 1.00E-06, 1.00E-07 and 5.00E-07 incidents/yr. It was found that the individual risk for the various consequence models involving a release form a 100 mm orifice exceed the assumed acceptable limits in their majority.

Overall individual risk contours were plotted for the highest likelihood segment (H2-H3) to visually demonstrate risk versus the acceptability criteria.

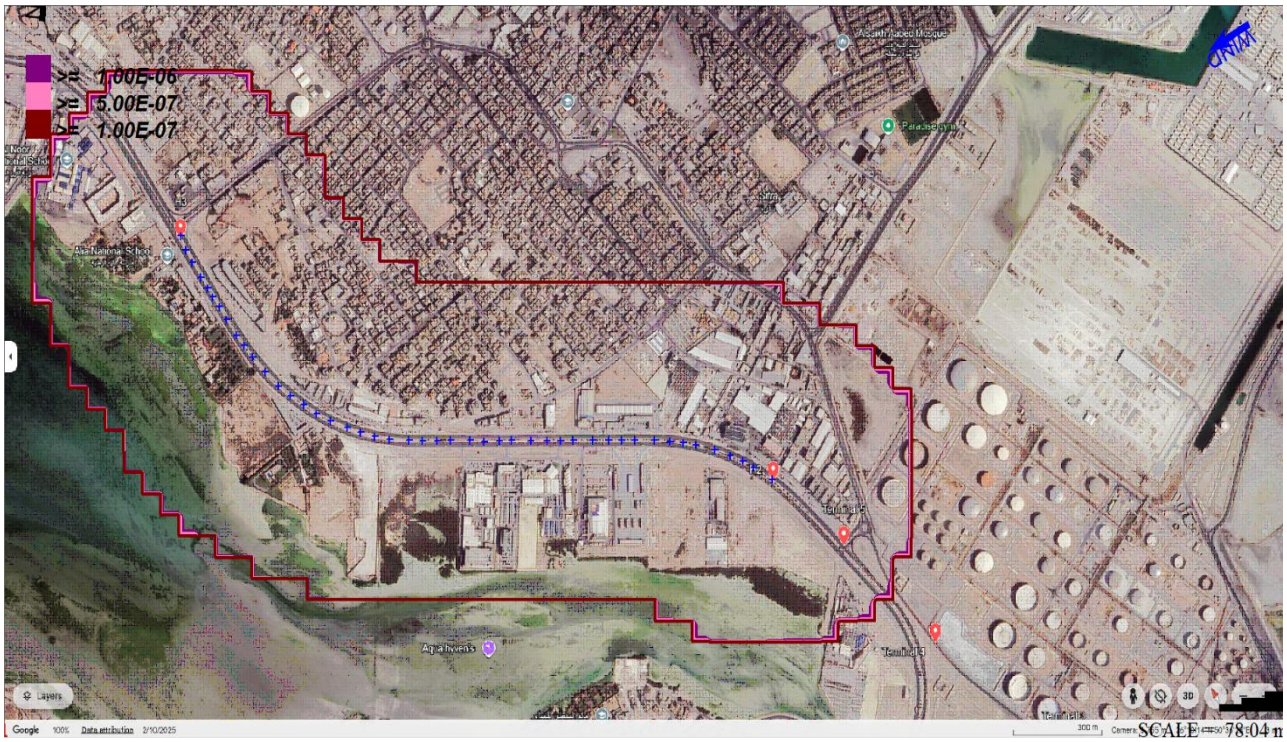


Fig. 21: Overall Individual Risk Contours (H2-H3)

ii. Societal Risk

The probabilities of an ignited LOC impacting an assumed overall (population) occupancy of 500 persons per segment (road and surroundings) was calculated and is summarized in Table (12).

Table (12): Risk of LOC leading to Fire With Occupancy

Segment	Risk with Occupancy
H2-H3	0.0000163
H3-H4	0.0000158
H4-H5	0.0000158
H0-H1	0.0000107
Terminal 5 – H1	0.0000098
D3-D4	0.0000082
D2-D3	0.0000048
Terminal 5 – H2	0.0000023
D1-D2	0.0000021
L4-L5	0.0000011

An F-N Curve is constructed SuperChems® using the calculated risk in Table (12) as the basis and a cumulative rate of fatality. The risk figures are plotted against ALARP risk acceptance criteria as per the UK HSE. It is concluded that most consequences arising from a release from a 100 mm orifice lead to societal risk figures exceeding acceptable ALARP risk and are thus unacceptable.

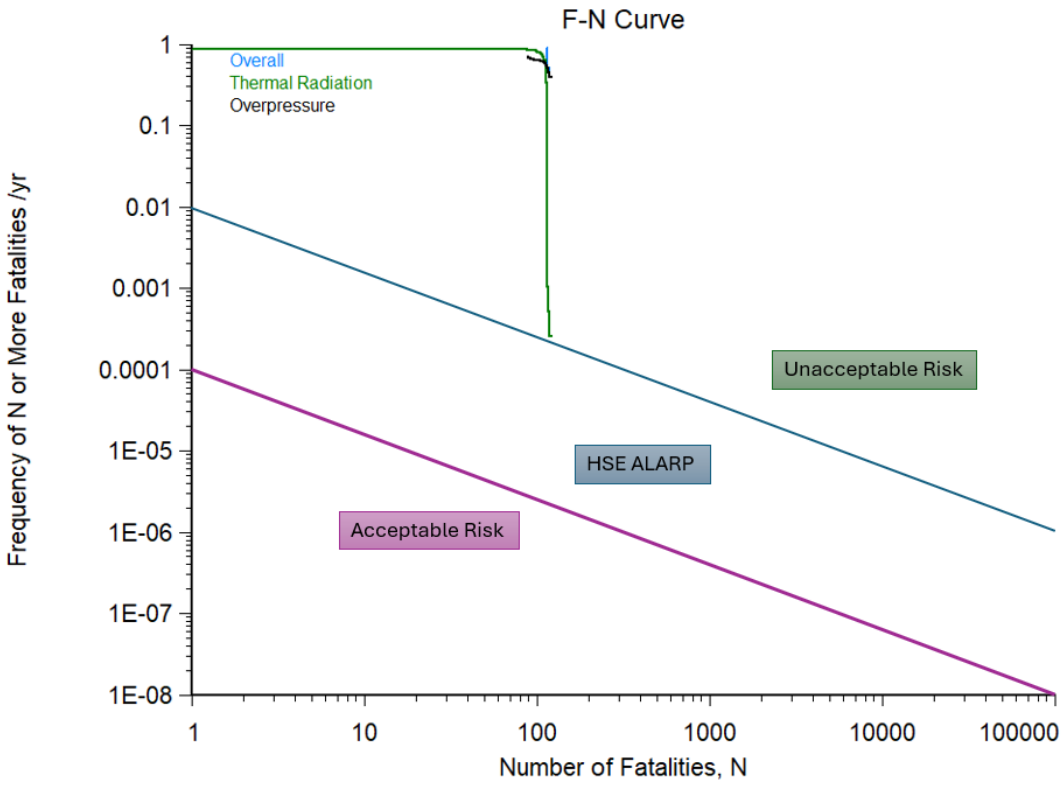


Fig. 22: Societal Risk for Gaseous Hydrogen Transport Scenarios Considering Overall Occupancy for Segment H2-H3

4.2 Discussion and Recommendations

The findings of this study underscore the critical importance of adopting a robust, multi-layered safety framework for the road transportation of hydrogen fuel in Bahrain. The quantitative risk assessment (QRA) revealed that, under current assumptions and configurations, the transportation of compressed gaseous hydrogen (GH2) poses significant individual and societal risks—often exceeding internationally accepted thresholds such as those outlined by the UK HSE and the Dutch Purple Book.

a. Key Observations from the Study

- Gaseous Hydrogen Risks: The scenarios involving GH2 tankers, particularly with larger orifice ruptures (e.g., 100 mm), consistently resulted in unacceptable societal risk levels. This is primarily due to

hydrogen's wide flammability range (4–75% in air), low ignition energy (0.02 mJ), and high flame velocity (up to 3.2 m/s), which significantly increase the probability and severity of jet fires, flash fires, and explosions.

- Liquid Hydrogen (LH2) Scenarios: While LH2 scenarios generally resulted in lower thermal radiation footprints and risk contours, they introduce unique hazards such as cryogenic burns, rapid phase transitions, and BLEVE (Boiling Liquid Expanding Vapor Explosion) potential. These risks are not negligible and require specialized containment and handling protocols.
- Segment-Specific Risk: The study identified that a small number of road segments (e.g., Shaikh Jaber Al Sabah Highway) account for a disproportionately high share of transportation risk. This suggests that targeted interventions on these segments could yield significant safety improvements.

b. Recommendations for Risk Mitigation

i. Encourage Liquid Hydrogen Transportation

Given the lower ignition probability and more manageable dispersion characteristics of LH2, it is recommended that Bahrain prioritize the development of a cryogenic hydrogen transportation infrastructure. This includes:

- Double-walled vacuum-insulated tankers with pressure relief systems.
- Dedicated LH2 unloading bays with spill containment and vapor recovery systems.
- Operator training in cryogenic safety and emergency response.

While liquid hydrogen results in lower individual and societal risks for the considered release scenarios; however, it is not necessarily a conclusive

deduction that the transportation of liquid hydrogen by road can be considered “safe”. Thus, encouraging liquid hydrogen transportation must be accompanied by rigorous engineering controls to manage the risks of cryogenic exposure, rapid vaporization, and BLEVE.

ii. Implementing a Hierarchical Safety Design Philosophy

Following the DNV’s hydrogen safety hierarchy, Bahrain should adopt a three-tiered design strategy:

1. Primary Prevention – Avoid the formation of explosive mixtures:
    - Use leak-tight fittings and hydrogen-compatible materials (e.g., stainless steel, aluminum alloys).
    - Install continuous hydrogen leak detection sensors with real-time telemetry.
    - Ensure adequate ventilation in enclosed or semi-enclosed areas.
2. Secondary Prevention – Avoid ignition sources:
    - Enforce intrinsically safe electrical systems in hydrogen handling zones.
    - Implement static discharge control (e.g., grounding, bonding).
    - Prohibit use of personal electronics near hydrogen transfer points.
3. Tertiary Protection – Mitigate consequences:
    - Design blast-resistant barriers and thermal shielding around high-risk zones.
    - Use automatic shut-off valves and remote isolation systems.
    - Establish emergency venting protocols and safe dispersion zones.

iii. Establish National Hydrogen Safety Codes and Standards

Bahrain currently lacks a unified regulatory framework for hydrogen transportation. It is recommended to:

1. Adopt and localize international standards such as:

- ISO 19880-1 (Hydrogen fueling stations)
- NFPA 2 (Hydrogen Technologies Code)
- SAE J2601 (Fueling protocols for gaseous hydrogen vehicles)

2. Develop a Bahrain Hydrogen Safety Code in collaboration with:
   - Bapco Energies
   - Ministry of Oil and Environment
   - Ministry of Interior's General Directorate of Civil Defense
   - Bahrain Standards and Metrology Directorate

This code should define setback distances, allowable inventory limits, inspection intervals, and emergency response protocols.

iv. Prioritize High-Risk Segments for Infrastructure Upgrades

This study identified that a few road segments contribute to more than 75% of the total transportation risk. These segments and highways should be prioritized for:

- Dedicated hydrogen transport lanes or time-restricted access windows
- Enhanced road maintenance, lighting, signage, and road features upkeep
- Installation of roadside hydrogen sensors and automated incident detection systems

v. Develop a National Hydrogen Incident Database

To support continuous improvement, Bahrain should establish a centralized incident reporting and analysis platform for hydrogen-related events. This database should:

- Collect data on near-misses, leaks, fires, and explosions.
- Enable root cause analysis and trend identification.

- Feed into machine learning models for predictive risk analytics.

c. Strategic Roadmap for Implementation

To practically implement these recommendations, an implementation roadmap is suggested:

1. **Phase 1** – Year 2025-2030 – refine baseline study; run sensitivities; perform techno-economic feasibility evaluation for replacement of fuels with GH2 or LH2
2. **Phase 2** – Year 2030 – Establish Hydrogen Safety Task Force; adopt international code; begin public awareness
3. **Phase 3** – Year 2031-2035 – Upgrade high-risk road segments; pilot hydrogen transportation; train first responders
4. **Phase 4** – Year 2035 – 2040 – Launch national hydrogen incident database; implement smart monitoring systems
5. **Phase 5** – Year 2040-2060 – Scale-up infrastructure; enforce Bahrain Hydrogen Safety Code; integrate with net-zero roadmap and optimize per progress

It is very important to note that there are many more handling related considerations, and many other consequences and hazards that revolve around liquid hydrogen which were not considered in this study. Specifically, the cryogenic temperature for storing the hydrogen, and hereby, the cryogenic temperatures upon release need to be studied and carefully quantified. Cryogenic releases even if unignited can lead to consequences such embrittlement of structures and equipment, frost bites, and possibility for ignition of a settling vapor cloud, all of which are unsafe conditions leading to heightened risk.

It is recommended that further analysis and future studies are performed considering the framework set by this paper to refine the baseline study

further and develop a more detailed and accurate study in the future as more data becomes available. It is also recommended that risk acceptance criteria specific to Bahrain be set by the government rather than depending on criteria that may be exaggerated, unconservative, or inconsistent with the population densities and occupancies in Bahrain. Much more research can be conducted and is recommended in the coming years for safe integration and transportation of hydrogen fuel in Bahrain and its ultimate substitution of Gasoline.

4.3 Concluding Remarks

This thesis aimed to establish a framework for a quantitative risk analysis for the road transportation of hydrogen in the Kingdom of Bahrain considering the Kingdom's net zero targets for the year 2060.Accordingly, a transportation risk analysis was performed assuming the current road network in Bahrain and the existing retail fueling locations. The study was based on an extensive accident frequency and likelihood analysis, detailed consequence modeling, and a combination of the results of the said studies to establish risk figures. The findings indicate that the consequences resulting from LOCs leading to fire from compressed gaseous tankers may result in risk exceeding HSE risk acceptance criteria and ALARP thresholds. While overall individual risk along the highest incident likelihood segments may seem to be acceptable, overall societal risk is far higher than ALARP levels. Additionally, the overall individual risk being acceptable is subject to the selected incident location and may result in residential or commercial facilities falling within the unacceptable risk region. The results of this study reveal that the transportation of both gaseous or liquid hydrogen entails potentially unacceptable risks if done without any mitigating measures and warrant thorough, detailed quantitative investigation of how best to transport hydrogen within the Kingdom of Bahrain.

While this study provides a viable framework for risk analysis on transportation of hydrogen in Bahrain, as the study was limited to the assumptions detailed in section 3.2 and can be significantly enhanced – provided the availability of data – to provide a much more reliable baseline study. To be more specific, the base line study can be enhanced by including sensitivity cases that address most viable transportation configurations to investigate whether the individual and societal risk figures can be brought down to the acceptable regions. Such sensitivities can include considering different initial conditions within the transporting vehicle and reduced transported inventories. Other sensitivities which ought to be considered are the actual occupancies of road segments based on population data for the different governates and highway utilization. Last but not least, this baseline study can be reestablished using actual risk acceptance criteria developed for Bahrain.

This baseline study opens the door and provides incentives to carry out a thorough techno-economic feasibility evaluation of the use of hydrogen as fuel in Bahrain by the year 2060 onwards. This can also be the basis for research on how to optimize fuel transportation inventories and routes using advanced linear or non-linear optimization techniques. Additionally, an in-depth study of the green hydrogen supply chain for the case of Bahrain is required.

All in all, and in light of the net-zero targets for Bahrain, this study provides great insight on the risks associated with hydrogen should it become the fuel of choice and warrants investigation of how to best integrate it such that the public is not endangered, and the safety of the road network is not compromised.

References

1- Ahmed, A. A., Al Labadidi, M., Hamada, A. T., & Orhan, M. F. (2022). Design and utilization of a direct methanol fuel cell. *Membranes, 12*(12), 1266. https://doi.org/10.3390/membranes12121266

2- Ajanovic, A., Sayer, M., & Haas, R. (2022). The economics and the environmental benignity of different colors of hydrogen. *International Journal of Hydrogen Energy, 47*(57), 24136–24154. https://doi.org/10.1016/j.ijhydene.2022.05.037

3- American Petroleum Institute (API). (2014). *API Standard 521: Pressure-relieving and depressuring systems*.

4- Arturson, G. (1981). The Los Alfaques disaster: A boiling-liquid, expanding-vapour explosion. *Burns, 7*(4), 233–251. https://doi.org/10.1016/0305-4179(81)90104-2

5- Australian Bureau of Statistics. (2020). *Survey of motor vehicle use, Australia (12-months-ended-30-June-2020)*. https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

6- Aziz, M. (2021). Hydrogen transportation: A comprehensive review. *Energies, 14*(14), 5917.

7- Bahrain Meteorological Directorate. (n.d.). *Meteorological services*. https://www.mtt.gov.bh/content/meteorological-services

8- Bahrain News Agency. (2021, October 24). Bahrain announces intention to bring carbon emissions to net zero by 2060. *BNA*. https://www.bna.bh/

9- Bellis, M. (2021, September 1). Hydrogen fuel cells innovation for the 21st century. https://www.thoughtco.com/hydrogen-fuel-cells-1991799

10- Bhosale, A. C., S. R., S., Ramkumar, R., Choudhury, S. R., & Raghunathan, R. (2020). Phosphoric acid fuel cells. In *Reference module in earth systems and environmental sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-819727-1.00006-6

11- Boyle, R. (1672). *Tracts ... Containing new experiments, touching the relation betwixt flame and air. And about explosions*. Richard Davis.

12- Chemistry LibreTexts. (2023). 18.5: Occurrence, preparation, and compounds of hydrogen. https://chem.libretexts.org

13- Cheng, Q., Zhang, R., Shi, Z., & Lin, J. (2024). Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners. *International Journal of Light-weight Materials and Manufacture, 7*(2), 269–284. https://doi.org/10.1016/j.jlmm.2024.02.002

14- Cryolor. (2024). *Cryolor LH2 brochure*. https://www.cry-olor.com/sites/cryolor/files/2024-06/cryolor-lh2-brochure-01-24.pdf

15- Data.gov.bh. (2024). *07-accidents-classified-by-region*. https://www.data.gov.bh/explore/dataset/07-accidents-classified-by-region

16- DeCamp, W., & Herskovitz, K. (2015). The theories of acci-dent causation. In *Security Supervision and Management: Theory and Practice of Asset Protection* (4th ed., pp. 71–78). https://doi.org/10.1016/B978-0-12-800113-4.00005-5

17- Deng, C., Li, M., Wang, Y., & He, J. (2022). Comparative study of hydrogen storage methods: A review. *International Journal of Hydrogen Energy, 47*(16), 7944–7965. https://doi.org/10.1016/j.ijhydene.2022.02.210

18- Durkin, K., Khanafer, A., Liseau, P., Stjernström-Eriksson, A., Svahn, A., Tobiasson, L., Andrade, T. S., & Ehnberg, J. (2024). Hydrogen-powered vehicles: Comparing the powertrain efficiency and sustainability of fuel cell versus internal combustion engine cars. *Energies, 17*(5), 1085. https://doi.org/10.3390/en17051085

19- Ehiagwina, F. O., Kehinde, O. O., Sidiq, A., Afolabi, L. O., & Olatinwo, I. S. (2022). Fault tree analysis and its modifications as tools for reliability and risk analysis of engineering systems – An overview. *International Journal of Research Publication and Reviews, 3*(1), 383–396.

20- Elkins, J. W. (1999). Chlorofluorocarbons (CFCs). In D. E. Alexander & R. W. Fairbridge (Eds.), *The Chapman & Hall encyclopedia of environmental science* (pp. 78–80). Kluwer Academic. https://gml.noaa.gov/hats/publictn/elkins/cfcs.html

21- Encyclopaedia Britannica. (2023). Hydrogen. In *Britannica*. https://www.britannica.com/science/hydrogen

22- European Industrial Gases Association (EIGA). (2002). *Handbook on hydrogen safety: LH2 safety*. https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf

23- Fan, L., Tu, Z., & Chan, S. H. (2021). Recent development of hydrogen and fuel cell technologies: A review. *Energy Reports, 7*, 8421–8446. https://doi.org/10.1016/j.egyr.2021.09.033

24- Filonchyk, M., Peterson, M. P., Zhang, L., Hurynovich, V., & He, Y. (2024). Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. *Science of the Total Environment, 935*, 173359. https://doi.org/10.1016/j.scitotenv.2024.173359

25- Gauckler, L. J., Beckel, D., Buergler, B. E., Jud, E., Muecke, U. P., Prestat, M., Rupp, J. L., & Richter, J. (2004). Solid oxide fuel cells: Systems and materials. *CHIMIA, 58*(12), 837. https://doi.org/10.2533/000942904777677047

26- Grantham Research Institute on Climate Change and the Environment. (2023). Why is net zero so important in the fight against climate change? *London School of Economics and Political Science*. https://www.lse.ac.uk

27- Green Vehicle Guide. (n.d.). Greenhouse gas emissions. https://www.greenvehicleguide.gov.au/pages/UnderstandingEmissions/VehicleEmissions

28- H2tools. (n.d.). *Basic hydrogen properties chart*. https://h2tools.org/basic-hydrogen-properties-chart

29- Hamada, A. T., Orhan, M. F., & Kannan, A. M. (2023). Alkaline fuel cells: Status and prospects. *Energy Reports, 9*, 6396–6418. https://doi.org/10.1016/j.egyr.2023.09.075

30- Health and Safety Executive [HSE]. (2014). *Unloading petrol from road tankers: Dangerous substances and explosive atmospheres regulations 2002. Approved code of practice* (2nd ed., L133). HSE. https://www.hse.gov.uk/pubns/books/l133.htm

31- Health and Safety Executive [HSE]. (n.d.). ALARP: As low as reasonably practicable. https://www.hse.gov.uk/comah/alarp.htm

32- iFluids. (n.d.). *Road transport risk*. https://ifluids.com.qa/road-transport-risk/

33- International Renewable Energy Agency. (2020). *Global renewables outlook: Energy transformation 2050*. IRENA. https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

34- Kangwanpongpan, T., Makarov, D. V., Cirrone, D., & Molkov, V. (Accepted/In press). LES model of flash-boiling and pressure recovery phenomena during release from large-scale pressurised liquid hydrogen storage tank. *International Journal of Hydrogen Energy*. https://pure.ulster.ac.uk/en/publications/les-model-of-flash-boiling-and-pressure-recovery-phenomena-during

35- Kumar, P. (2013). Fire disaster following LPG tanker explosion at Chala in Kannur (Kerala, India): August 27, 2012. *Burns, 39*(7), 1479–1487. https://doi.org/10.1016/j.burns.2013.04.004

36- Landucci, G., Tugnoli, A., Busini, V., Derudi, M., Rota, R., & Cozzani, V. (2011). The Viareggio LPG accident: Lessons learnt. *Journal of Loss Prevention in the Process Industries, 24*(4), 466–476. https://doi.org/10.1016/j.jlp.2011.04.001

37- Le, T. T., Sharma, P., Bora, B. J., Tran, V. D., Truong, T. H., Le, H. C., & Nguyen, P. Q. P. (2024). Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. *International Journal of Hydrogen Energy, 54*, 791–816. https://doi.org/10.1016/j.ijhydene.2023.12.027

38- Lide, D. R. (Ed.). (2005). *CRC Handbook of Chemistry and Physics* (86th ed.). CRC Press.

39- LibreTexts. (n.d.). Bond energies. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Chemical_Bonding/Fundamentals_of_Chemical_Bonding/Bond_Energies

40- MIT Climate Portal. (2023). How do greenhouse gases trap heat in the atmosphere? https://climate.mit.edu/ask-mit/how-do-greenhouse-gases-trap-heat-atmosphere

41- Nguyen, V. N., & Blum, L. (2016). Reversible fuel cells. In *Compendium of hydrogen energy: Volume 3: Hydrogen energy conversion* (pp. 115–145). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-363-8.00005-0

42- Oxford Business Group. (2022). Bahrain sees challenges and opportunities on the path to carbon neutrality. *OBG*. https://oxfordbusinessgroup.com/

43- Peris-Sayol, G., Payá-Zaforteza, I., Balasch-Parisi, S., & Alós-Moya, J. (2016). Detailed analysis of the causes of bridge fires and their associated damage levels. *Journal of Performance of Constructed Facilities, 31*(3), 04016108. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000977

44- Perry, R. H., Green, D. W., & Maloney, J. O. (1999). *Perry's chemical engineers' handbook* (7th ed.). McGraw-Hill.

45- Planas-Cuchi, E., Gasulla, N., Ventosa, A., & Casal, J. (2004). Explosion of a road tanker containing liquefied natural gas. *Journal of Loss Prevention in the Process Industries, 17*(4), 315–321. https://doi.org/10.1016/j.jlp.2004.05.005

46- Praveen, R. P., Keloth, V., Abo-Khalil, A. G., Alghamdi, A. S., Eltamaly, A. M., & Tlili, I. (2020). An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. *Energy Policy, 147*, 111864. https://doi.org/10.1016/j.enpol.2020.11186

47- Soleimani, A., Hosseini Dolatabadi, S., Heidari, M., et al. (2024). Progress in hydrogen fuel cell vehicles and up-and-coming technologies for eco-friendly transportation: An international assessment. *Multiscale and Multidisciplinary Modeling, Experimental and Design, 7*, 3153–3172. https://doi.org/10.1007/s41939-024-00482-8

48- Teesing. (n.d.). *700 bar hydrogen refueling*. https://teesing.com/en/library/hydrogen/700-bar-hydrogen-refueling

49- Tellez-Cruz, M. M., Escorihuela, J., Solorza-Feria, O., & Compañ, V. (2021). Proton exchange membrane fuel cells (PEMFCs): Advances and challenges. *Polymers, 13*(18), 3064. https://doi.org/10.3390/polym13183064

50- UNECE. (n.d.). *About ADR*. United Nations Economic Commission for Europe. https://unece.org/about-adr

51- U.S. Department of Energy. (n.d.). Hydrogen fuel basics. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

52- U.S. Energy Information Administration. (n.d.). Hydrogen. Retrieved November 27, 2024, from https://www.eia.gov/energyexplained/hydrogen

53- Voelcker, J. (2022, September 26). Hydrogen fuel-cell vehicles: Everything you need to know. *Deassociation*. https://www.deassociation.ca/newsfeed/hydrogen-fuel-cell-vehicles-everything-you-need-to-know

54- Voelcker, J. (2024, April 29). Hydrogen fuel-cell vehicles: Everything you need to know. *Car and Driver*. https://www.caranddriver.com/features/a41103863/hydrogen-cars-fcev/

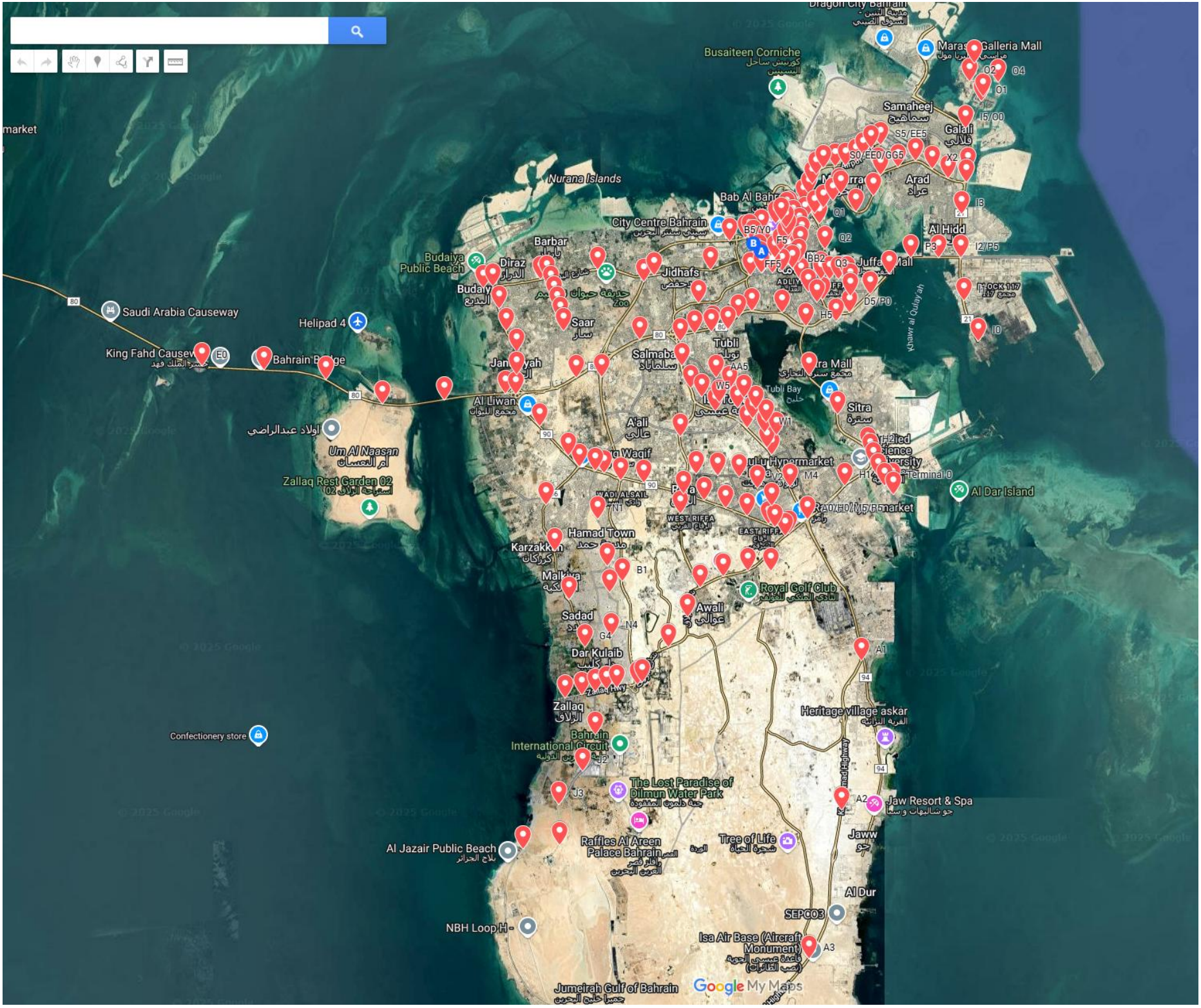
55- Wang, W., Li, J., & Li, Y. (2024). Consumer willingness to purchase hydrogen fuel cell vehicles: A meta-analysis of the literature. *International Journal of Hydrogen Energy, 50*(Part B), 1536–1557. https://doi.org/10.1016/j.ijhydene.2023.07.256

56- World Population Review. (2024). Average height by country 2024. https://worldpopulationreview.com/country-rankings/average-height-by-country

57- Yuh, C., & Farooque, M. (2009). Fuel cells – Molten carbonate fuel cells: Materials and life considerations. In *Encyclopedia*

of Electrochemical Power Sources (pp. 497–507). Elsevier. https://doi.org/10.1016/B978-044452745-5.00270-7

Appendix A – Nodal Map


Busaiteen Corniche
Galleria Mall
Samaheej
Galali
Arad
Nurana Islands
Bab Al Bahr
City Centre Bahrain
Al Hidd
Barbar
Budaiya Public Beach
Diraz
Jidhafs
Budaiy
Saudi Arabia Causeway
Helipad 4
King Fahd Causeway
Bahrain Bridge
Saar
Tubli
Tubli Bay
Sitra
Al Liwan
Salmabad
A'ali
Um Al Naasan
Zallaq Rest Garden 02
Al Dar Island
Hamad Town
Karzakkan
Malkiya
Royal Golf Club
Awali
Sadad
Dar Kulaib
Zallaq
Heritage village askar
Confectionery store
Bahrain International Circuit
The Lost Paradise of Dilmun Water Park
Jaw Resort & Spa
Raffles Al Areen Palace Bahrain
Tree of Life
Jaww
Al Jazair Public Beach
Al Dur
SEPCO3
NBH Loop H
Isa Air Base (Aircraft Monument)
Jumeirah Gulf of Bahrain
Google My Maps

Appendix B – Thermo-Physical Properties of Hydrogen

Table (13): Thermo-Physical Properties of Hydrogen

Properties	Value	Reference
Molecular Weight (g/mol)	2.02	(Perry, Green, & Maloney, 1999)
Lower Heating Value @ 25°C and 1 atm (kJ/g)	119.93	(Lide, 2005)
Higher Heating Value @ 25°C and 1 atm (kJ/g)	141.86	(Lide, 2005)
Viscosity at 20°C and 1 atm (g/cm/sec)	8.813e-5	(Lide, 2005)
Melting Temperature (°C)	-259.2	(Perry, Green, & Maloney, 1999)
Critical Temperature (°C)	-240	(Lide, 2005)
Critical Pressure (MPa)	1.3	(Lide, 2005)
Boiling Temperature at 1 atm (°C)	-252.7	(Perry, Green, & Maloney, 1999)
Density of gaseous hydrogen at 0°C (kg/m^3)	0.08375	(H2tools, n.d.)
Density of liquid hydrogen at -253 °C (kg/m^3)	70.85	(Lide, 2005)

Density of solid hydrogen at -259 °C (kg/m^3)	858	(Lide, 2005)
Critical Density (kg/m^3)	31.2	(Lide, 2005)
Heat capacity of gaseous hydrogen at 0°C (cal/mol.K)	6.84113	(Perry, Green, & Maloney, 1999)
Heat capacity of liquid hydrogen at -256 °C (kJ/kg.°C)	8.1	(Lide, 2005)
Heat capacity of solid hydrogen at -259.8 °C (kJ/kg.°C)	2.63	(Lide, 2005)
Heat of vaporization at -252.7°C (cal/mol)	216	(Perry, Green, & Maloney, 1999)
Heat of fusion at -259.2 °C (cal/mol)	28	(Perry, Green, & Maloney, 1999)
Thermal conductivity at 20°C and 1 atm (W/m-K)	0.1825	(Perry, Green, & Maloney, 1999)
Research octane number (RON)	>130	(Lide, 2005)
Specific gravity of gas hydrogen at 20 °C and 1 atm	0.06948 (A)	(Perry, Green, & Maloney, 1999)

Specific gravity of liquid hydrogen at -253 °C and 1 atm	$0.0709^{-252.7°}$	(Perry, Green, & Maloney, 1999)
Latent heat of vaporization (kJ/kg)	461	(Lide, 2005)
Auto ignition temperature (°C)	500	(H2tools, n.d.)
Specific heat at constant pressure, Cp ta 20°C and 1 atm (J/g-K)	14.29	(H2tools, n.d.)
Specific heat at constant volume, Cv ta 20°C and 1 atm (J/g-K)	10.16	(H2tools, n.d.)
Specific Volume at 20°C and 1 atm (m^3/kg)	11.94	(H2tools, n.d.)
Internal Energy at 20°C and 1 atm (Kj/kg)	2648.3	(H2tools, n.d.)
Ignition energy in air (J)	2e-5	(H2tools, n.d.)
Flame temperature in air (°C)	2045	(H2tools, n.d.)

Standard Net Enthalpy of Combustion (J/kmol) x 1E-09	-0.24182	(Perry, Green, & Maloney, 1999)
Ideal Gas Gibbs Energy of formation (J/kmol) x 1E-07	0	(Perry, Green, & Maloney, 1999)
Ideal Gas Enthalpy of Formation (J/kmol) x 1E-07	0	(Perry, Green, & Maloney, 1999)
Ideal Gas Entropy (J/kmol.K) x 1E-05	1.30571	(Perry, Green, & Maloney, 1999)
Critical Temperature (K)	33.19	(Perry, Green, & Maloney, 1999)
Critical Pressure (MPa)	1.313	(Perry, Green, & Maloney, 1999)
Critical Volume (m^3/kmol)	0.064147	(Perry, Green, & Maloney, 1999)
Acentric Factor	-0.215993	(Perry, Green, & Maloney, 1999)
Diffusivity (m^2/h)	1.697	(EIGA, 2002)

Appendix C – Gaseous Hydrogen Models' Inputs and Outputs

Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle

Table (14): Vapor Jet Model Inputs and Outputs – 100 mm Orifice

Model Inputs	**Value**
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	45°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	66.84
Elevation (m)	62.42
Width (m)	30.68
Projected Jet Area (m^2)	0.23
Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	17.14
Elevation (m)	12.59
Width (m)	7.71
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	154.67

Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	90.83
Time to reach limiting concentration – based on centerline velocity (s)	1.13

Table (15): Vapor Jet Model: Gaseous Hydrogen – 100 mm orifice – 45° Release Angle – Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentration (ppm)
270.34	105.25	151.31	0.64	10000.00
127.70	58.85	102.13	0.35	20000.00
66.84	30.68	62.42	0.23	40000.00
1.34	0.67	2.34	0.01	750000.00

Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle

Table (16): Vapor Jet Model - Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10

Release Rate (kg/s)	136.51
Release Angle (°)	0°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	180.09
Elevation (m)	0.94
Width (m)	38.44
Projected Jet Area (m^2)	1778.41
Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	26.46
Elevation (m)	***-2.88* (ground at zero – N/A result)***
Width (m)	7.75
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	368.04
Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	180.09
Time to reach limiting concentration – based on centerline velocity (s)	2.70

Table (17): Vapor Jet Model: Gaseous Hydrogen – 100 mm orifice – 0° Release Angle – Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentra-tion (ppm)
821.92	156.14	0.00	33222.37	10000.00
393.14	77.72	0.39	7940.41	20000.00
180.09	38.44	0.94	1778.41	40000.00
1.89	0.79	1.00	0.00	750000.00

Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle

Table (18): Vapor Jet Model - Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	**Value**
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	-45°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	206.07
Elevation (m)	0.00
Width (m)	38.69
Projected Jet Area (m^2)	1837.32

Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	39.84
Elevation (m)	***-3.89* (ground at zero – N/A result)***
Width (m)	7.77
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	398.86
Curvilinear Distance to Upper Concentration Limit (m)	2.55
Curvilinear Distance to Lower Concentration Limit (m)	206.69
Time to reach limiting concentration – based on centerline velocity (s)	2.92

Table (19): Vapor Jet Model: Gaseous Hydrogen – 100 mm orifice – -45° Release Angle – Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentration (ppm)
856.22	158.01	0.00	34125.03	10000.00
422.16	78.60	0.00	8198.82	20000.00
206.07	38.69	0.00	1837.32	40000.00
1.92	0.79	0.00	0.00	750000.00

Fireball Model: Gaseous Hydrogen, 100 mm orifice

Table (20): Fireball Model Outputs - Gaseous Hydrogen – 100mm Orifice

Fireball Model Outputs	
Fraction of Combustion Energy Radiated	0.11
Maximum Fireball Diameter (m)	276.330
Maximum Fireball elevation (m)	455.175
Fireball Duration (s)	16.76

Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle

Table (21): Gas Flame Jet Model Inputs and Outputs – 100 mm Orifice – 45° Release Angle

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	45°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**

Flame Jet Length (m)	125.03
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	93.11
Elevation (m)	81.57
Width at 0.1m (m)	43.09
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	25.58
Elevation (m)	18.16
Width (m)	11.52
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	284.50
Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	123.35
Time to reach limiting concentration – based on centerline velocity (s)	2.08

Table (22): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
275.46	225.70	1600.00
189.00	140.79	4000.00
171.35	124.30	5000.00

Table (23): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	114.91	128.25	134.14	191.04
50.00	95.77	108.37	116.78	166.15
99.00	63.28	74.66	87.50	129.97

Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle

Table (24): Gas Flame Jet Model – Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	0°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	275.94
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	270.58
Elevation (m)	0.81
Width at 0.1m (m)	55.31
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	

Downwind Distance (m)	44.13
Elevation (m)	***-4.82* Ground level at 0 m – N/A result***
Width (m)	11.64
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	787.54
Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	270.58
Time to reach limiting concentration – based on centerline velocity (s)	5.77

Table (25): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 0° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
412.21	216.45	1600.00
347.08	128.75	4000.00
336.06	112.36	5000.00

Table (26): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 0° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	304.72	311.18	314.29	348.42
50.00	297.03	301.88	305.58	332.91
99.00	287.79	290.59	294.28	312.08

Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle

Table (27): Gas Flame Jet Model – Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	-45°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	304.34
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	298.1
Elevation (m)	0
Width at 0.1m (m)	55.81
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	

Downwind Distance (m)	60.47
Elevation (m)	***-5.84* Ground level at 0 m – N/A result***
Width (m)	11.67
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	831.15
Curvilinear Distance to Upper Concentration Limit (m)	2.55
Curvilinear Distance to Lower Concentration Limit (m)	299.23
Time to reach limiting concentration – based on centerline velocity (s)	6.09

Table (28): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – - 45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
433.50	212.73	1600.00
370.55	124.70	4000.00
360.02	108.62	5000.00

Table (29): Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – - 45° Release Angle – Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, unprotected. m	Second degree burn. m	First degree burn. m
10.00	330.37	336.44	339.37	371.82
50.00	323.17	327.70	331.17	357.01
99.00	296.77	302.57	320.60	0.00

Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle

Table (30): Vapor Jet Model Inputs and Outputs – 25 mm Orifice

Model Inputs	**Value**
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	45°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	66.84
Elevation (m)	62.42
Width (m)	30.68
Projected Jet Area (m^2)	0.23
Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	17.14
Elevation (m)	12.59
Width (m)	7.71
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	154.67
Curvilinear Distance to Upper Concentration Limit (m)	1.89

Curvilinear Distance to Lower Concentration Limit (m)	90.83
Time to reach limiting concentration – based on centerline velocity (s)	1.13

Table (31): Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentration (ppm)
270.34	105.25	151.31	0.64	10000.00
127.70	58.85	102.13	0.35	20000.00
66.84	30.68	62.42	0.23	40000.00
1.34	0.67	2.34	0.01	750000.00

Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle

Table (32): Vapor Jet Model - Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	**Value**
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	0°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	180.09
Elevation (m)	0.94
Width (m)	38.44
Projected Jet Area (m^2)	1778.41
Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	26.46
Elevation (m)	***-2.88* (ground at zero – N/A result)***
Width (m)	7.75
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	368.04

Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	180.09
Time to reach limiting concentration – based on centerline velocity (s)	2.70

Table (33): Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentration (ppm)
821.92	156.14	0.00	33222.37	10000.00
393.14	77.72	0.39	7940.41	20000.00
180.09	38.44	0.94	1778.41	40000.00
1.89	0.79	1.00	0.00	750000.00

Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle

Table (34): Vapor Jet Model - Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	**Value**
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	-45°
Model Output (Results)	**Value**
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	206.07
Elevation (m)	0.00
Width (m)	38.69
Projected Jet Area (m^2)	1837.32
Concentration (ppm)	40,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	39.84
Elevation (m)	***-3.89* (ground at zero – N/A result)***
Width (m)	7.77
Concentration (ppm)	40,000
Mass Estimates	
Total Mass (kg)	398.86

Curvilinear Distance to Upper Concentration Limit (m)	2.55
Curvilinear Distance to Lower Concentration Limit (m)	206.69
Time to reach limiting concentration – based on centerline velocity (s)	2.92

Table (35): Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Flammable Hazard Zone Estimates

Downwind distance (m)	Width (m)	Elevation (m)	Footprint (m^2)	Concentration (ppm)
856.22	158.01	0.00	34125.03	10000.00
422.16	78.60	0.00	8198.82	20000.00
206.07	38.69	0.00	1837.32	40000.00
1.92	0.79	0.00	0.00	750000.00

Fireball Model: Gaseous Hydrogen, 25 mm orifice

Table (36): Fireball Model Outputs - Gaseous Hydrogen, 25 mm Orifice

Fireball Model Outputs	
Fraction of Combustion Energy Radiated	0.11
Maximum Fireball Diameter (m)	276.330
Maximum Fireball elevation (m)	455.175
Fireball Duration (s)	16.76

Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle

Table (37): Gas Flame Jet Model Inputs and Outputs - 25 mm orifice - 45° Release Angle

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	45°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**

Flame Jet Length (m)	125.03
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	93.11
Elevation (m)	81.57
Width at 0.1m (m)	43.09
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	
Downwind Distance (m)	25.58
Elevation (m)	18.16
Width (m)	11.52
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	284.50
Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	123.35
Time to reach limiting concentration – based on centerline velocity (s)	2.08

Table (38): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
275.46	225.70	1600.00
189.00	140.79	4000.00
171.35	124.30	5000.00

Table (39): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, unprotected. m	Second degree burn. m	First degree burn. m
10.00	114.91	128.25	134.14	191.04
50.00	95.77	108.37	116.78	166.15
99.00	63.28	74.66	87.50	129.97

Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle

Table (40): Gas Flame Jet Model- Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	136.51
Release Angle (°)	0°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	275.94
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	270.58
Elevation (m)	0.81
Width at 0.1m (m)	55.31
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	

Downwind Distance (m)	44.13
Elevation (m)	***-4.82* Ground level at 0 m – N/A result***
Width (m)	11.64
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	787.54
Curvilinear Distance to Upper Concentration Limit (m)	1.89
Curvilinear Distance to Lower Concentration Limit (m)	270.58
Time to reach limiting concentration – based on centerline velocity (s)	5.77

Table (41): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
412.21	216.45	1600.00
347.08	128.75	4000.00
336.06	112.36	5000.00

Table (42): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, unprotected. m	Second degree burn. m	First degree burn. m
10.00	304.72	311.18	314.29	348.42
50.00	297.03	301.88	305.58	332.91
99.00	287.79	290.59	294.28	312.08

Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle

Table (43): Gas Flame Jet Model- Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	50.00
Release Pressure (barg)	500.00
Release Elevation (m)	1.00
Release Diameter (m)	0.025
Release Rate (kg/s)	136.51
Release Angle (°)	-45°
Target Elevation (m)	1.72
Release Duration (s)	30
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	304.34
Exit Velocity (m/s)	601.22
Speed of Sound (m/s)	1371.08
Mach Number	0.44
Centerline Limiting Concentration Estimates	
Downwind Distance (m)	298.1
Elevation (m)	0
Width at 0.1m (m)	55.81
Concentration (ppm)	28,000
Lower Edge Limiting Concentration Estimates	

Downwind Distance (m)	60.47
Elevation (m)	***-5.84* Ground level at 0 m – N/A result***
Width (m)	11.67
Concentration (ppm)	28,000
Mass Estimates	
Total Mass (kg)	831.15
Curvilinear Distance to Upper Concentration Limit (m)	2.55
Curvilinear Distance to Lower Concentration Limit (m)	299.23
Time to reach limiting concentration – based on centerline velocity (s)	6.09

Table (44): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance. m	Maximum 1/2 Cross-wind distance. m	Limiting Flux. W/m^2
433.50	212.73	1600.00
370.55	124.70	4000.00
360.02	108.62	5000.00

Table (45): Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	330.37	336.44	339.37	371.82
50.00	323.17	327.70	331.17	357.01
99.00	296.77	302.57	320.60	0.00

Appendix D – Liquid Hydrogen Models' Inputs and Outputs

Two Phase Jet model: Liquid Hydrogen, 45° Release Angle

Table (46): Two-Phase Jet Model Inputs and Outputs – 100 mm Orifice or 25 mm Orifice - 45° Release Angle

Model Inputs	**Value**
Release Temperature (°C)	-253
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10 and 0.025
Release Rate (kg/s)	136.51
Release Angle (°)	45°
Model Output (Results)	**Value**
Estimated Footprint	
Computed Concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	8.73
Maximum crosswind distance to limiting concentration (m)	2.30
Centerline elevation at limiting concentration (m)	9.36
Time to reach limiting concentration (s)	8.19
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	

Fraction of total mass rained out	0.821
Captured fraction of total mass rained out	0.177
Drop downwind distance (m)	0.229
Liquid mass rainout rate (kg/s)	1.319
Liquid mass capture rate (kg/s)	0.285

Table (47): Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm, 45° Release Angle – Estimated Flammable Footprint

Estimated Flammable Footprint				
Downwind distance to limiting con-centration (m)	Maximum crosswind distance to limiting con-centration (m)	Centerline elevation at limiting con-centration (m)	Computed Concentra-tion (ppm)	Minimum jet temperature (K)
18.59	4.34	14.46	10,000	20.14
12.68	3.23	11.64	20,000	20.14
8.73	2.30	9.36	40,000	20.14
0.52	0.28	1.30	750,000	20.14

Two Phase Jet model: Liquid Hydrogen, 0° Release Angle

Table (48): Two-Phase Jet Model- Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	-253
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10 and 0.025
Release Rate (kg/s)	136.51
Release Angle (°)	0°
Model Output (Results)	**Value**
Estimated Footprint	
Computed Concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	46.98
Maximum crosswind distance to limiting concentration (m)	3.24
Centerline elevation at limiting concentration (m)	2.15
Time to reach limiting concentration (s)	42.05
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	
Fraction of total mass rained out	0.822
Captured fraction of total mass rained out	0.265

Drop downwind distance (m)	0.256
Liquid mass rainout rate (kg/s)	1.321
Liquid mass capture rate (kg/s)	0.426

Table (49): Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm, 0° Release Angle – Estimated Flammable Footprint

Estimated Flammable Footprint				
Downwind distance to limiting con-centration (m)	Maximum crosswind distance to limiting con-centration (m)	Centerline elevation at limiting con-centration (m)	Computed Concentra-tion (ppm)	Minimum jet temperature (K)
122.24	6.93	3.41	10,000	20.14
77.00	4.82	2.77	20,000	20.14
46.98	3.24	2.15	40,000	20.14
0.58	0.23	0.87	750,000	20.14

Two Phase Jet model: Liquid Hydrogen, -45° Release Angle

Table (50): Two-Phase Jet Model- Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	-235
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10 and 0.025
Release Rate (kg/s)	136.51
Release Angle (°)	-45°
Model Output (Results)	**Value**
Estimated Footprint	
Computed Concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	46.11
Maximum crosswind distance to limiting concentration (m)	3.24
Centerline elevation at limiting concentration (m)	2.14
Time to reach limiting concentration (s)	39.98
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	
Fraction of total mass rained out	0.822
Captured fraction of total mass rained out	0.290

Drop downwind distance (m)	0.171
Liquid mass rainout rate (kg/s)	1.320
Liquid mass capture rate (kg/s)	0.465

Table (51): Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm, -45° Release Angle – Estimated Flammable Footprint

Estimated Flammable Footprint				
Downwind distance to limiting con-centration (m)	Maximum crosswind distance to limiting con-centration (m)	Centerline elevation at limiting con-centration (m)	Computed Concentra-tion (ppm)	Minimum jet temperature (K)
121.27	6.96	3.39	10,000	20.14
76.12	4.84	2.76	20,000	20.14
46.11	3.24	2.14	40,000	20.14
0.34	0.21	0.58	750,000	20.14

Heavy Gas: Instantaneous

Table (52): Heavy Gas: Instantaneous Model Inputs and Outputs

Model Inputs	**Value**
Temperature (°C)	-235
Ambient Pressure (barg)	0.00
Vapor to Feed (V/F) mole fraction	0.00
Cloud mass (kg)	3,500
Lower Limiting Concentration (ppm)	40,000
Upper Limiting Concentration (ppm)	750,000
Model Output (Results)	**Value**
Limiting Concentration Reached in Gaussian Regime	
Time required to reach limiting concentration (s)	1047.71
Maximum mass in cloud between upper and lower concentration lim-its (kg)	3080.92
Downwind distance to limiting concentration (m)	1533.65
Maximum cloud radius (m)	50.07
Footprint (m^2)	116,723.90

Fireball Model: Liquid Hydrogen

Table (53): Fireball Model Outputs, Liquid Hydrogen

Fireball Model Outputs	
Fraction of Combustion Energy Radiated	0.11
Maximum Fireball Diameter (m)	109.577
Maximum Fireball elevation (m)	180.497
Fireball Duration (s)	10.56

Two Phase Flame Jet model: Liquid Hydrogen, 45° Release Angle

Table (54): Two-Phase Flame Jet Model, Liquid Hydrogen, 45 release angle

Model Inputs	Value
Release Temperature (°C)	-253
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	1.41
Release Angle (°)	45°
Target Elevation (m)	1.72
Release Duration (s)	2500
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	13.01

Estimated Footprint	
Computed concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	8.73
Maximum crosswind distance to limiting concentration (m)	2.30
Time to reach limiting concentration (s)	8.19
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	
Fraction of total mass rained out	0.821
Captured fraction of total mass rained out	0.177
Drop downwind distance (m)	0.229
Liquid mass rainout rate (kg/s)	1.319

Table (55): Two-Phase Flame Jet: Liquid Hydrogen – 100 m orifice or 25 mm orifice – 45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance (m)	Maximum 1/2 Cross-wind distance (m)	Limiting Flux (W/m^2)
13.97	9.45	1600.00
9.68	5.40	4000.00
8.82	4.69	5000.00

Table (56): Two-Phase Flame Jet: Gaseous Hydrogen – 100 mm or 25 mm orifice – 45° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	25.42	25.92	32.94	38.06
50.00	21.72	22.23	28.70	33.32
99.00	16.22	16.76	22.49	26.25

Two Phase Flame Jet model: Liquid Hydrogen, 0° Release Angle

Table (57): Two-Phase Flame Jet Model- Sensitivity Case (0° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	-253
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	1.41
Release Angle (°)	45°
Target Elevation (m)	1.72
Release Duration (s)	2500
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	48.01
Estimated Footprint	
Computed concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	46.98
Maximum crosswind distance to limiting concentration (m)	3.24
Time to reach limiting concentra-tion (s)	42.05
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	

Fraction of total mass rained out	0.822
Captured fraction of total mass rained out	0.265
Drop downwind distance (m)	0.256
Liquid mass rainout rate (kg/s)	1.321
Liquid mass capture rate (kg/s)	0.426

Table (58): Two-Phase Flame Jet: Liquid Hydrogen – 25 mm orifice – 0° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance (m)	Maximum 1/2 Cross-wind distance (m)	Limiting Flux (W/m^2)
2.58	4.43	1600.00
2.58	1.76	4000.00
2.58	1.22	5000.00

Table (59): Two-Phase Flame Jet: Liquid Hydrogen – 25 mm orifice – 0° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, protected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	55.39	56.21	60.71	65.05
50.00	53.06	53.97	57.65	61.38
99.00	50.53	51.22	53.68	56.42

Two Phase Flame Jet model: Liquid Hydrogen, -45° Release Angle

Table (60): Two-Phase Flame Jet Model- Sensitivity Case (-45° Release Angle) - Model inputs and Outputs

Model Inputs	Value
Release Temperature (°C)	-253
Release Pressure (barg)	0.14
Release Elevation (m)	1.00
Release Diameter (m)	0.10
Release Rate (kg/s)	1.41
Release Angle (°)	-45°
Target Elevation (m)	1.72
Release Duration (s)	2500
Lower Flammability Limit (ppm)	40,000
Upper Flammability Limit (ppm)	750,000
Model Outputs (Results)	**Value**
Flame Jet Length (m)	47.04
Estimated Footprint	
Computed concentration (ppm)	40,000
Downwind Distance to limiting concentration (m)	46.11
Maximum crosswind distance to limiting concentration (m)	3.24
Time to reach limiting concentration (s)	39.98
Minimum jet temperature (K)	20.14
Two-Phase Jet Rainout	

Fraction of total mass rained out	0.822
Captured fraction of total mass rained out	0.290
Drop downwind distance (m)	0.141
Liquid mass rainout rate (kg/s)	1.320
Liquid mass capture rate (kg/s)	0.465

Table (61): Two-Phase Flame Jet: Liquid Hydrogen – -45° Release Angle - Flux Results at 1.72m

Flux at 1.72 m		
Maximum downwind distance (m)	Maximum 1/2 Cross-wind distance (m)	Limiting Flux (W/m^2)
2.58	1.44	1600.00
0.77	1.40	4000.00
0.72	1.04	5000.00

Table (62): Two-Phase Flame Jet: Liquid Hydrogen – -45° Release Angle - Probit Values Downwind Distance at 1.72m

Probit Values Downwind Distance at 1.72 m				
Probability of outcome in %	Fatality, pro-tected. m	Fatality, un-protected. m	Second de-gree burn. m	First degree burn. m
10.00	54.32	55.13	59.69	64.05
50.00	51.98	52.86	56.60	60.36
99.00	49.38	50.08	52.58	55.35

Appendix E – Graphical Results of Consequence Models

Gaseous Hydrogen Release Scenarios:

Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle

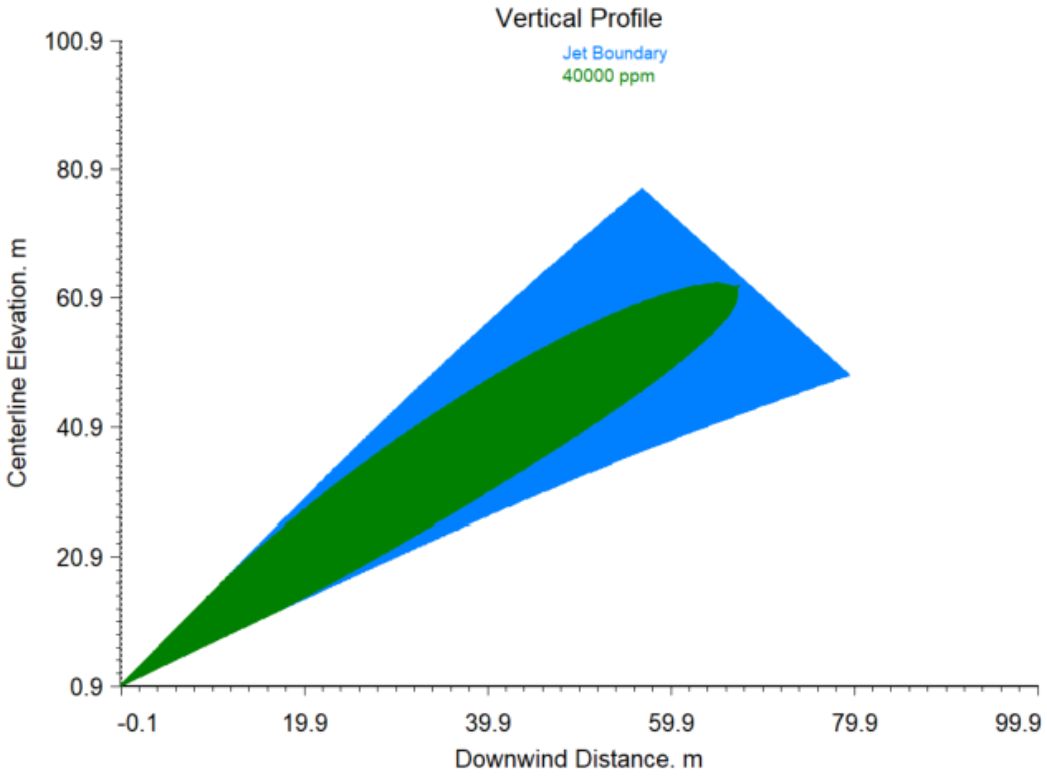


Fig. 23: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle – Vertical Profile

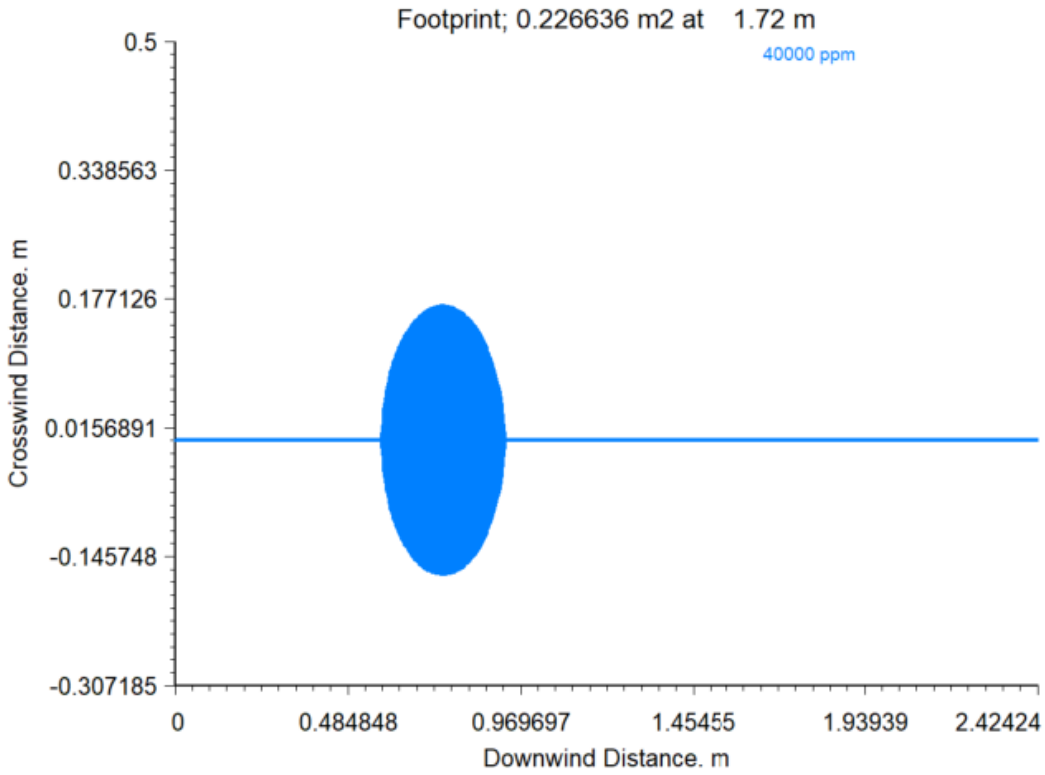


Fig. 24: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Footprint

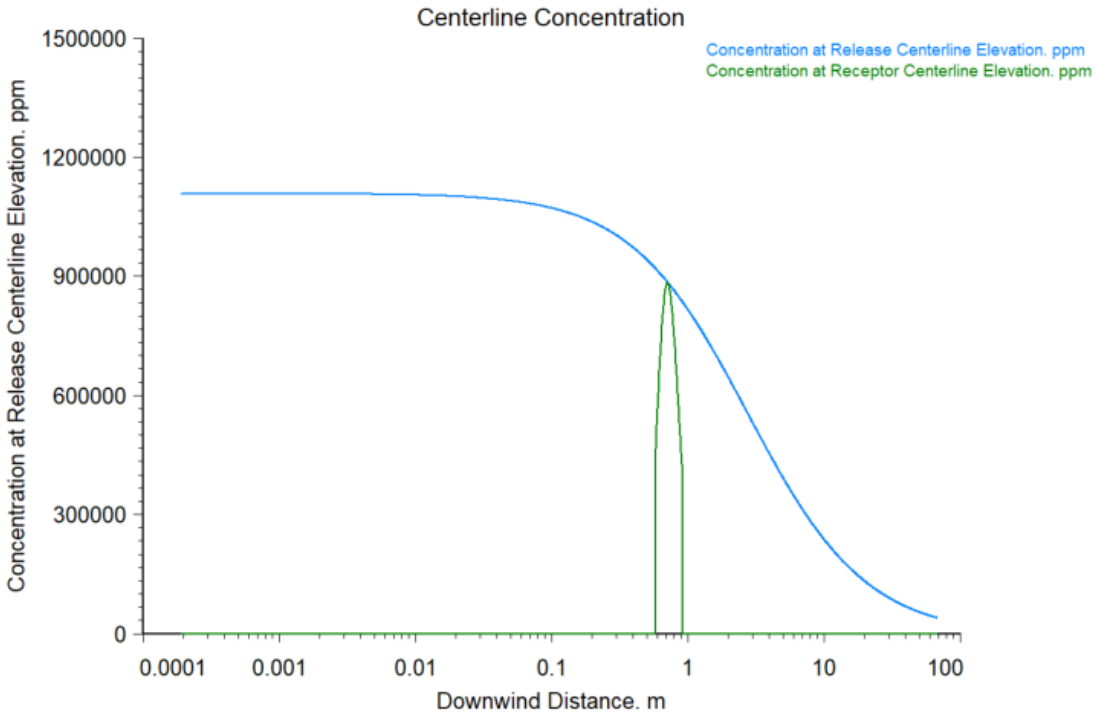


Fig. 25: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Centerline Concentration

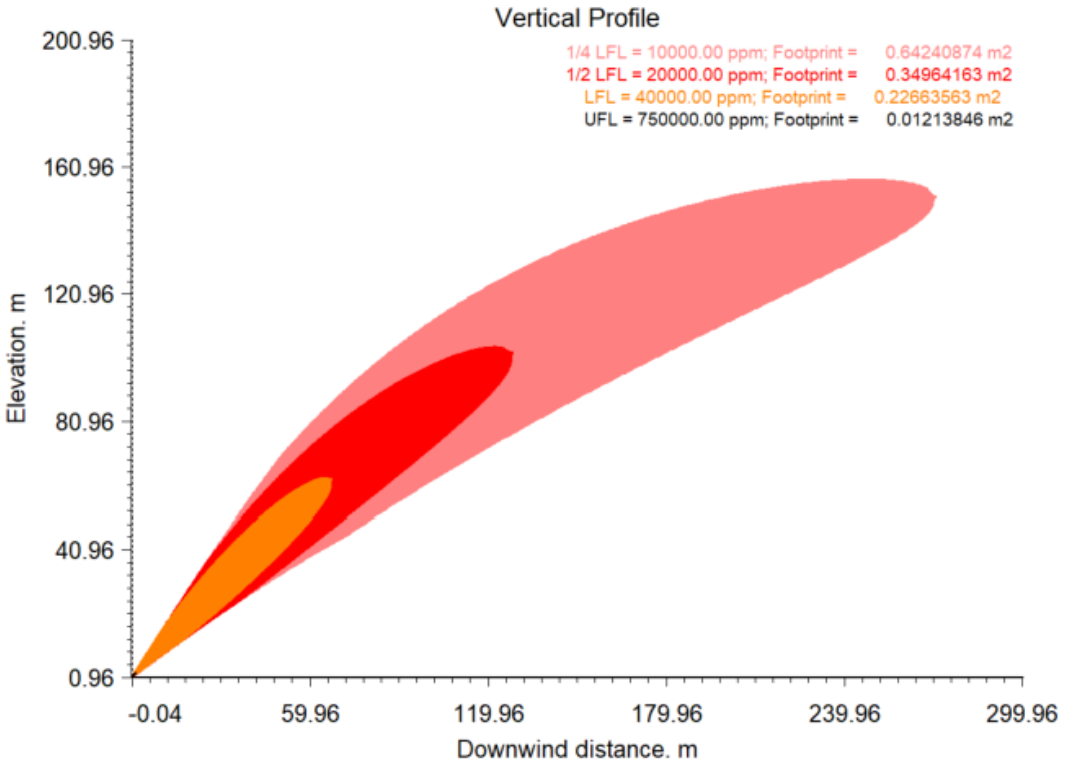


Fig. 26: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Flammable Contours Vertical Profile

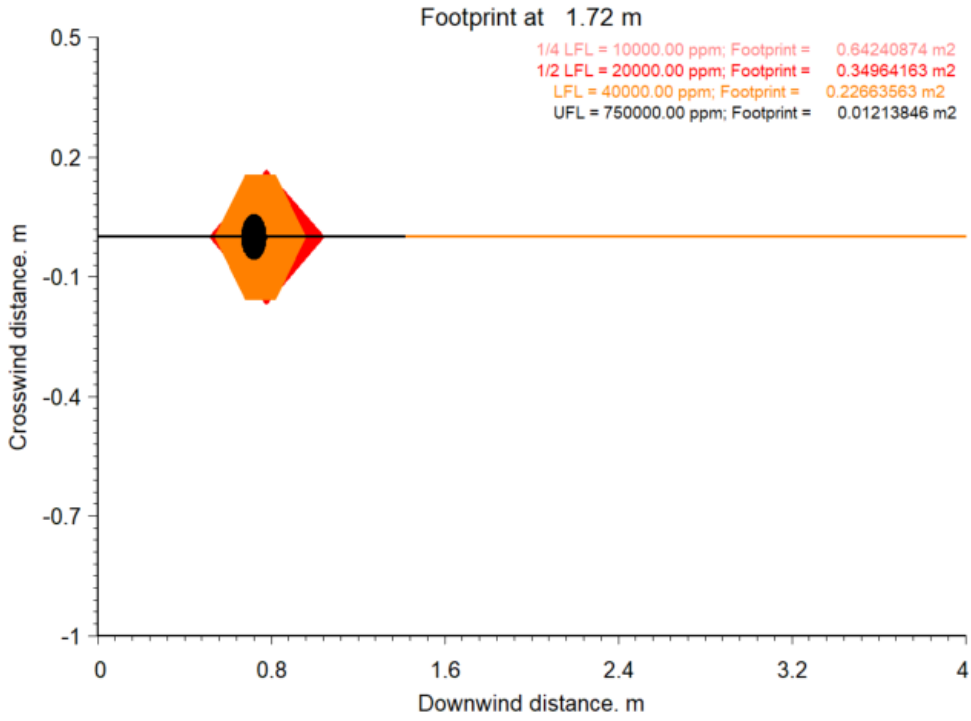


Fig. 27: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Flammable Contours Footprint at 1.72m



Fig. 28: Vapor Jet Consequences - H2-H3 Segment

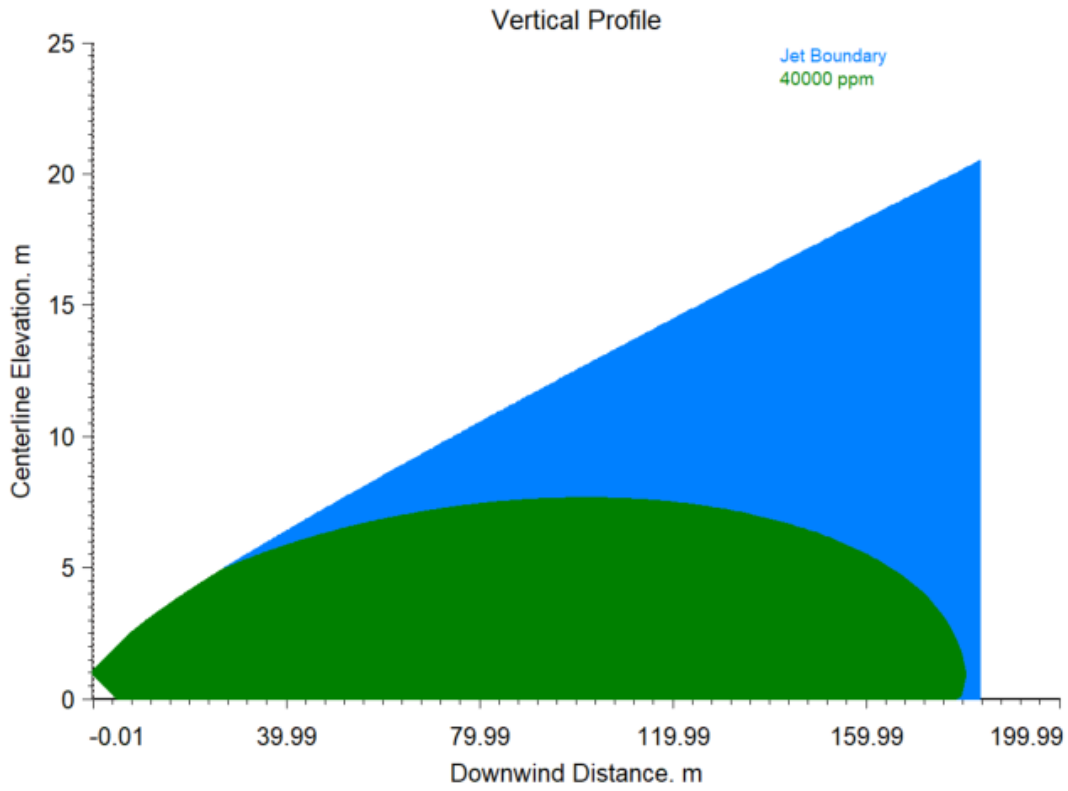


Fig. 29: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Vertical Profile

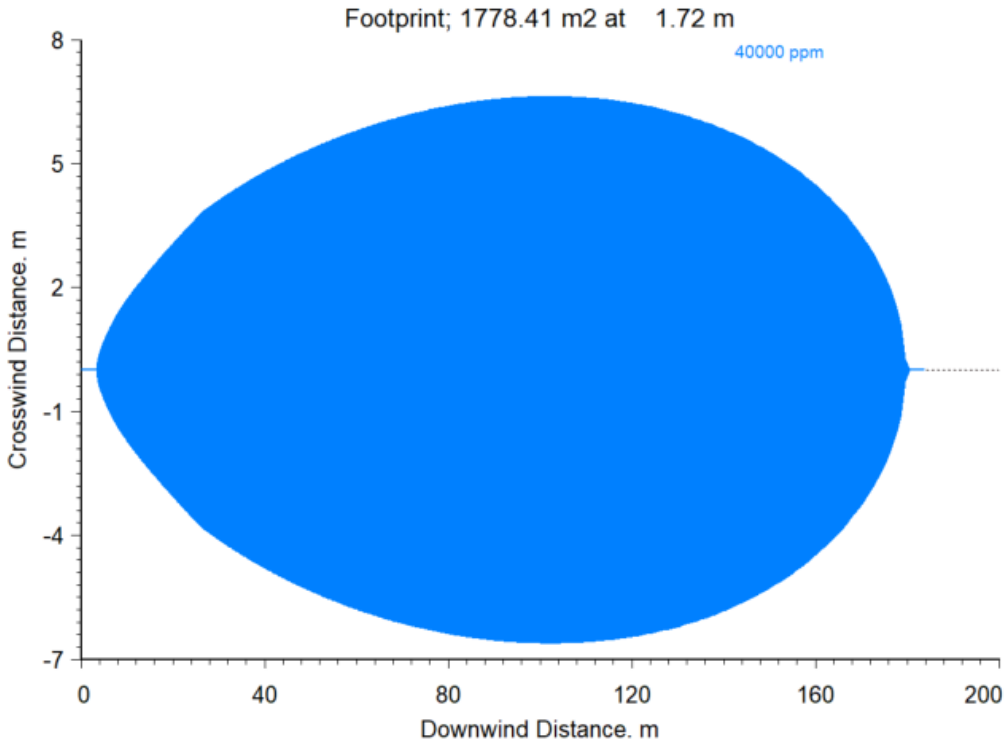


Fig. 30: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Footprint at 1.72m

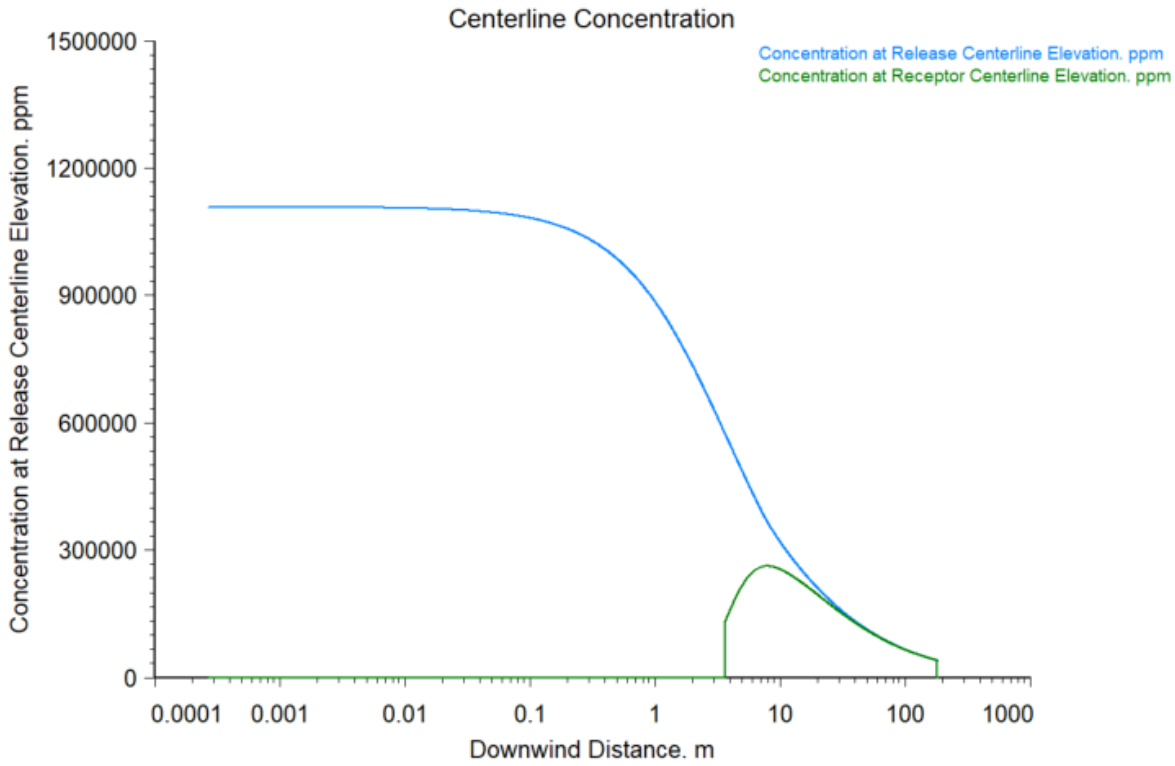


Fig. 31: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Centerline Concentration

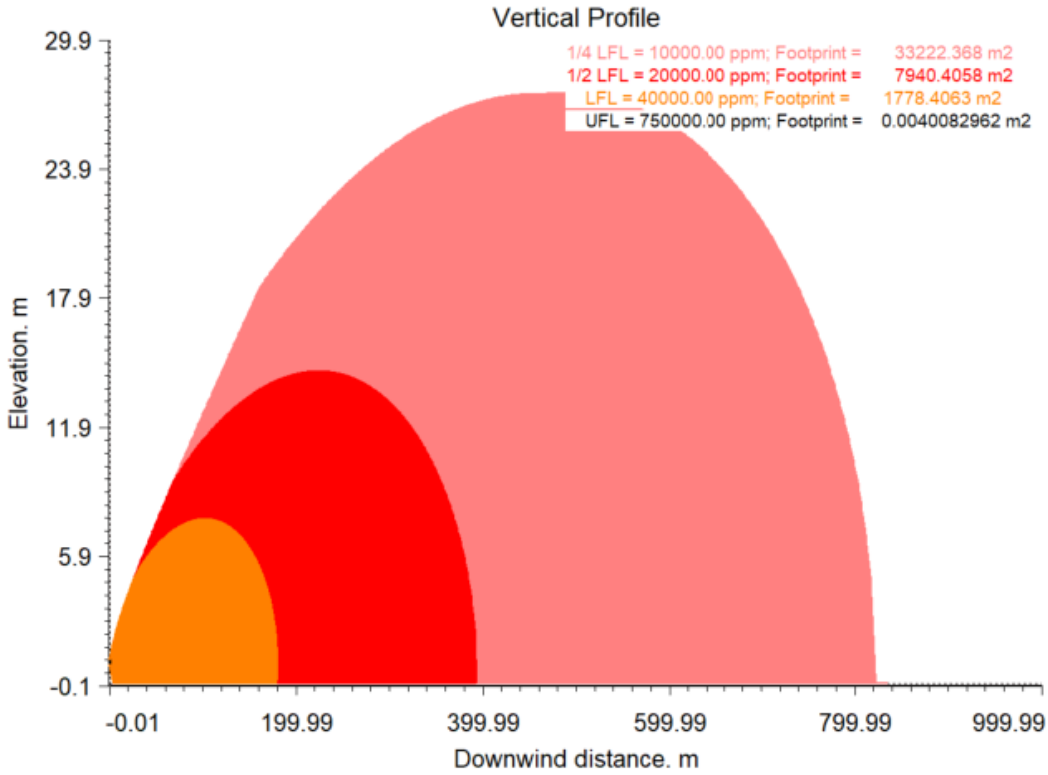


Fig. 32: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Flammable Contours Vertical Profile

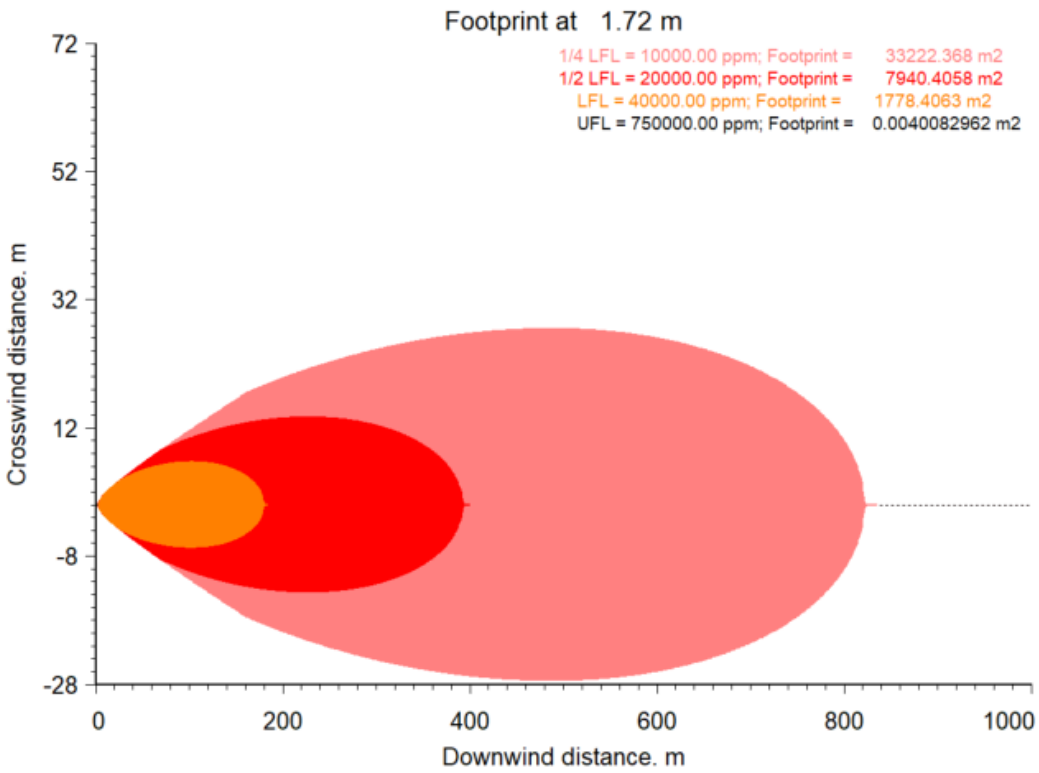


Fig. 33: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Footprint at 1.72m

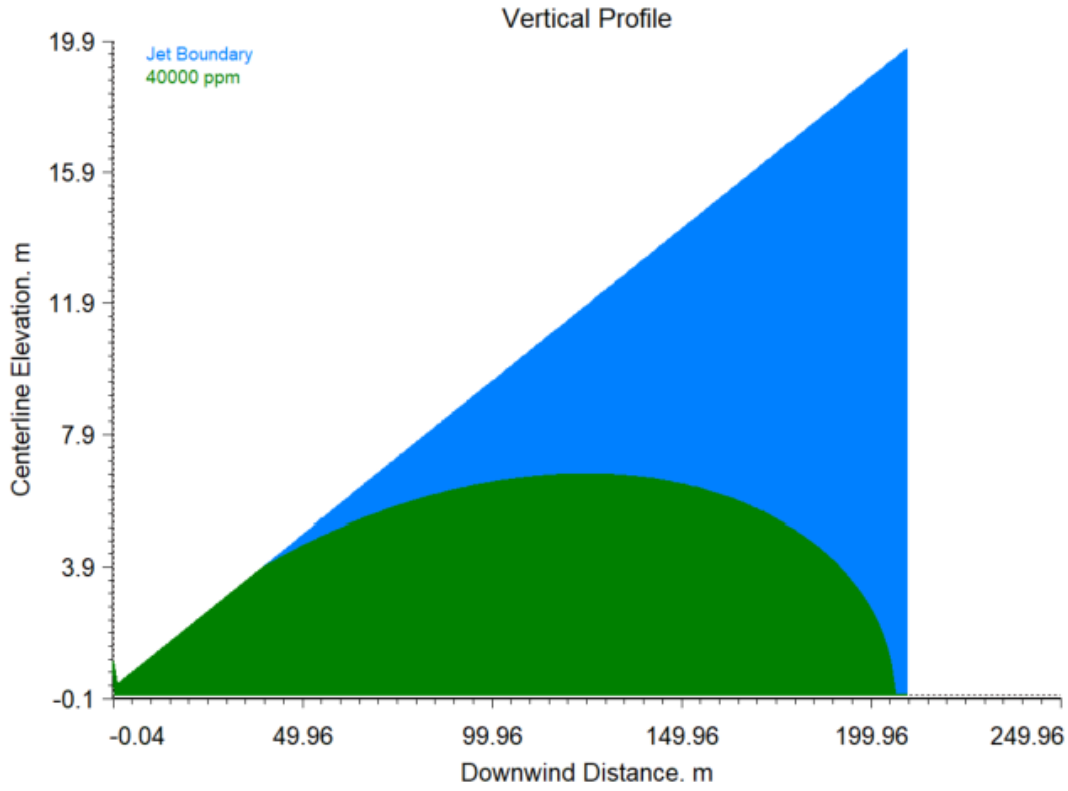


Fig. 34: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Vertical Profile

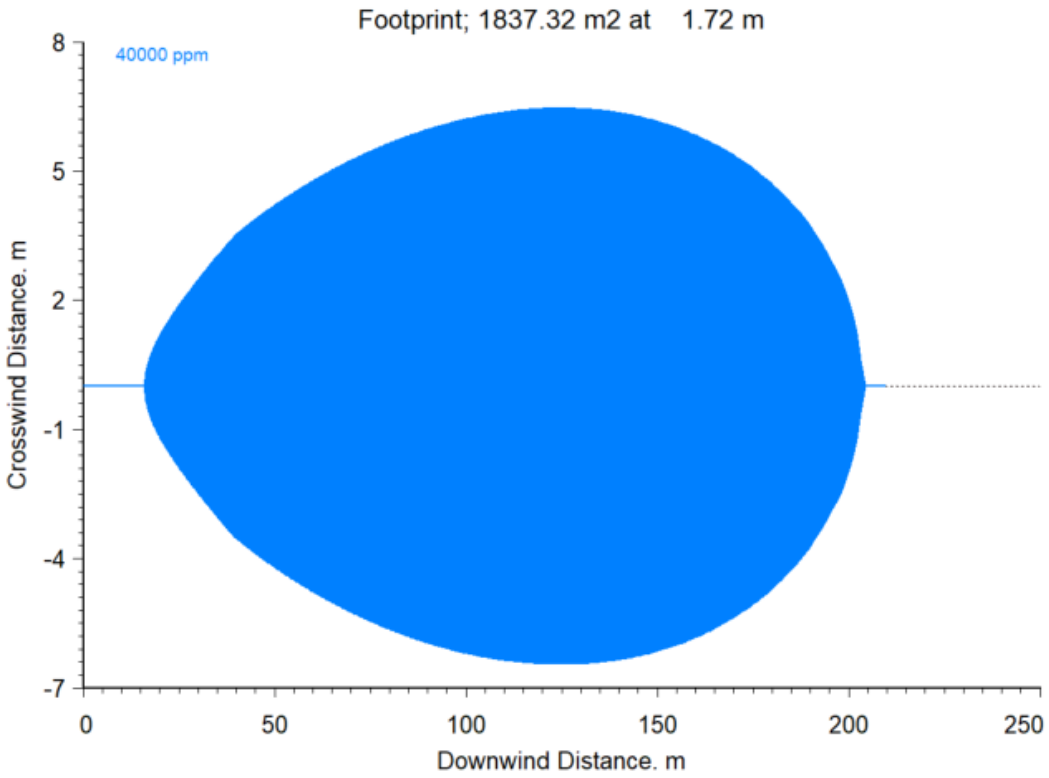


Fig. 35: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Footprint at 1.72m

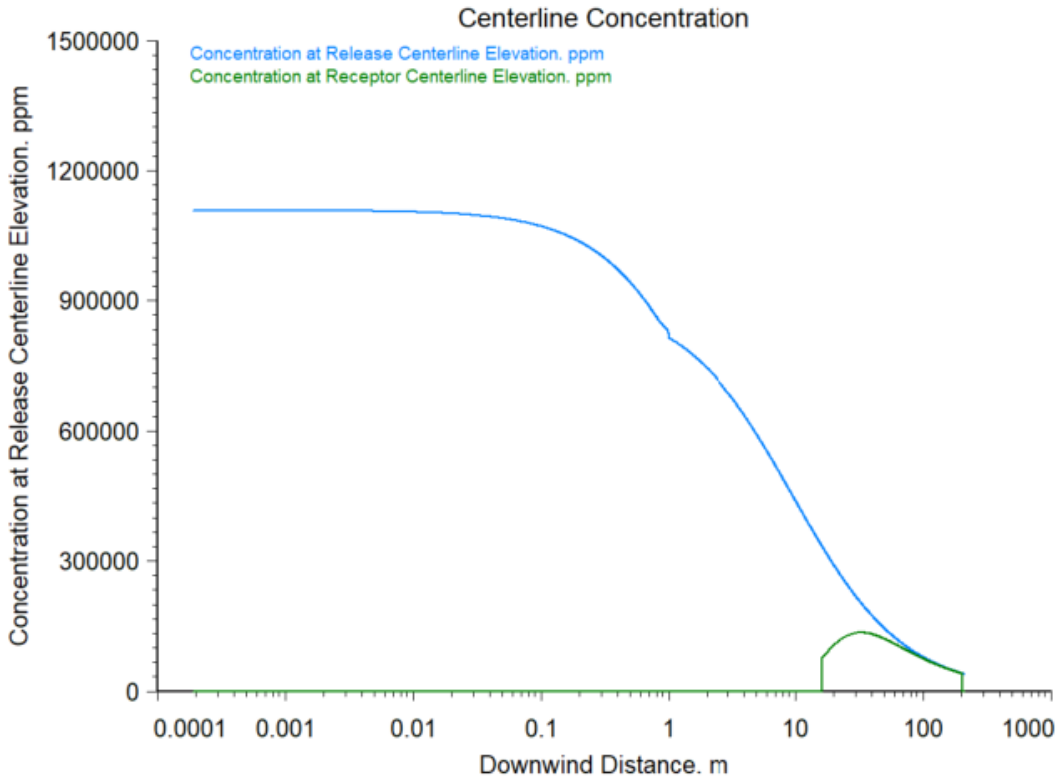


Fig. 36: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Centerline Concentration

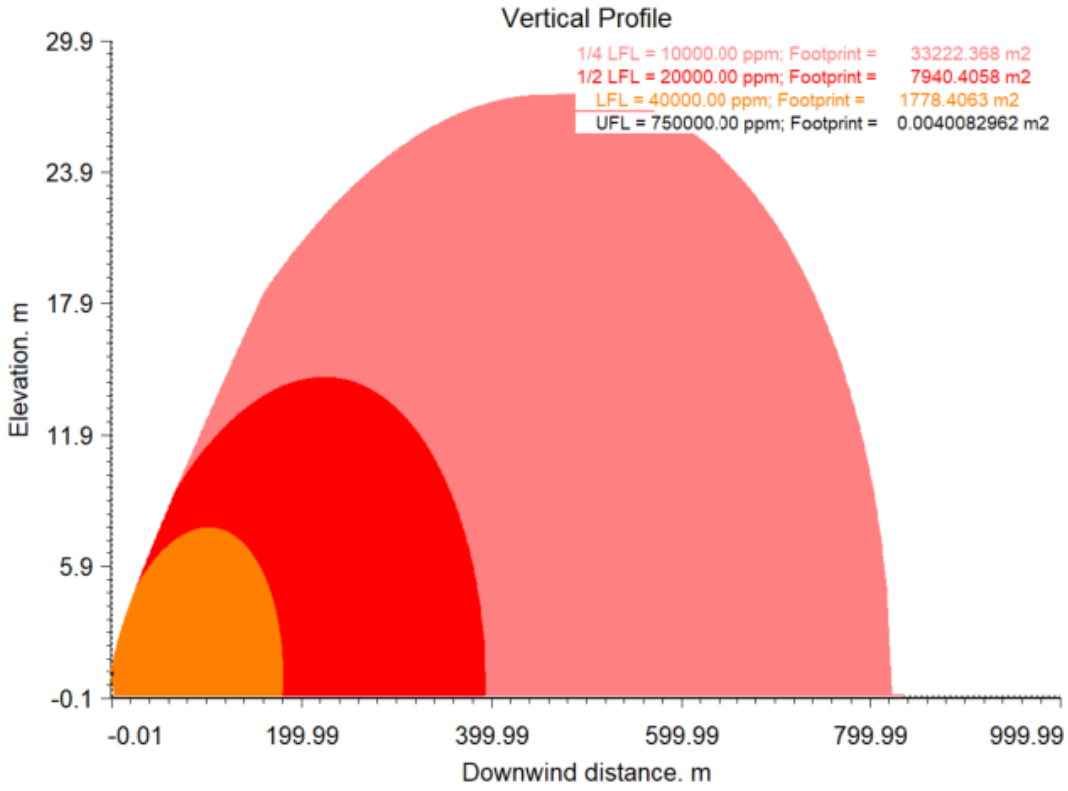


Fig. 37: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Flammable Contours Vertical Profile

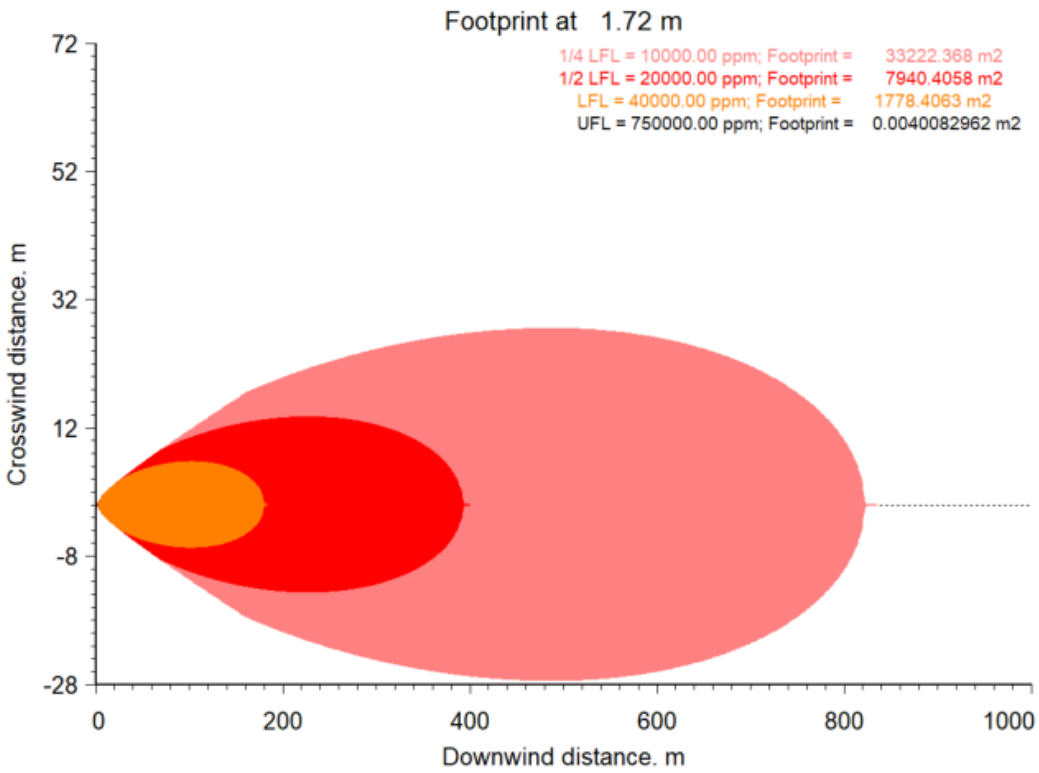


Fig. 38: Vapor Jet Model: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Flammable Contours Footprint at 1.72m

Fireball Model: Gaseous Hydrogen, 100 mm orifice

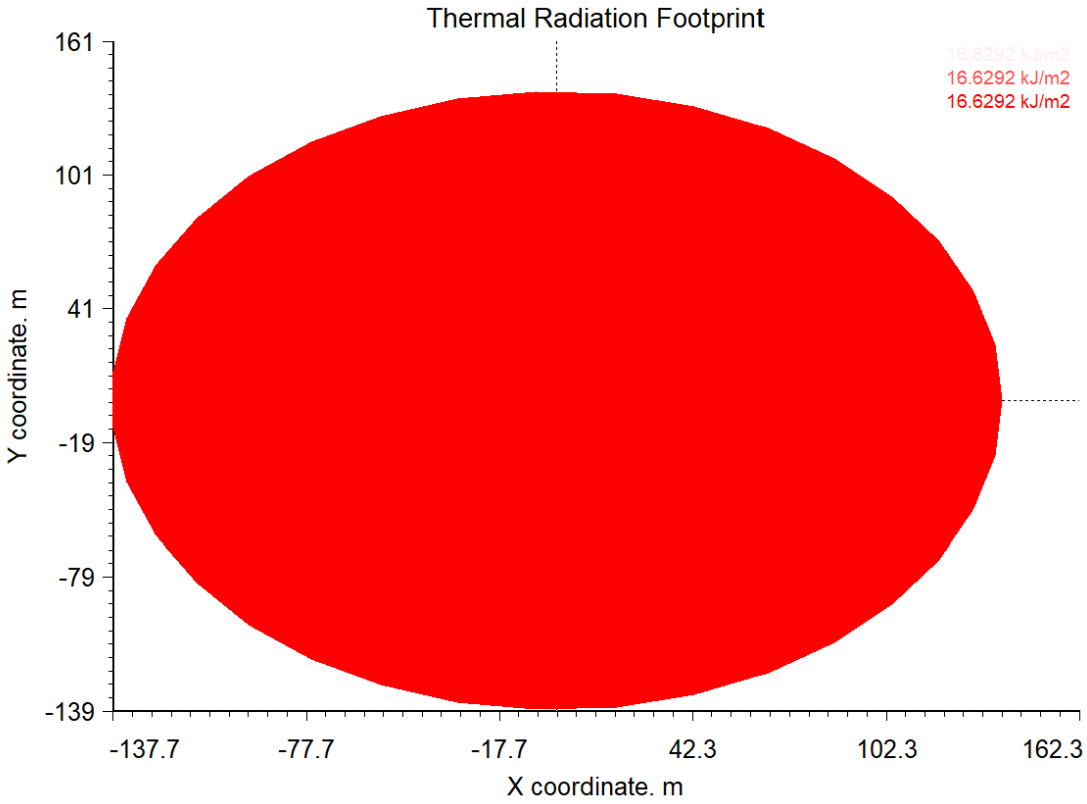


Fig. 39: Fireball Model: Gaseous Hydrogen, 100 mm orifice - Thermal Radiation Footprint

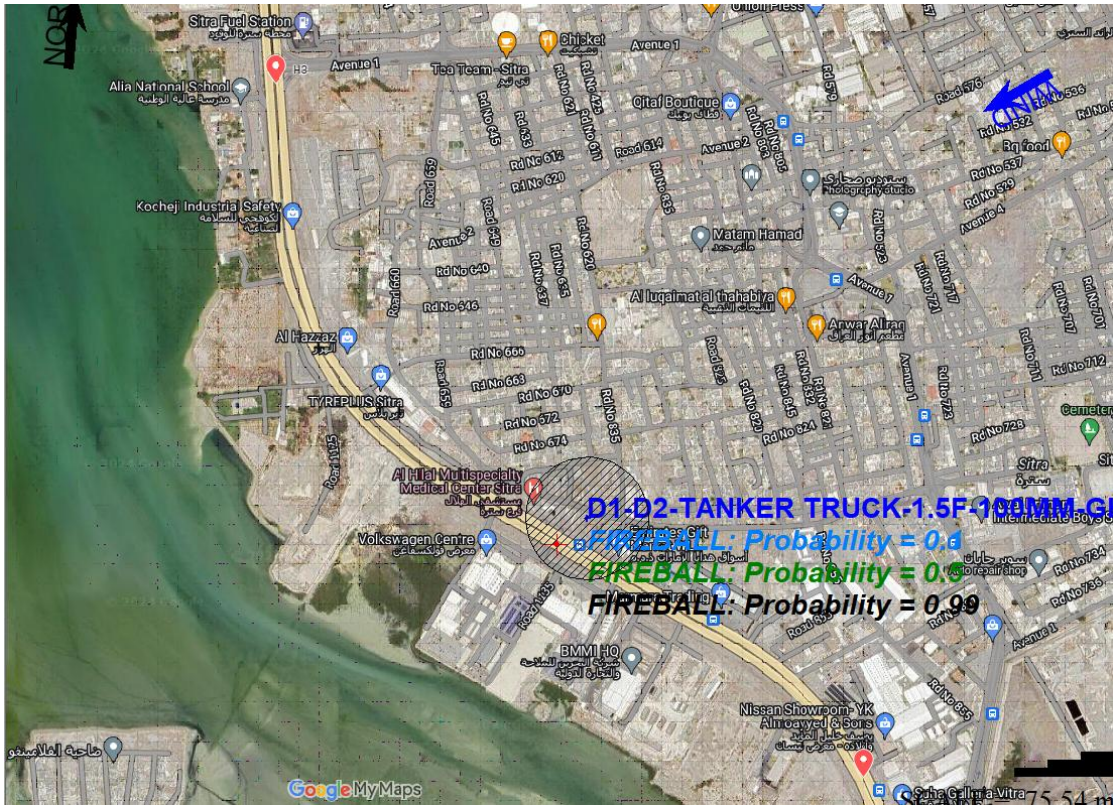


Fig. 40: Fireball Consequence - Segment H2-H3

Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle

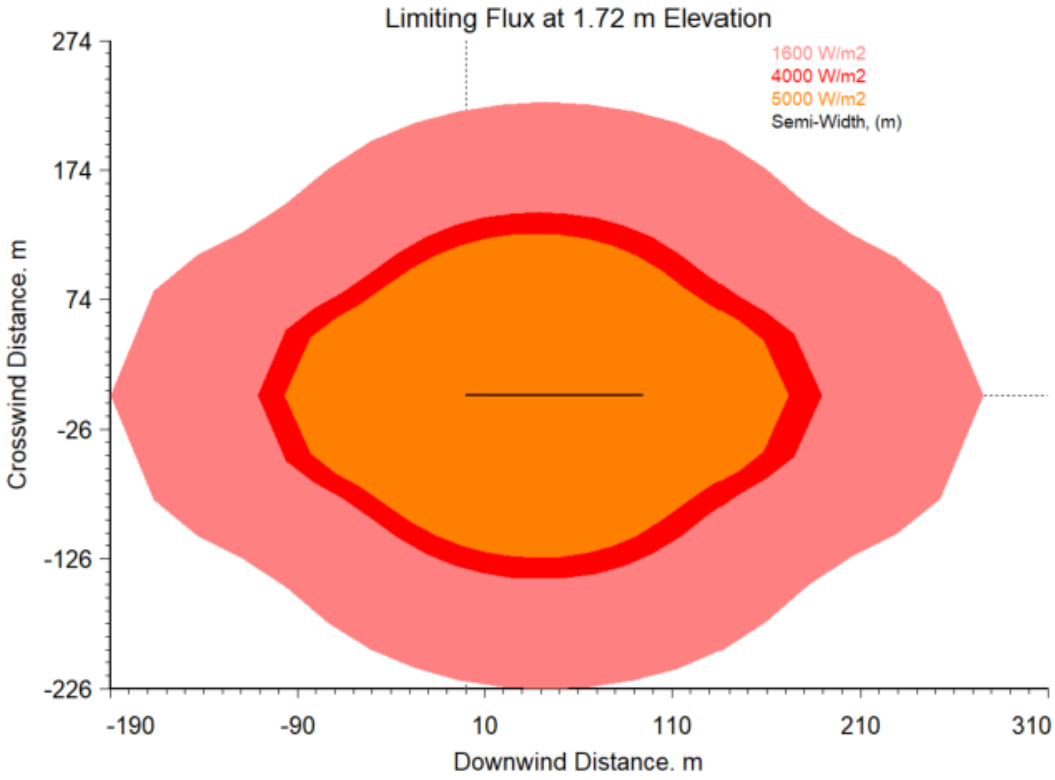


Fig. 41: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Limiting Flux at 1.72m Elevation

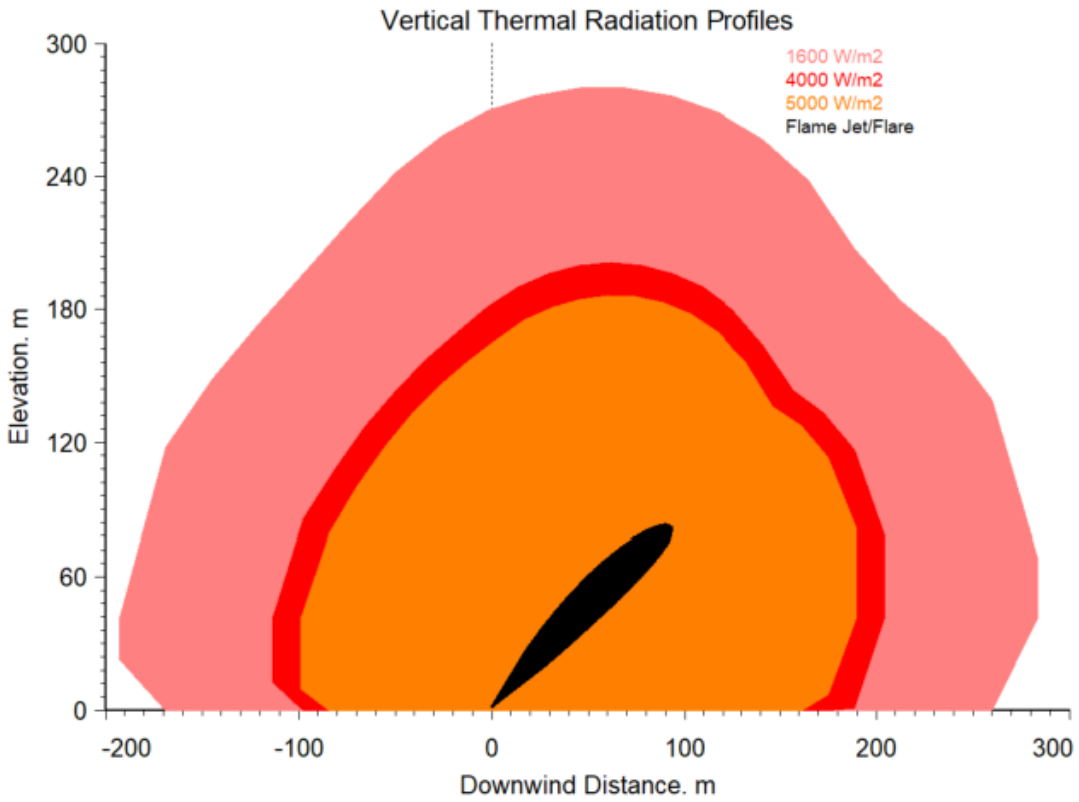


Fig. 42: Gas Flame Jet – Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Vertical Thermal Radiation Profiles

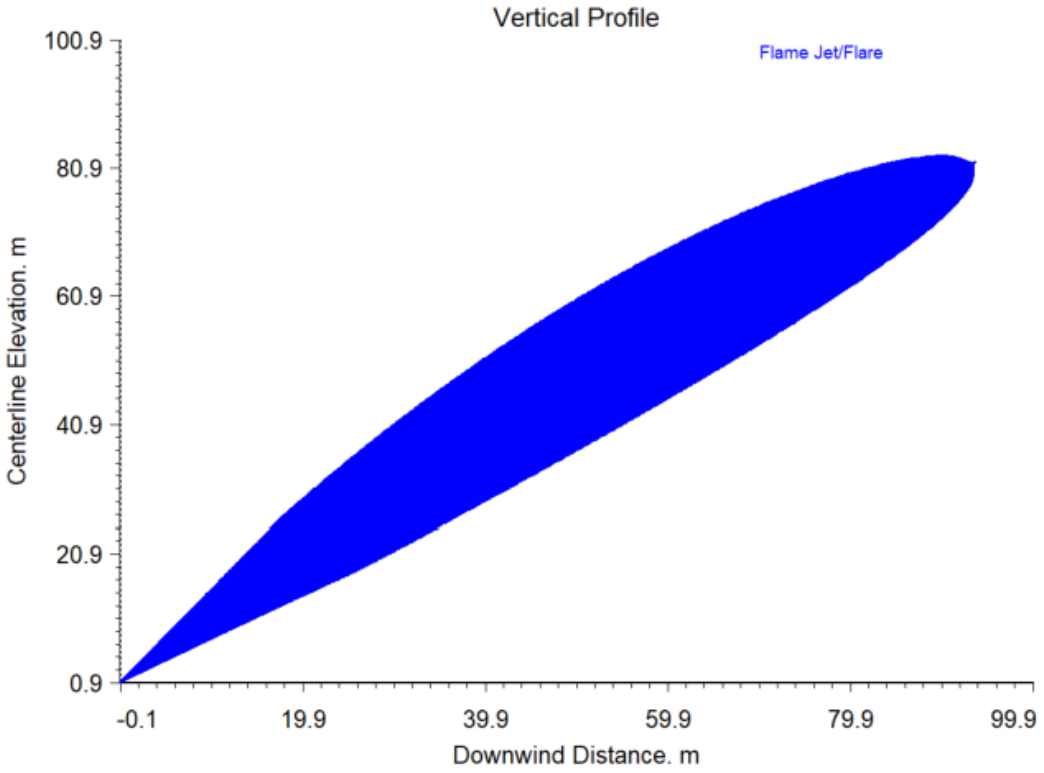


Fig. 43: Gas Flame Jet – Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Vertical Profile

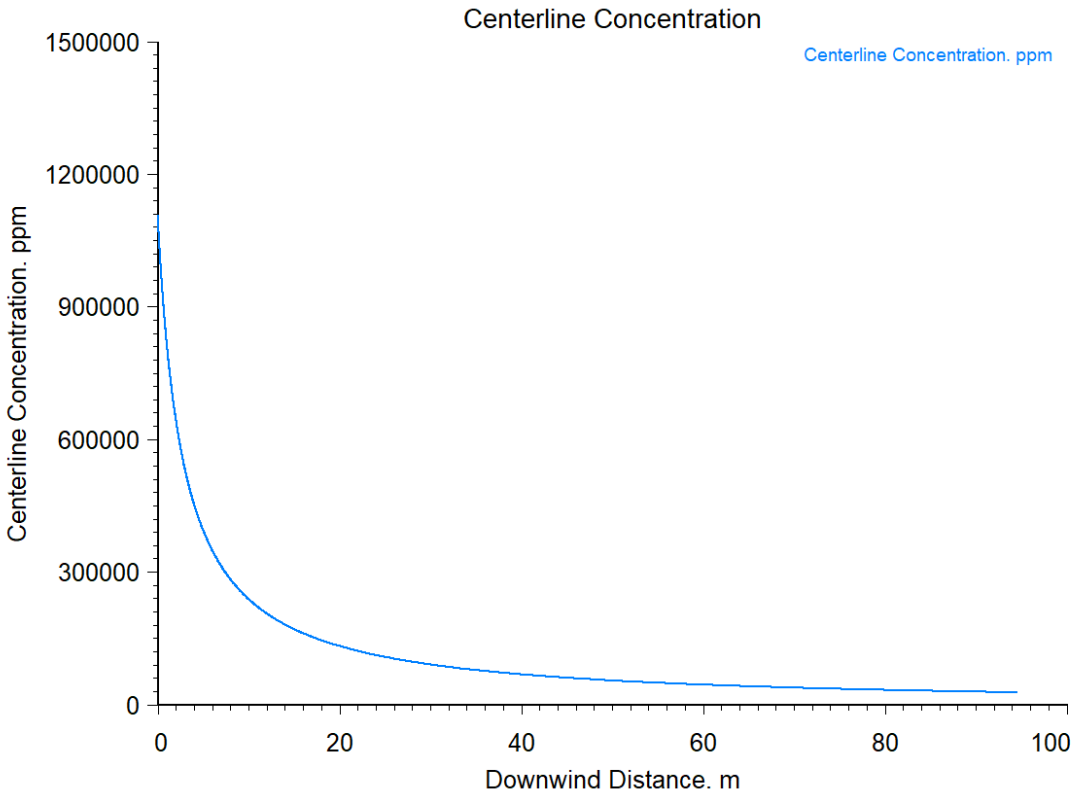


Fig. 44: Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Centerline Concentration

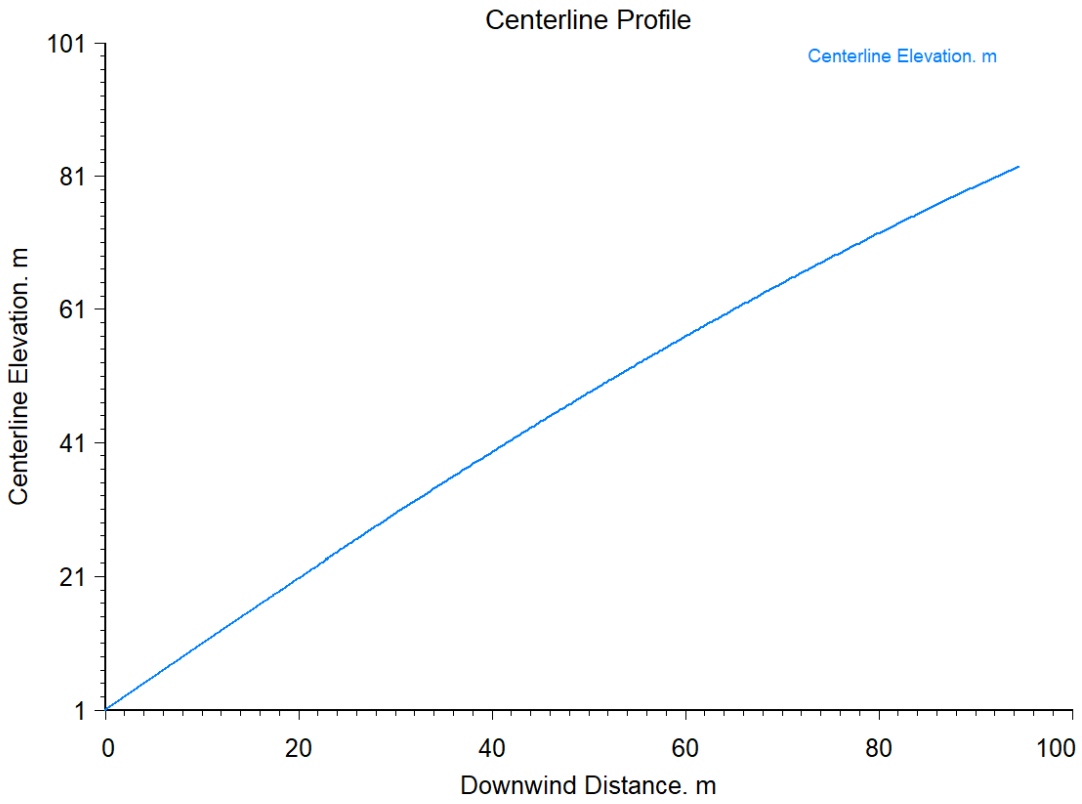


Fig. 45: Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – 45° Release Angle - Centerline Profile

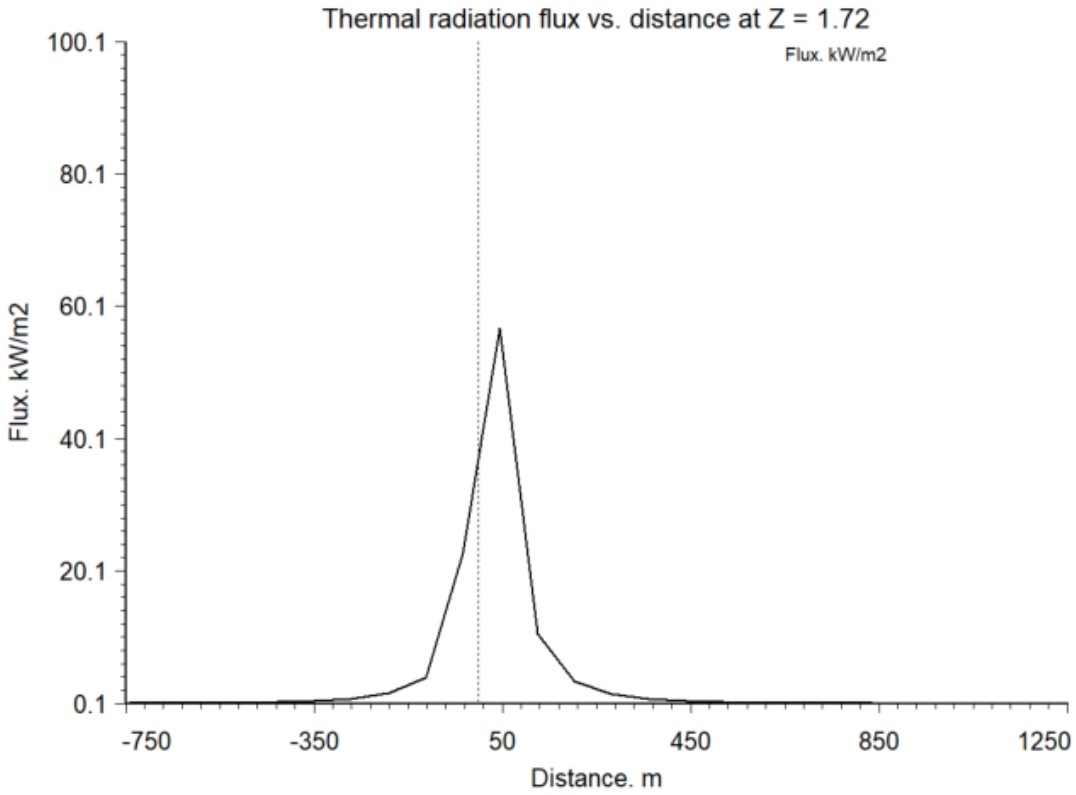


Fig. 46: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - thermal Radiation Flux vs. Distance at 1.72m

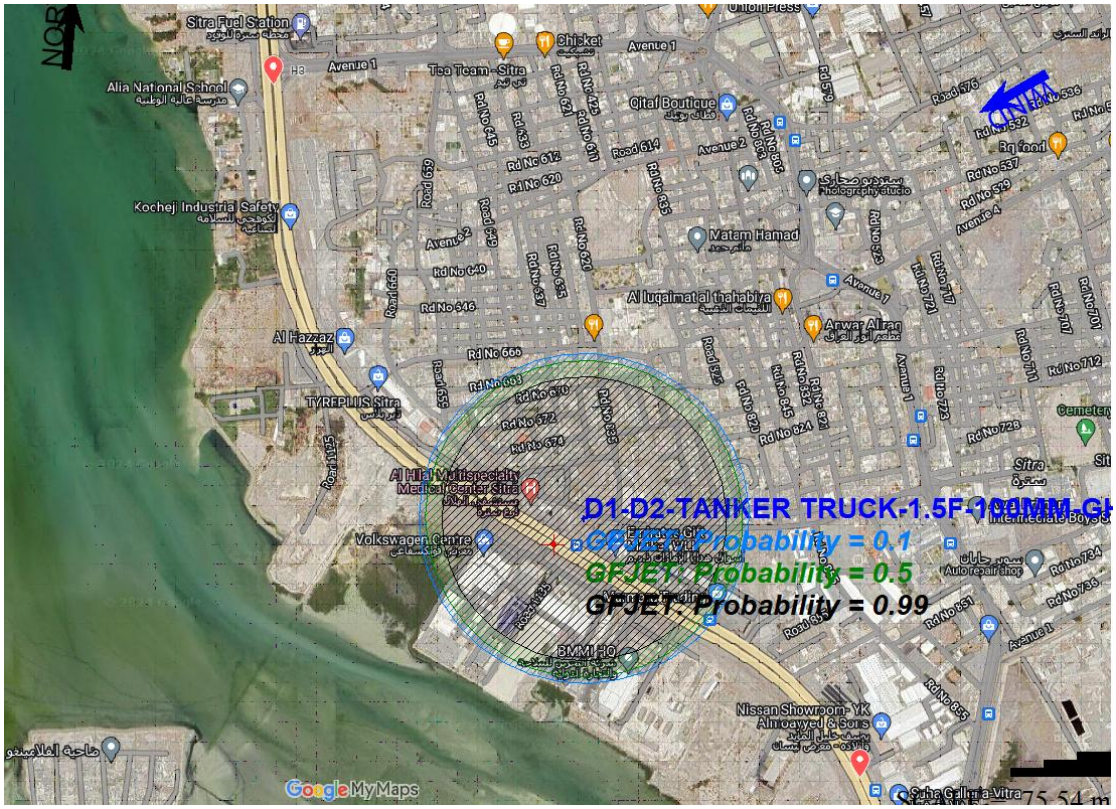


Fig. 47: Gas Flame Jet Consequences - Segment H2-H3

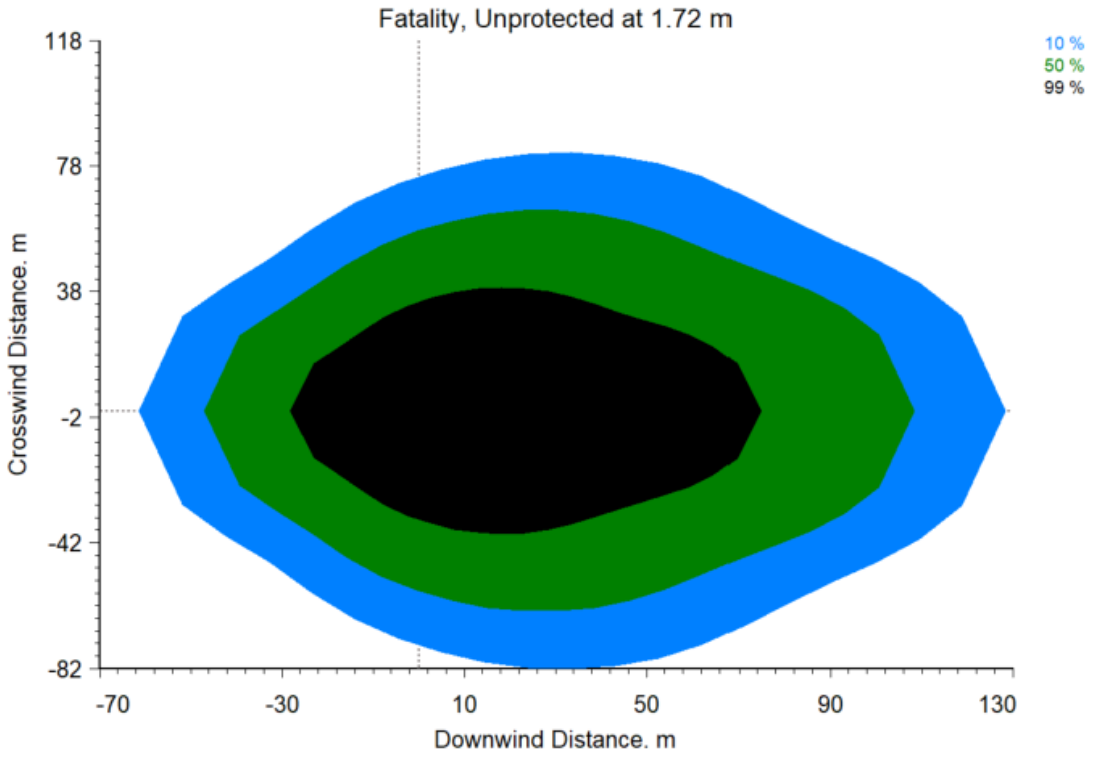


Fig. 48: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

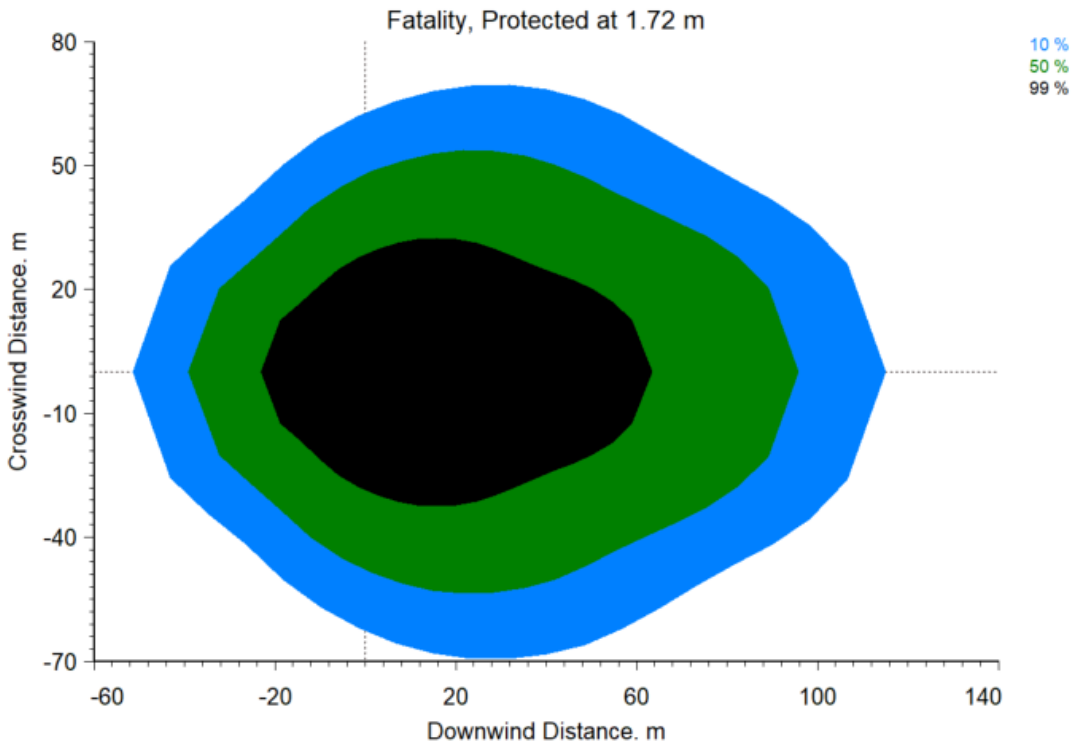


Fig. 49: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Probit Results - Fatality (Protected) at 1.72m

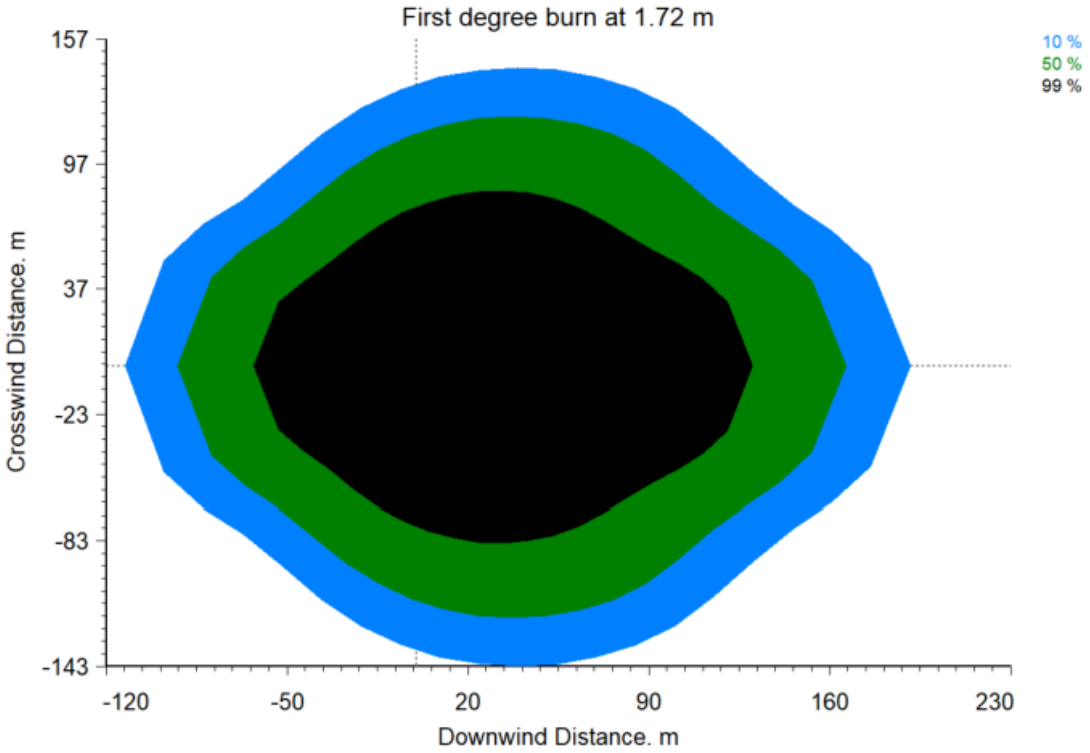


Fig. 50: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Probit Results – First Degree Burns at 1.72m

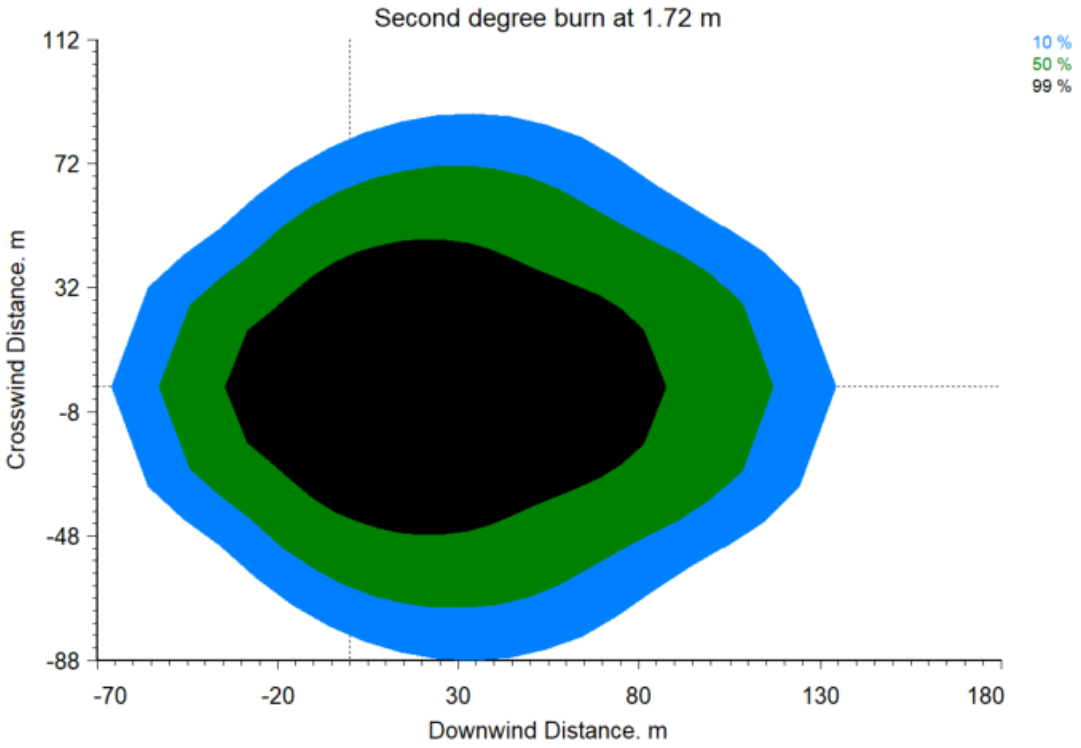


Fig. 51: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 45° Release Angle - Probit Results – Second Degree Burns at 1.72m

Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle

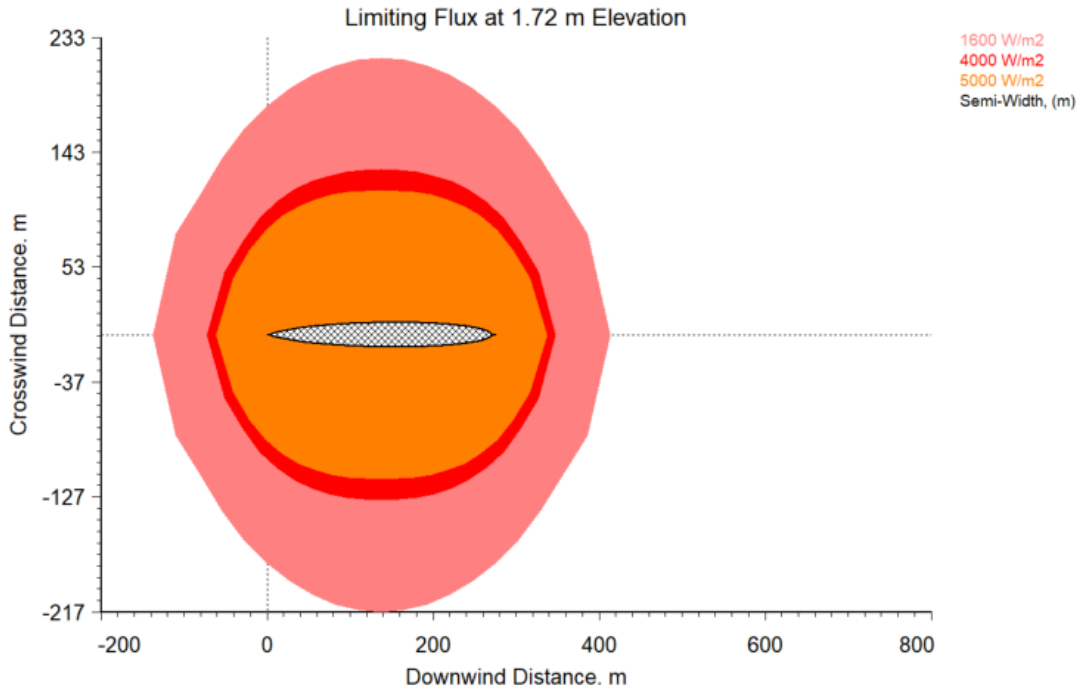


Fig. 52: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Limiting Flux at 1.72m Elevation

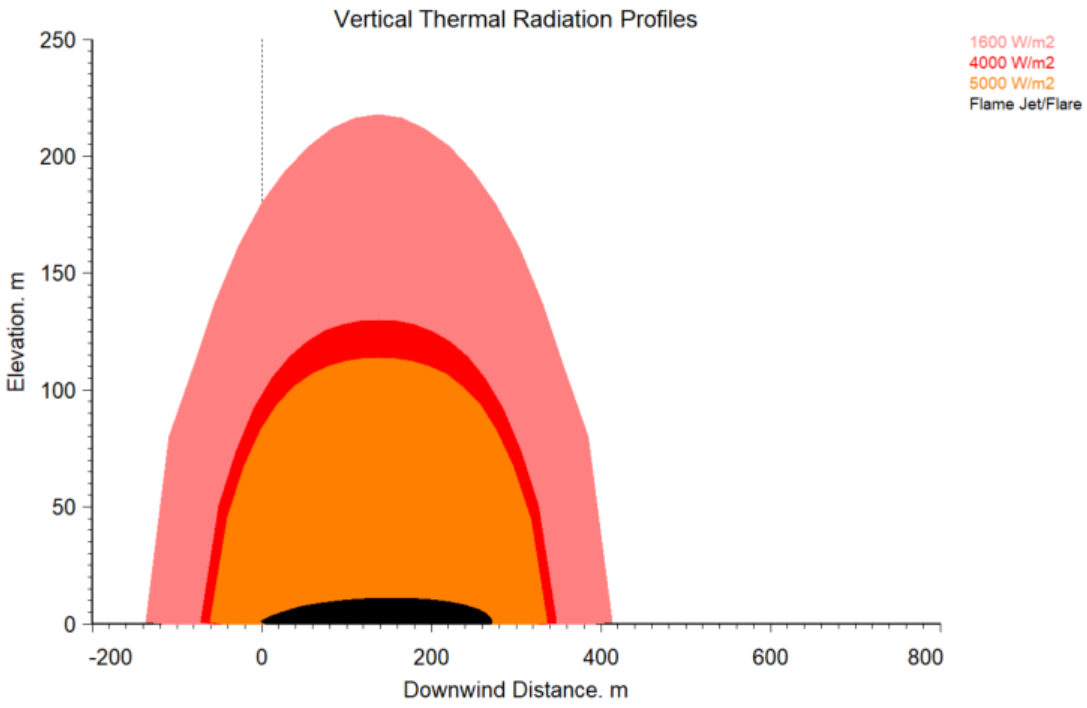


Fig. 53: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle – Vertical Thermal Radiation Profiles

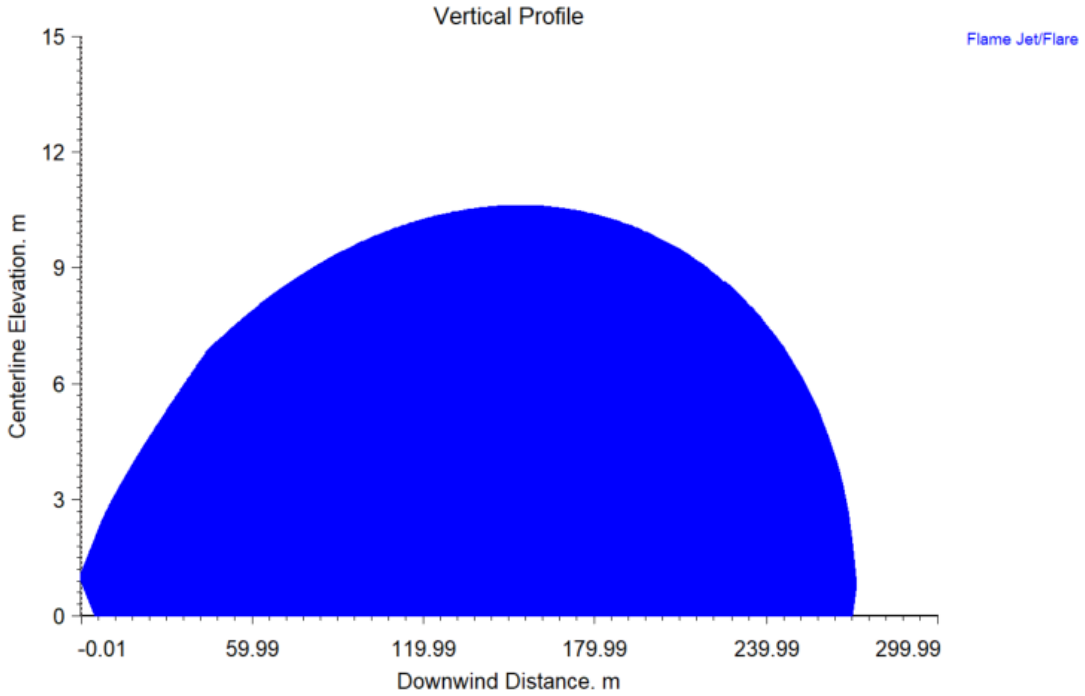


Fig. 54: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle – Vertical Profile

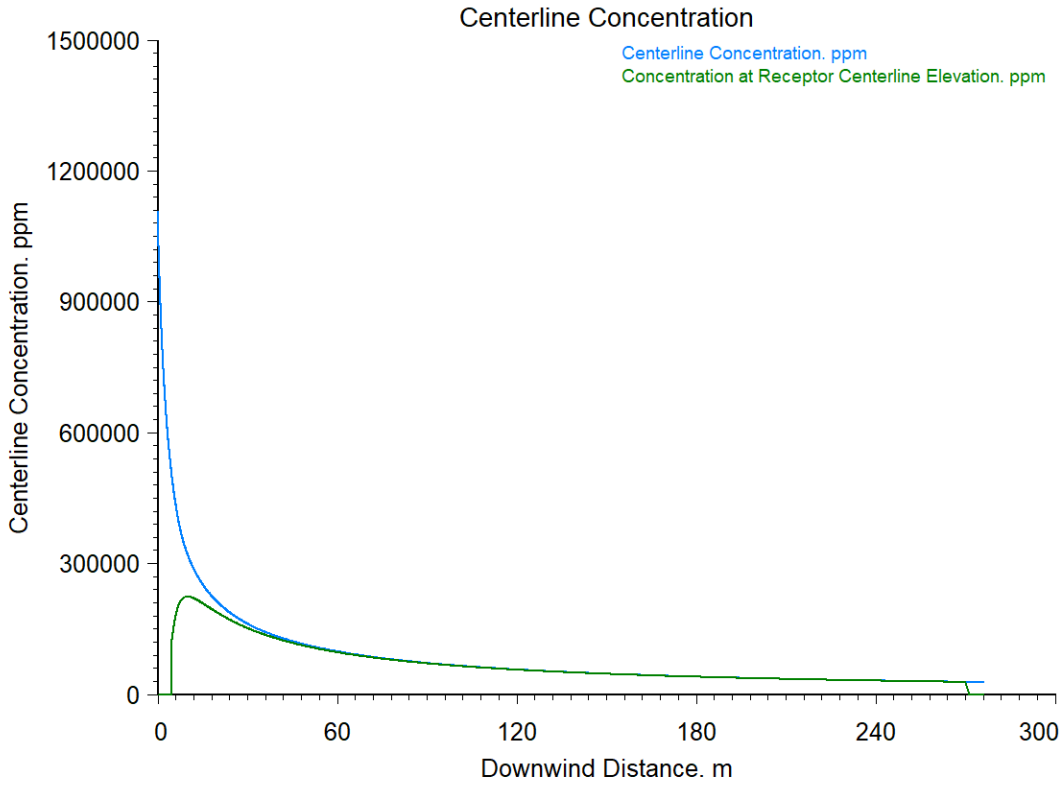


Fig. 55: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Centerline Concentration

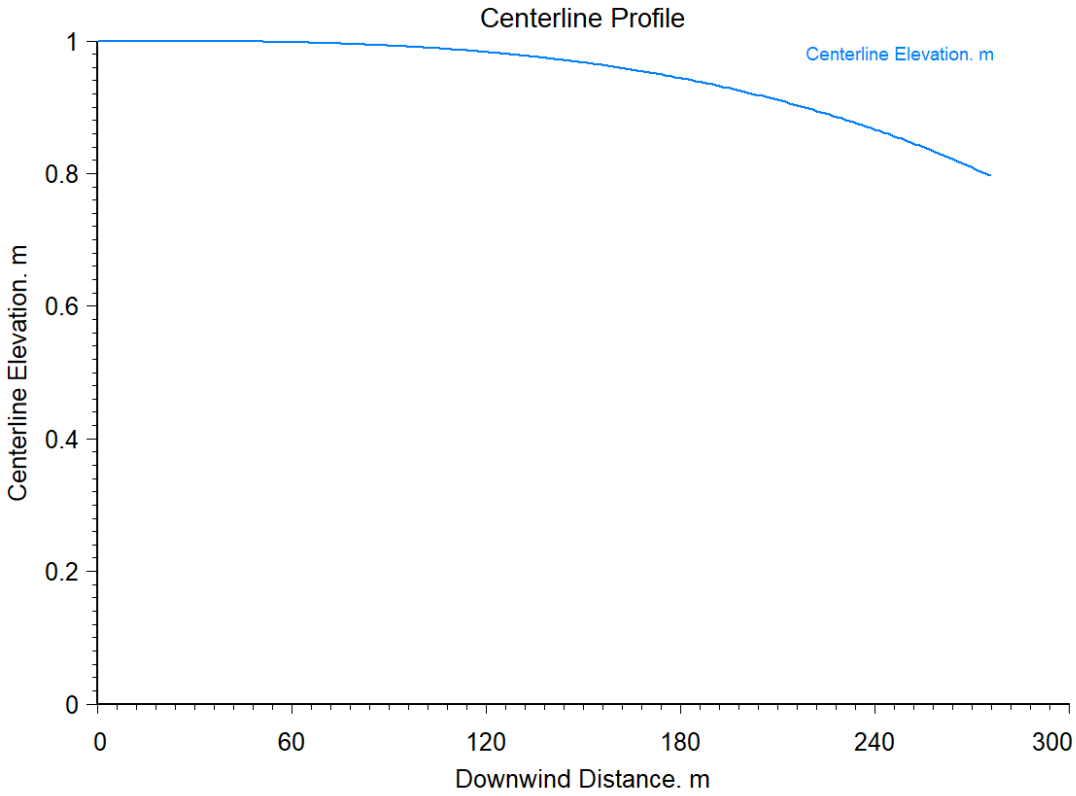


Fig. 56: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Centerline Profile

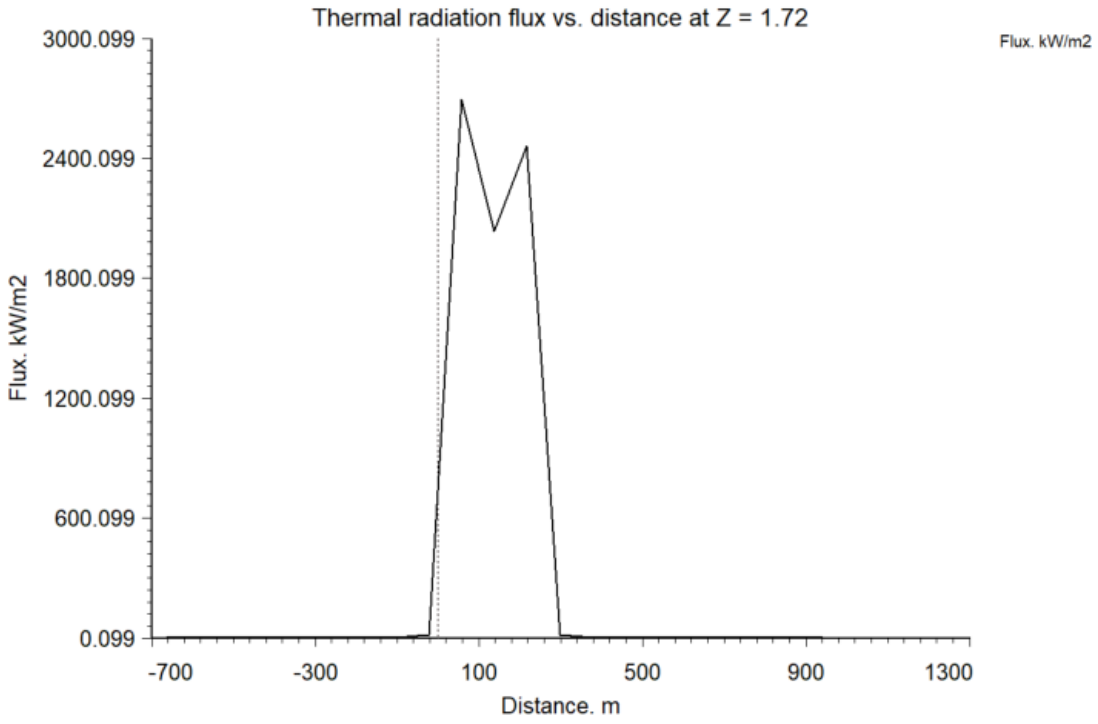


Fig. 57: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Thermal Radiation Flux vs. Distance at 1.72m

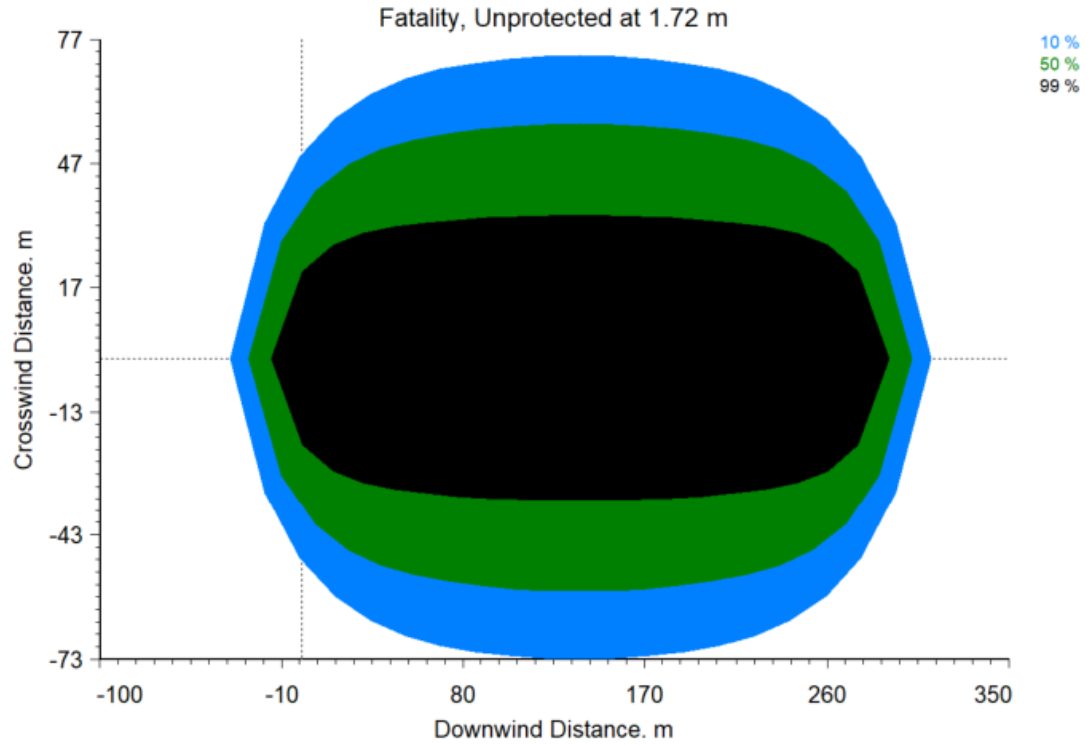


Fig. 58: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

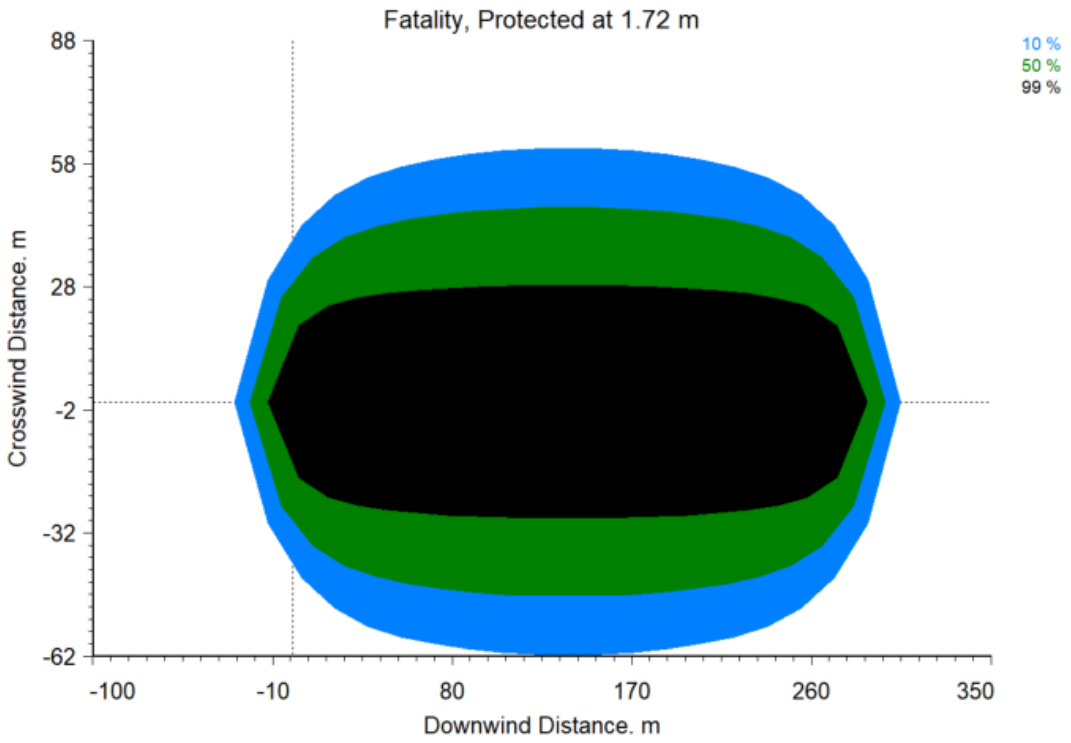


Fig. 59: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Probit Results - Fatality (Protected) at 1.72m

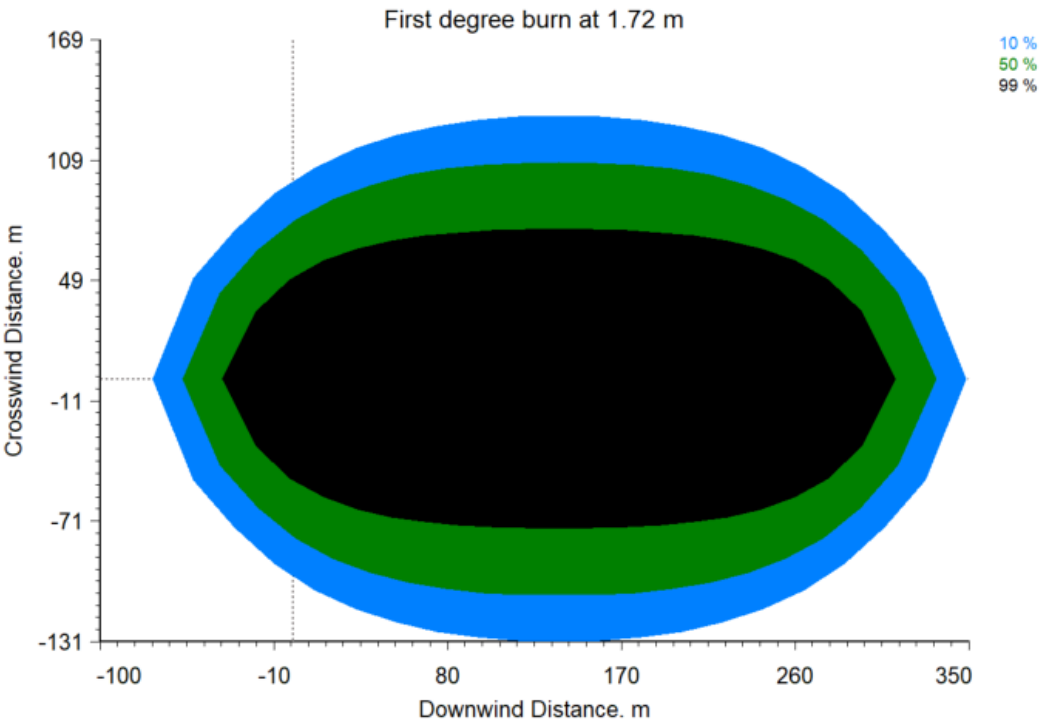


Fig. 60: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Probit Results – First Degree Burns at 1.72m

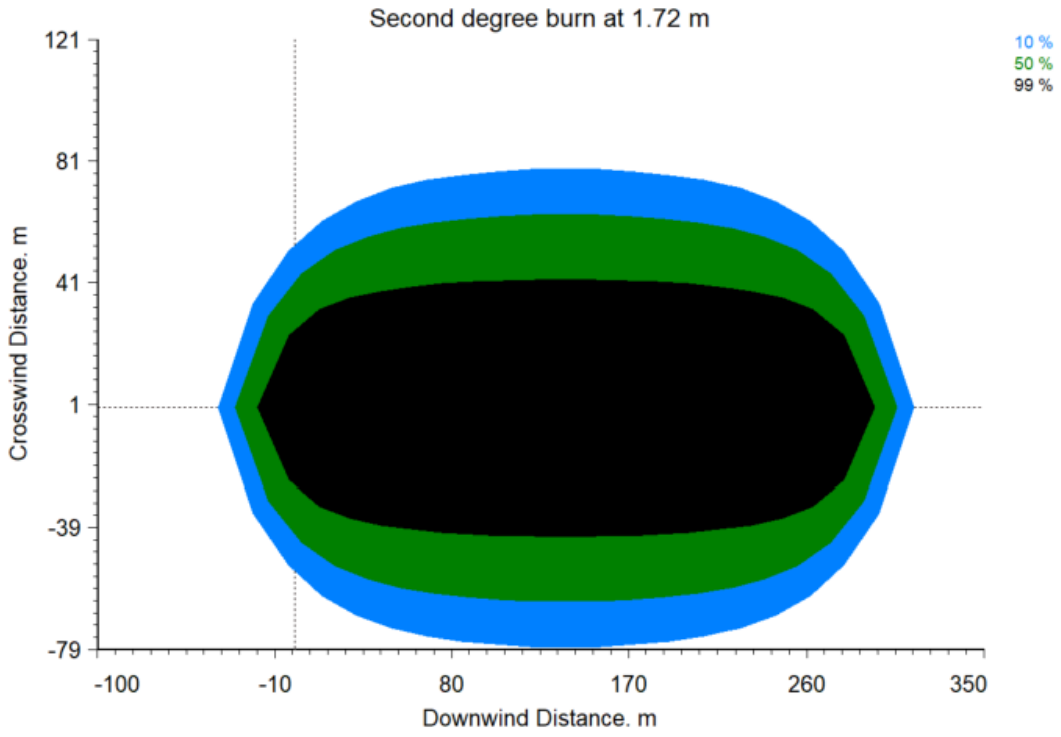


Fig. 61: Gaseous Hydrogen, 100 mm orifice, 0° Release Angle - Probit Results – Second Degree Burns at 1.72m

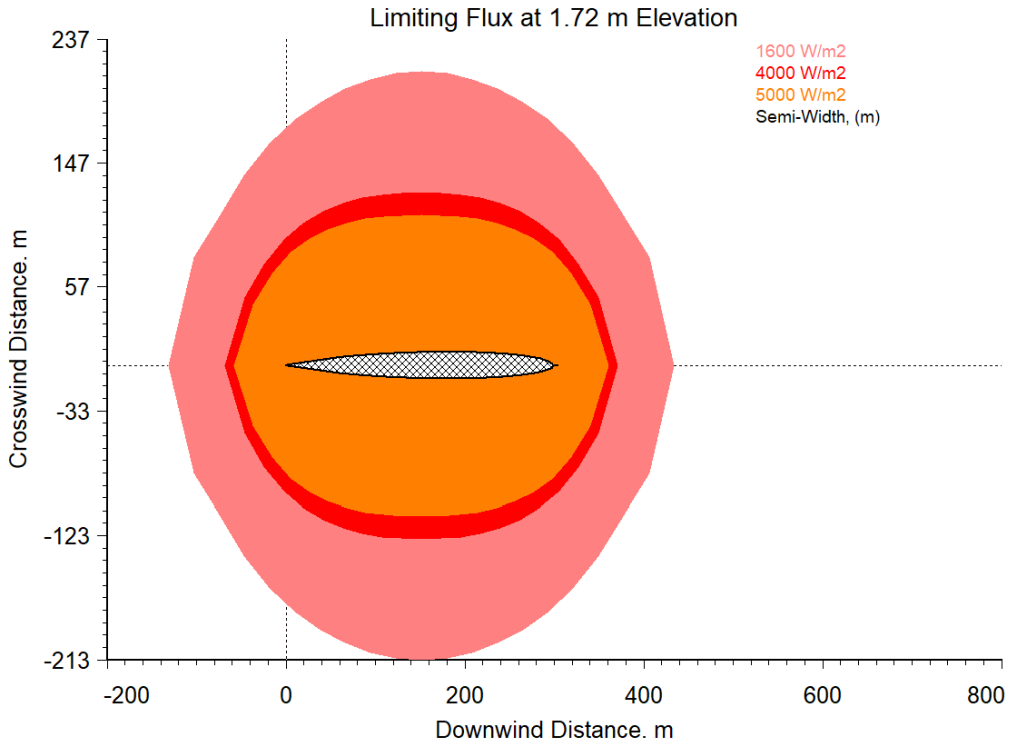


Fig. 62: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Limiting Flux at 1.72m Elevation

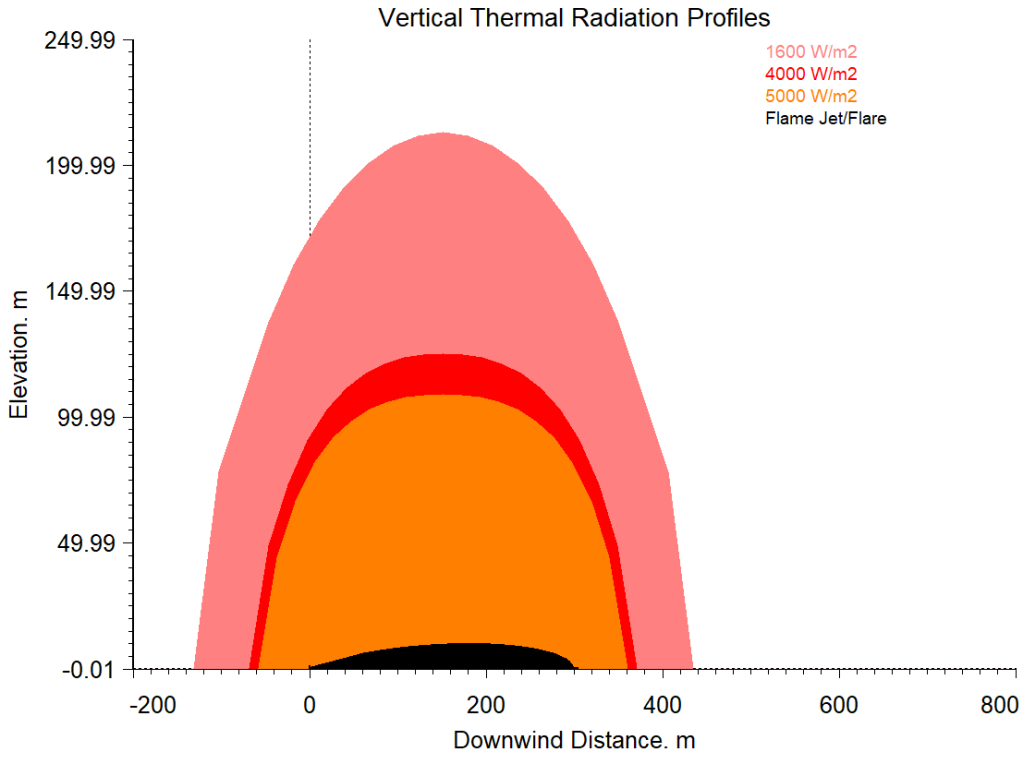


Fig. 63: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Vertical Thermal Radiation Profiles

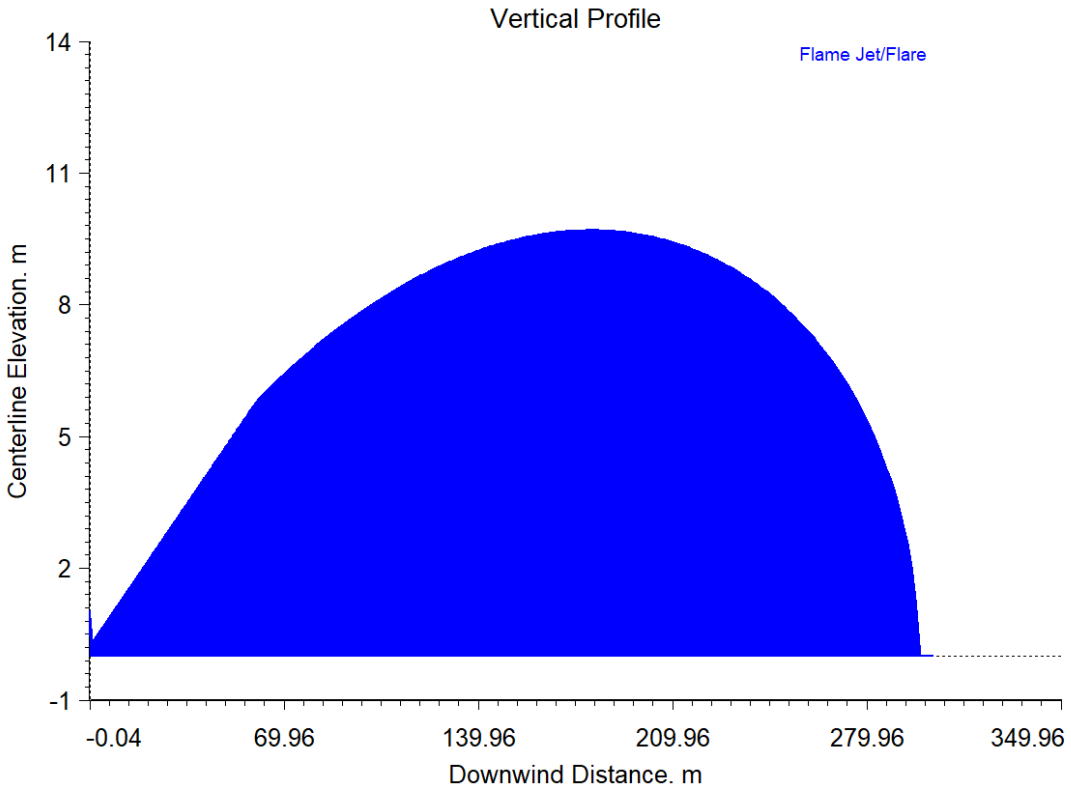


Fig. 64: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Vertical Profile

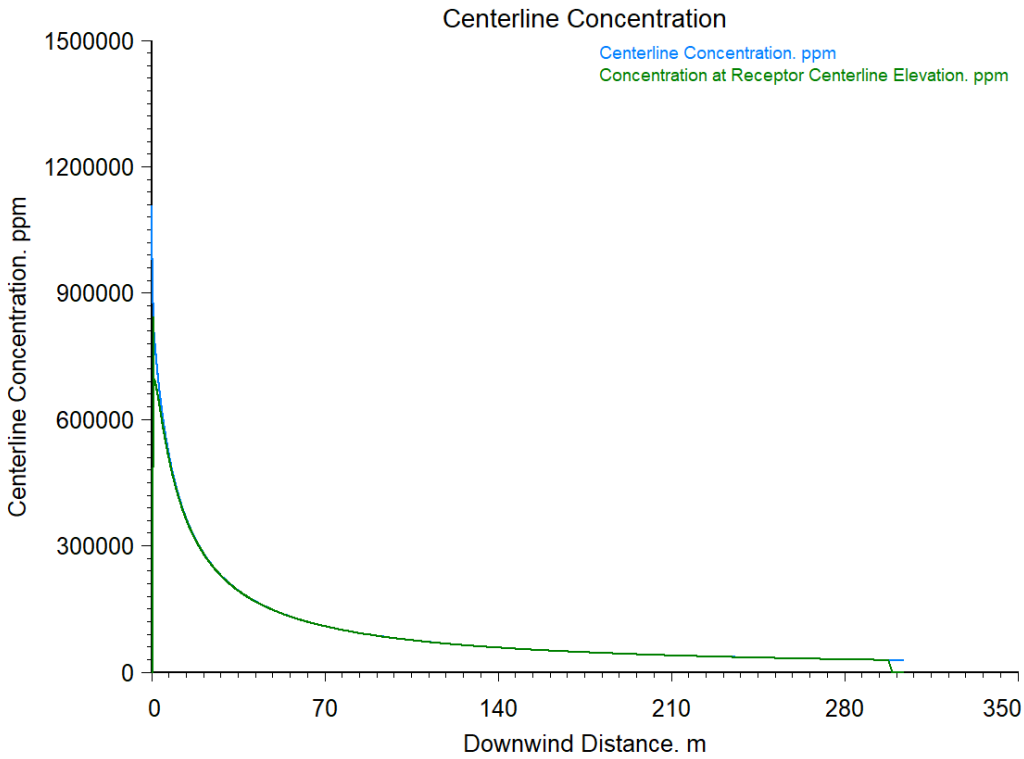


Fig. 65: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle – Centerline Concentration

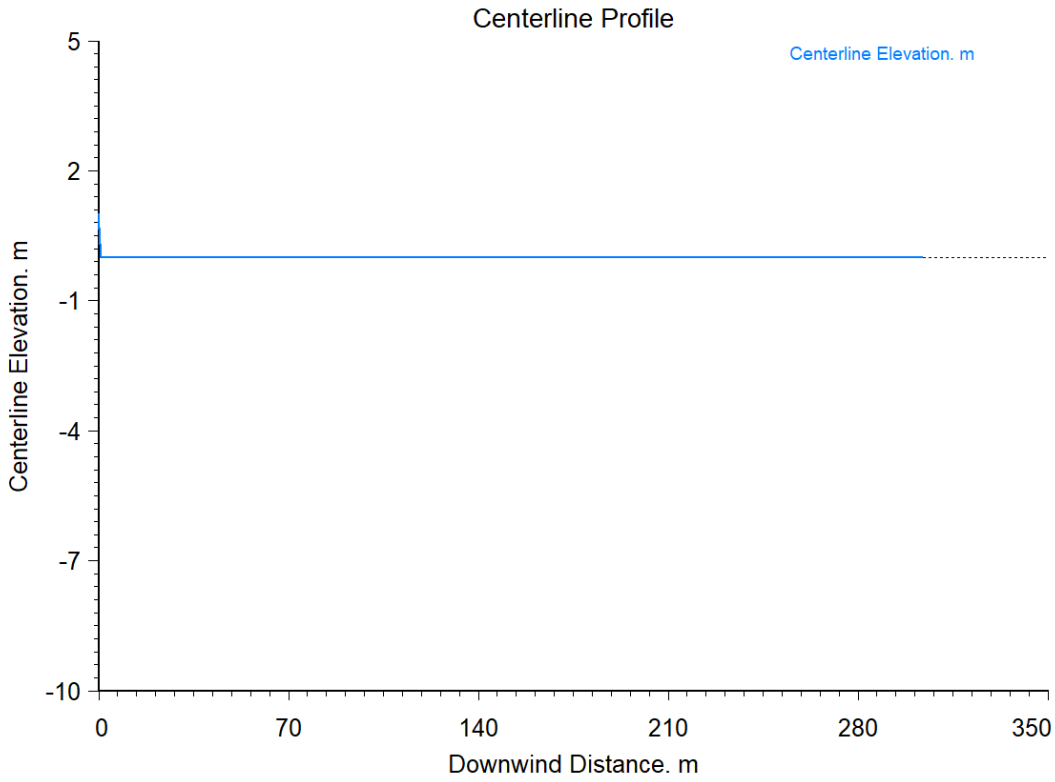


Fig. 66: Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – -45° Release Angle – Centerline Profile

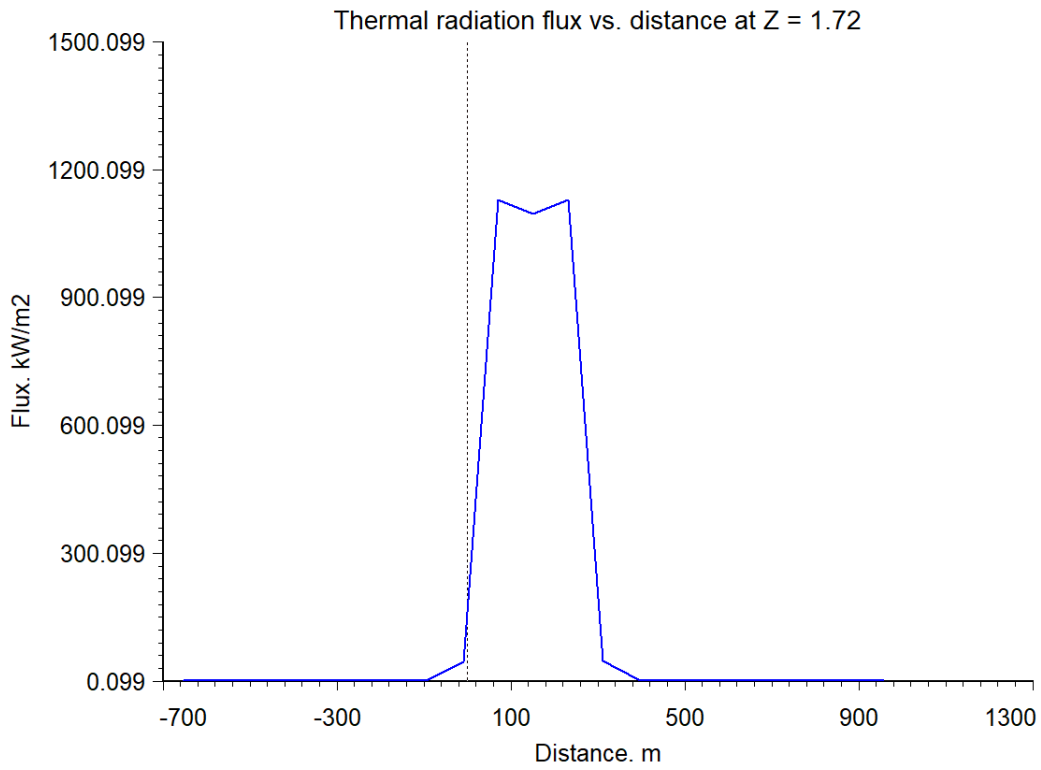


Fig. 67: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Thermal Radiation Flux vs. Distance at 1.72m

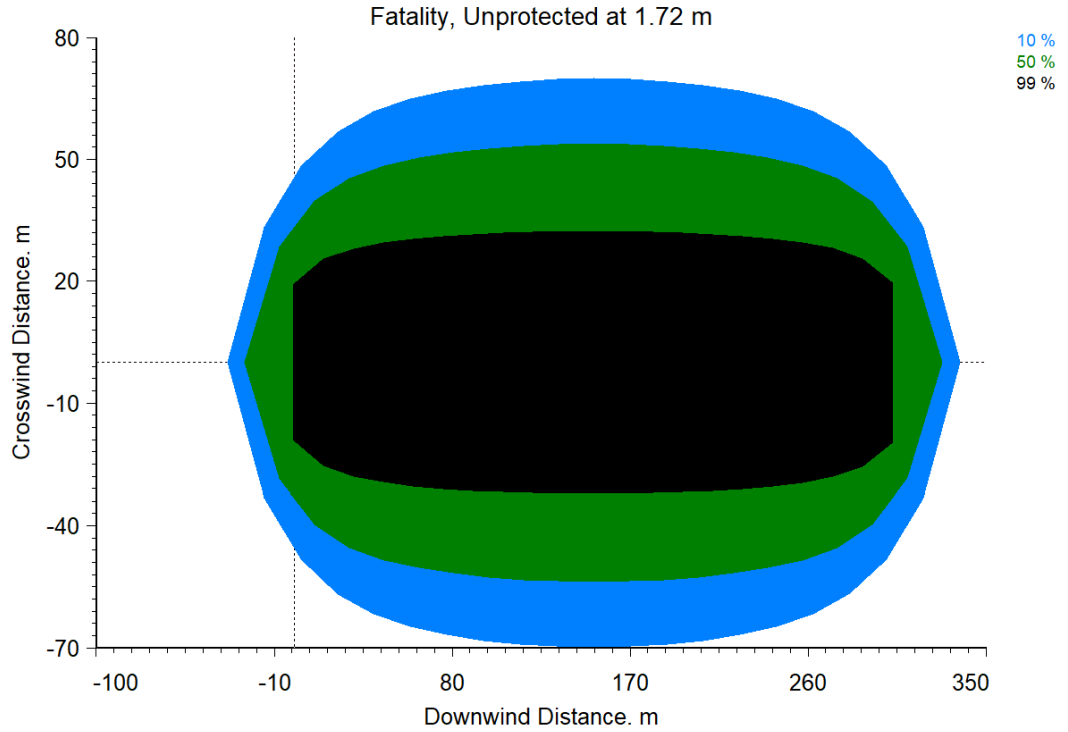


Fig. 68: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

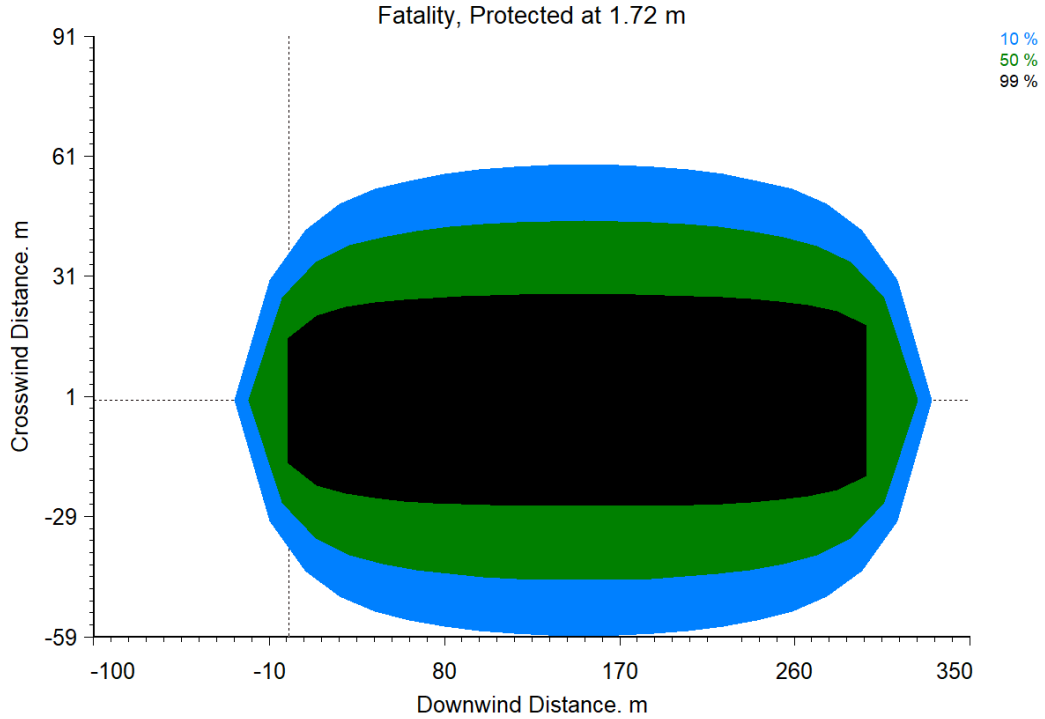


Fig. 69: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Probit Results - Fatality (Protected) at 1.72m

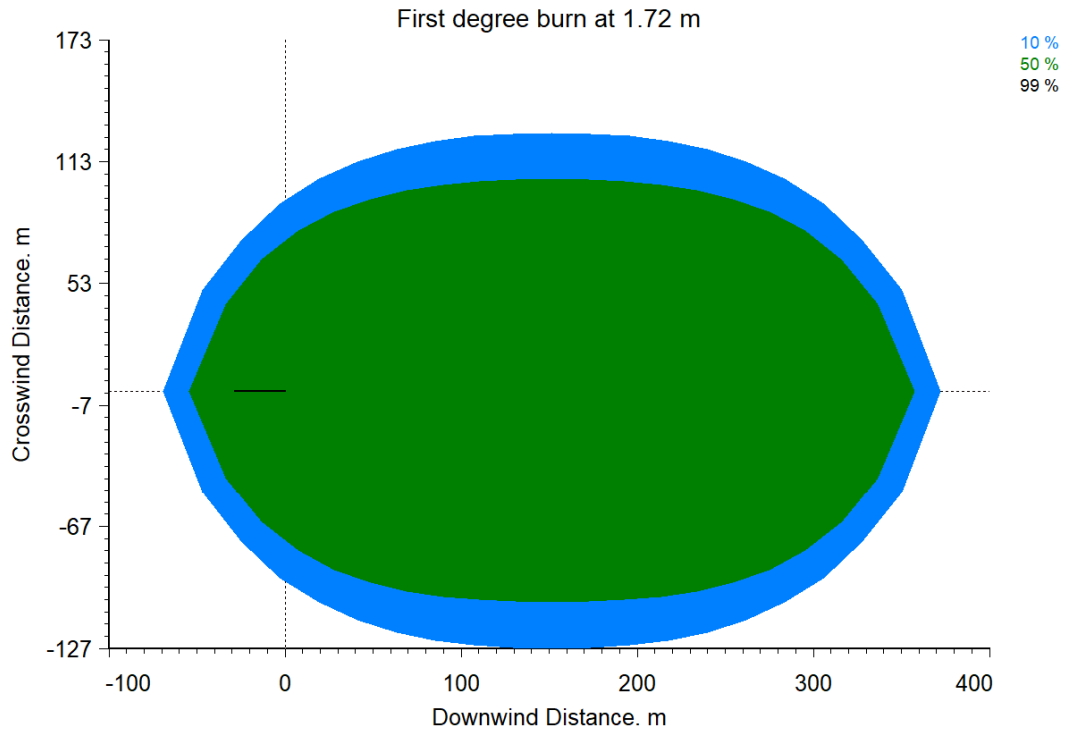


Fig. 70: Gas Flame Jet: Gaseous Hydrogen – 100 mm orifice – -45° Release Angle - Probit Results – First Degree Burns at 1.72m

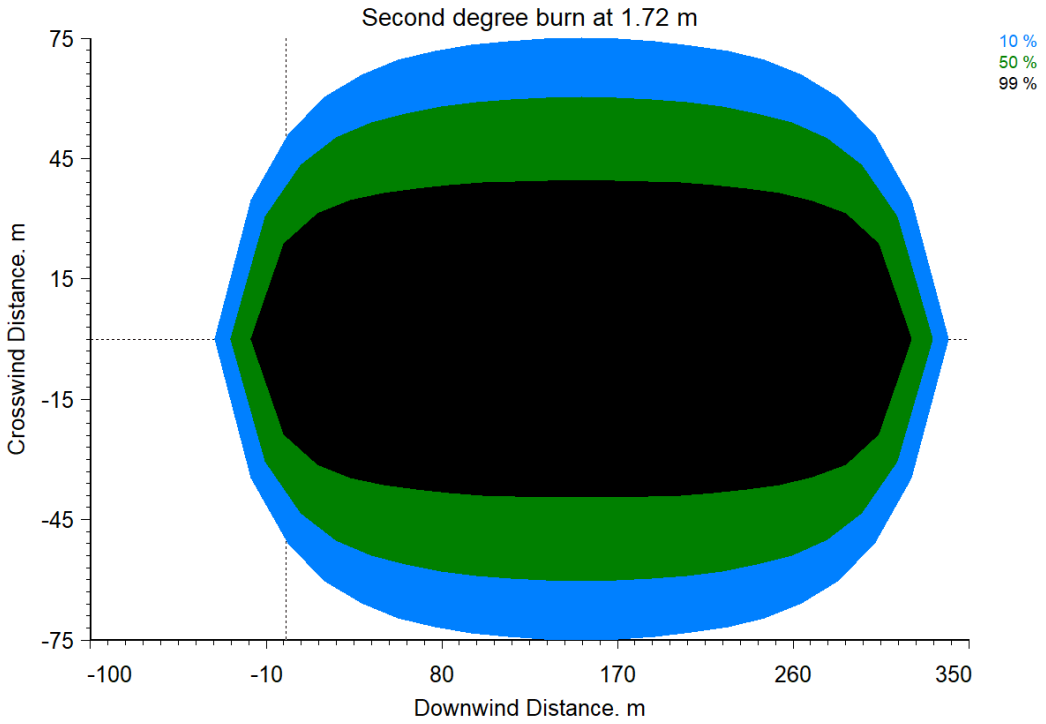


Fig. 71: Gas Flame Jet: Gaseous Hydrogen, 100 mm orifice, -45° Release Angle - Probit Results – Second Degree Burns at 1.72m

Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle

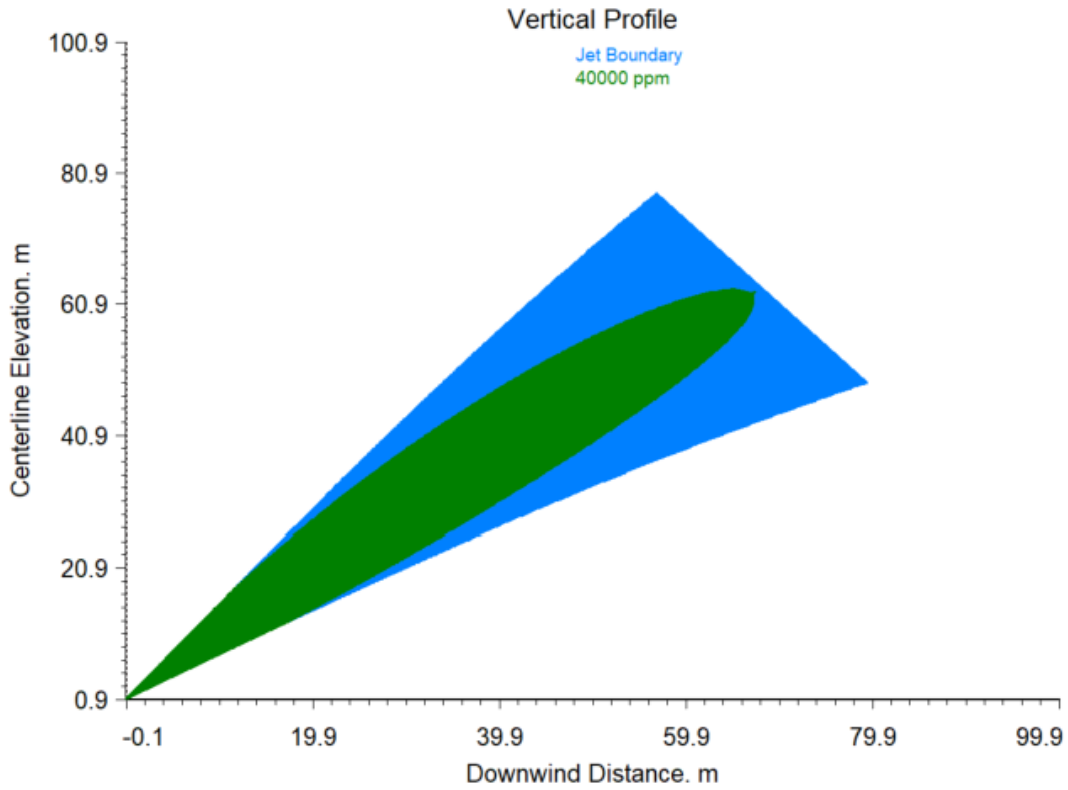


Fig. 72: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle – Vertical Profile

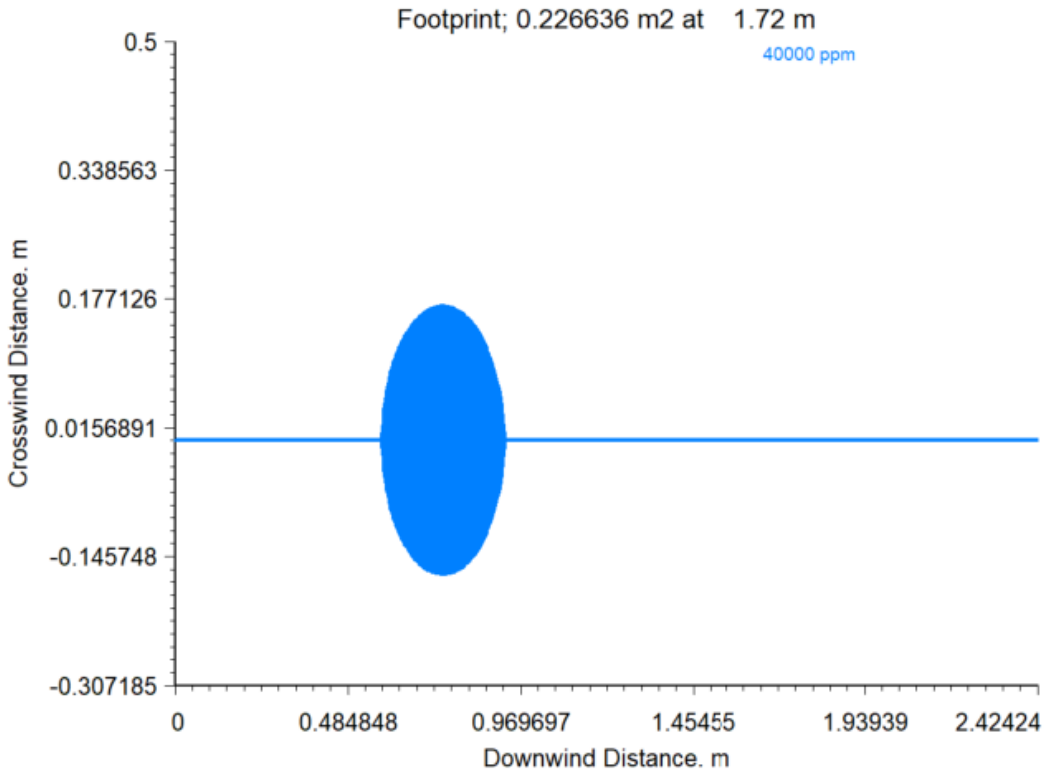


Fig. 73: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Footprint

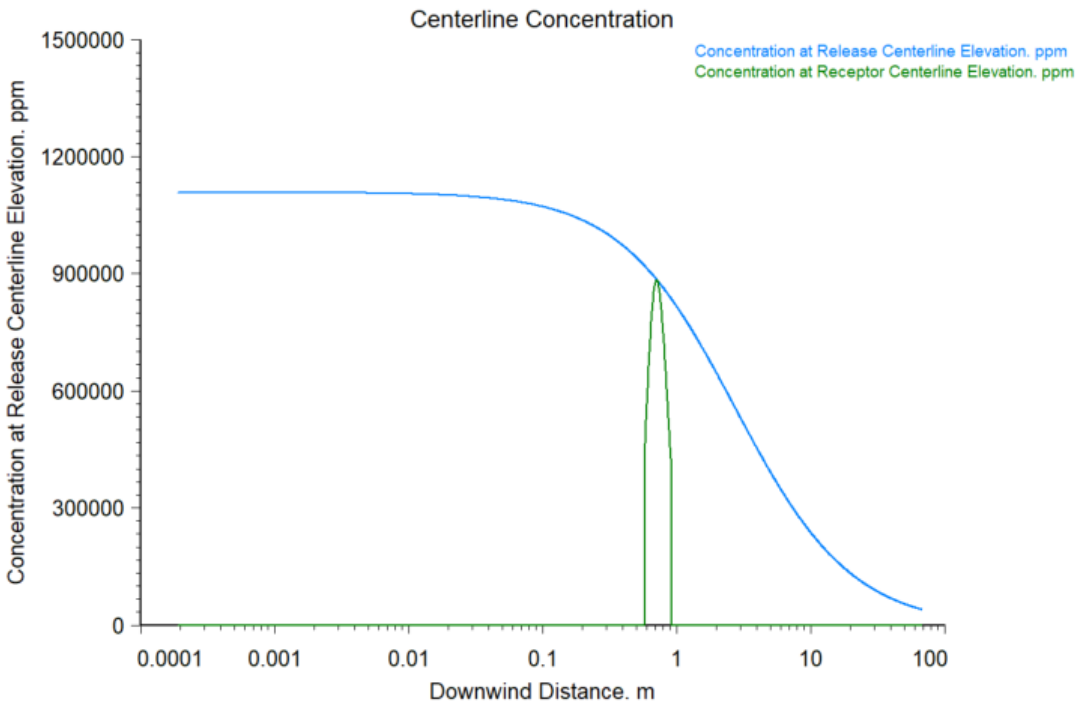


Fig. 74 : Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Centerline Concentration

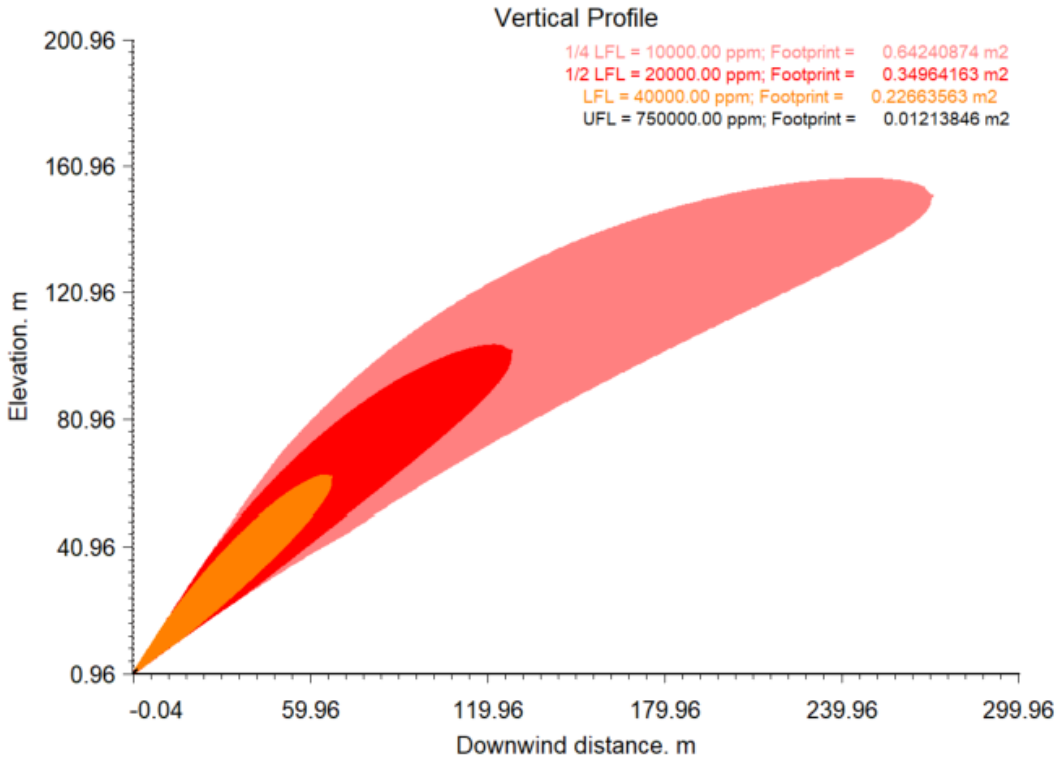


Fig. 75: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Flammable Contours Vertical Profile

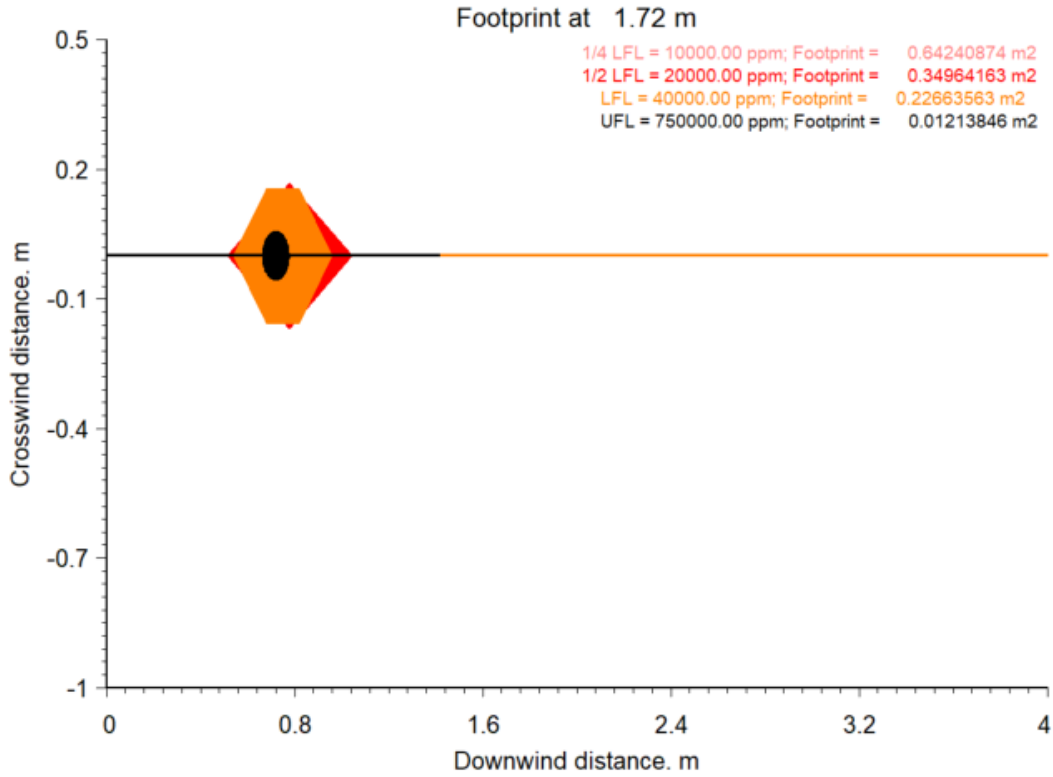


Fig. 76: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Flammable Contours Footprint at 1.72m



Fig. 77: Vapor Jet Consequences - 25 mm orifice - Segment H2-H3

Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle

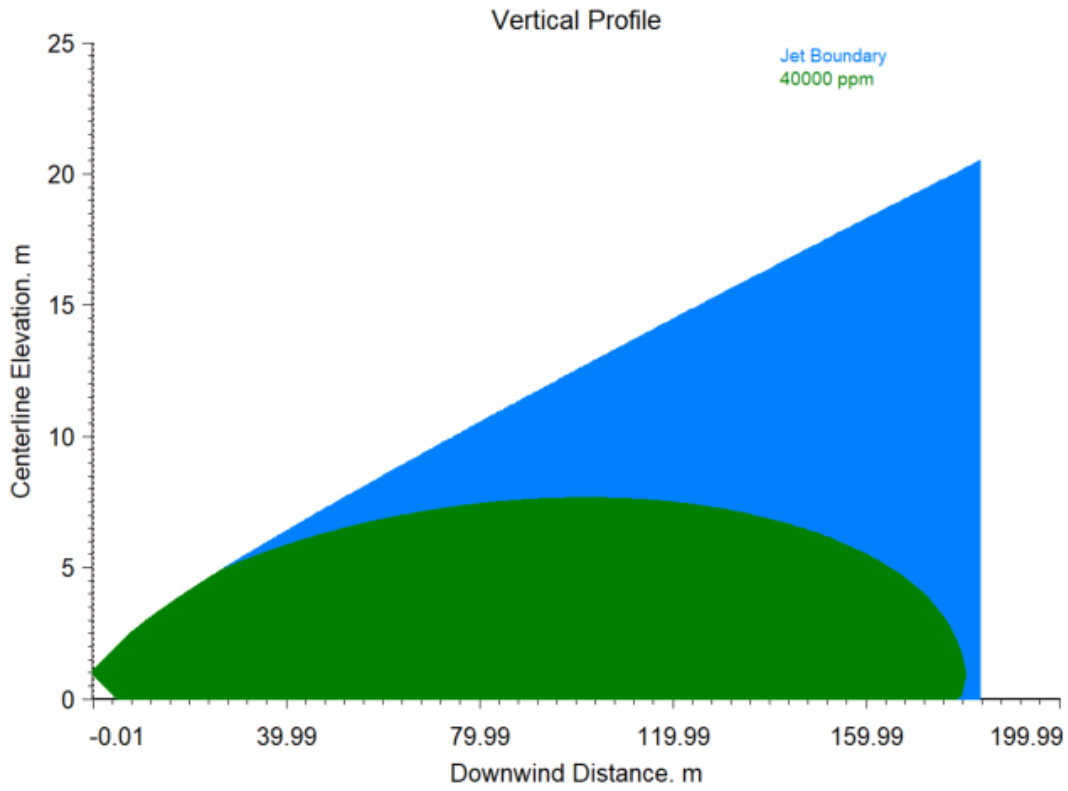


Fig. 78: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Vertical Profile

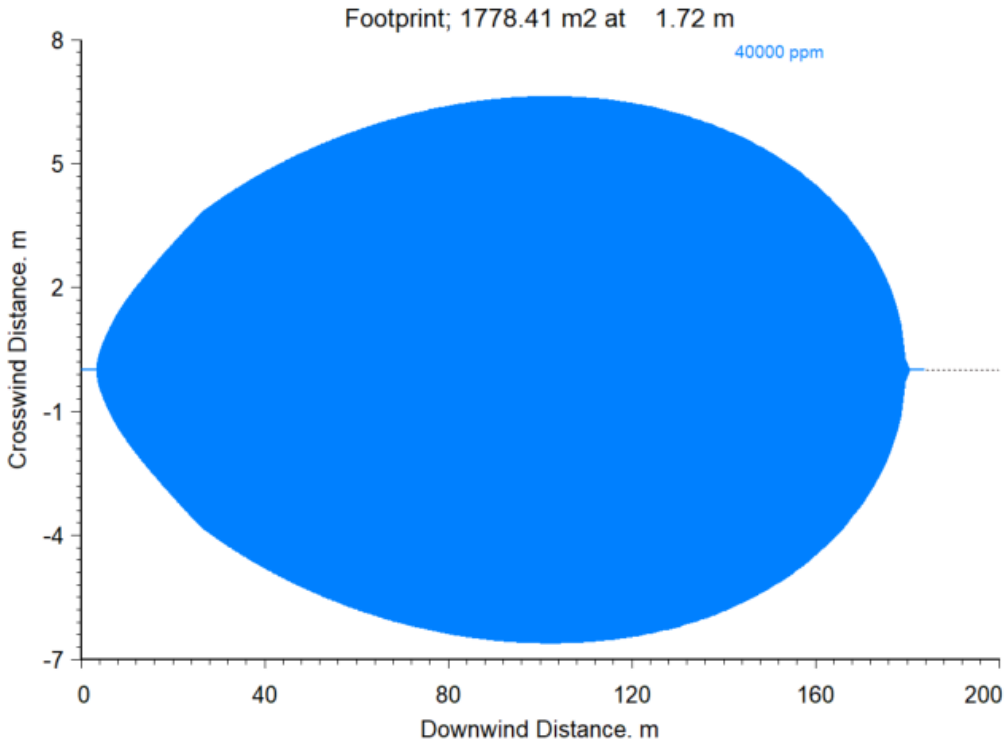


Fig. 79: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Footprint at 1.72m

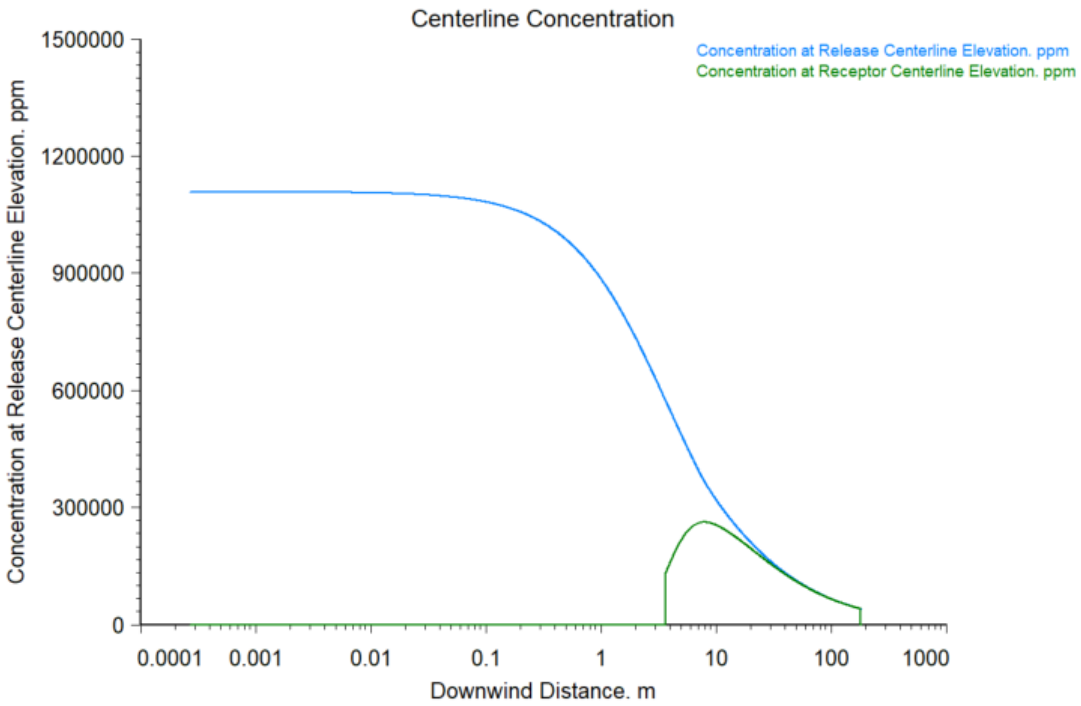


Fig. 80: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Centerline Concentration

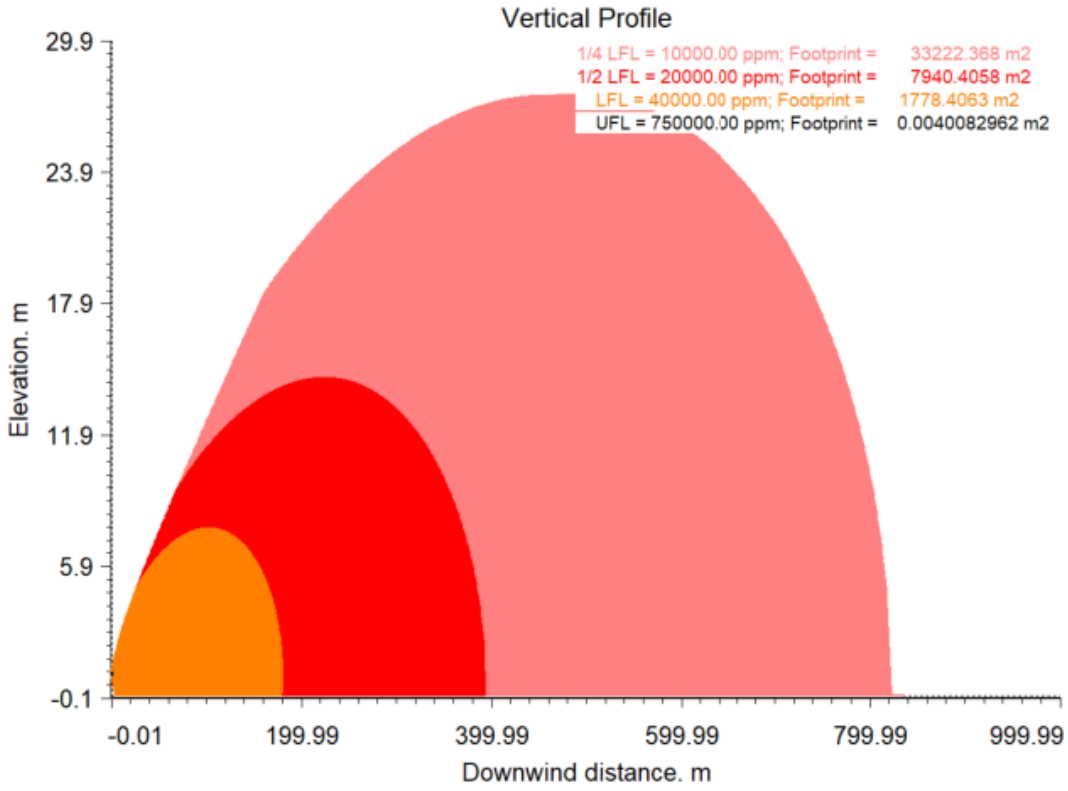


Fig. 81: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Flammable Contours Vertical Profile

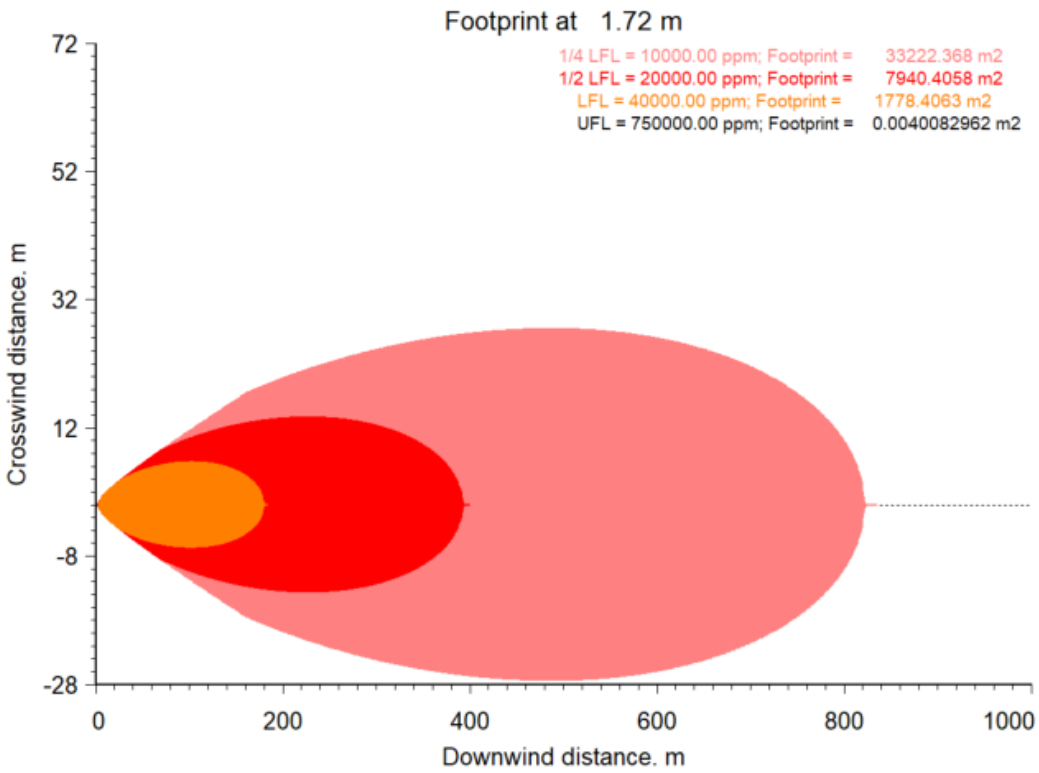


Fig. 82: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Footprint at 1.72m

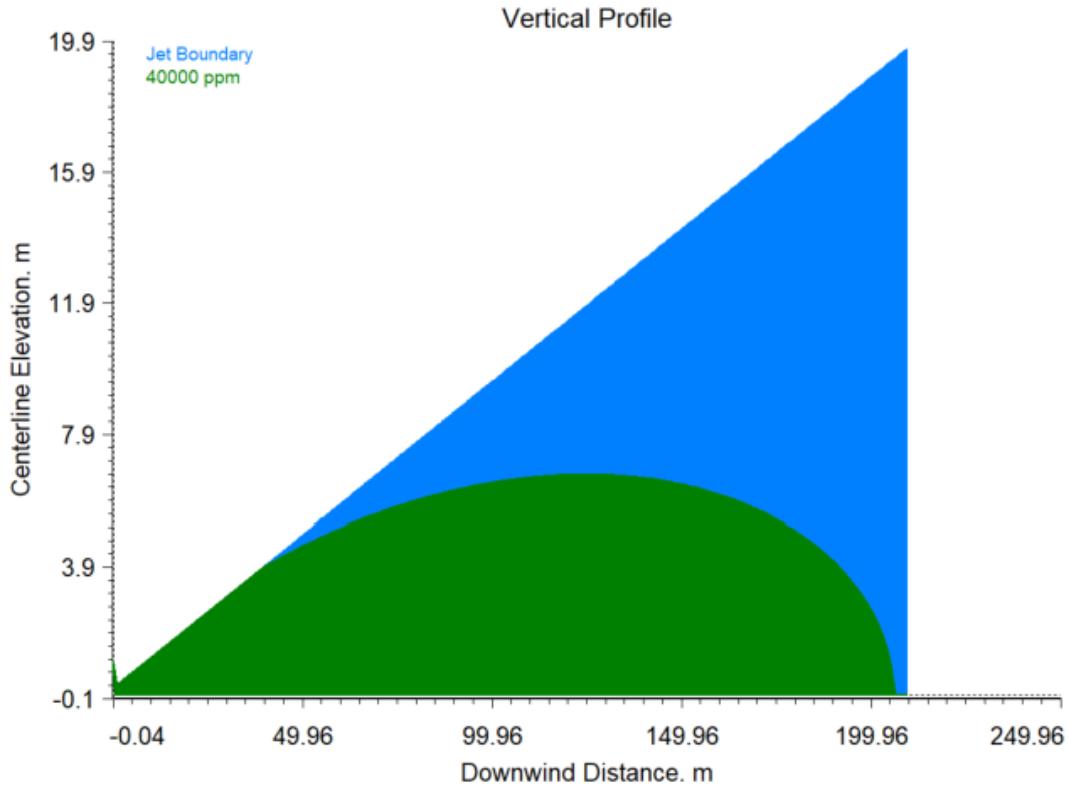


Fig. 83: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Vertical Profile

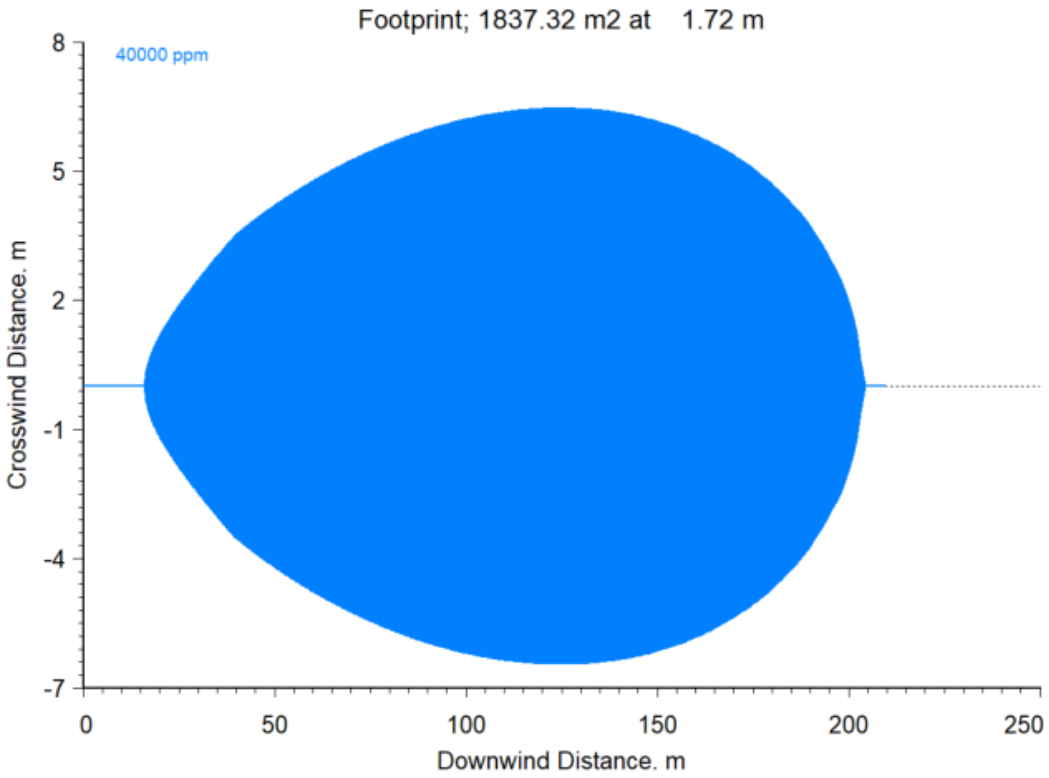


Fig. 84: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Footprint at 1.72m

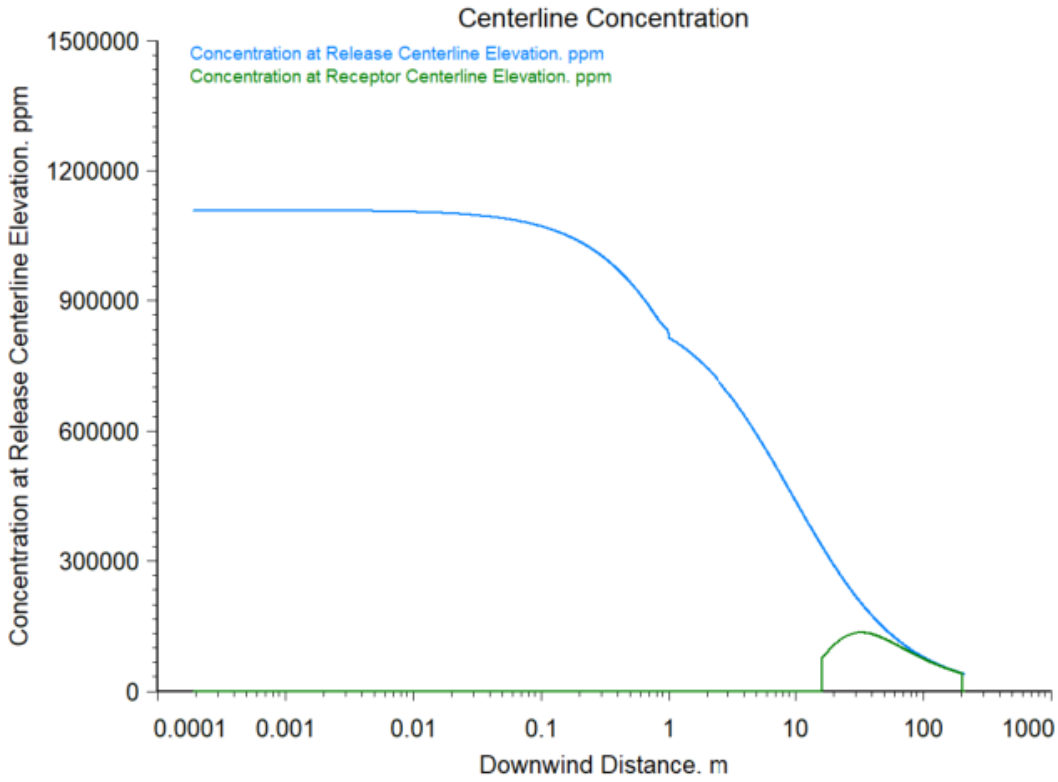


Fig. 85: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Centerline Concentration

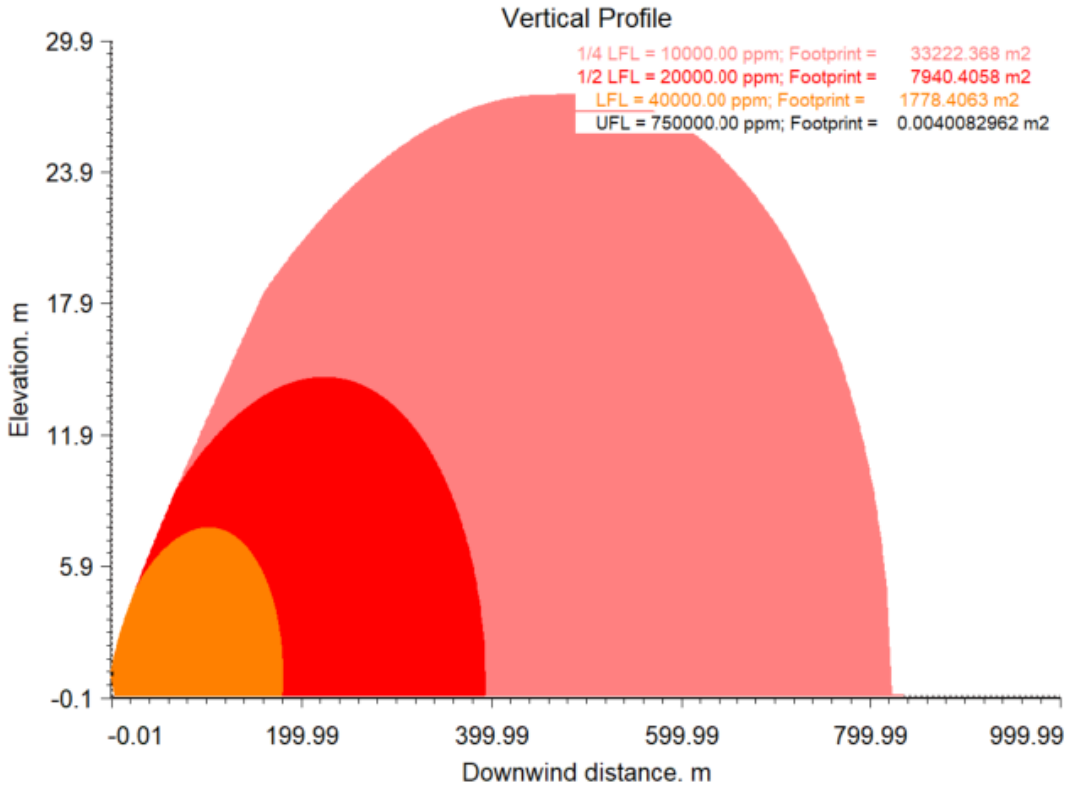


Fig. 86: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Flammable Contours Vertical Profile

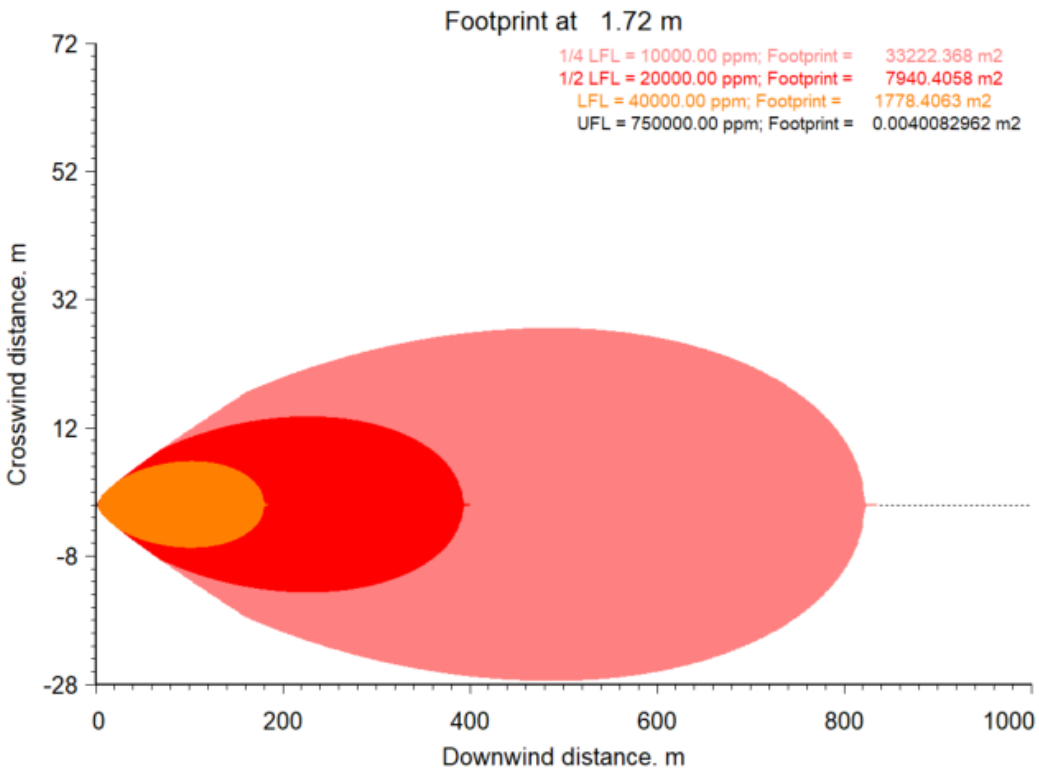


Fig. 87: Vapor Jet Model: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Flammable Contours Footprint at 1.72m

Fireball Model: Gaseous Hydrogen, 25 mm orifice

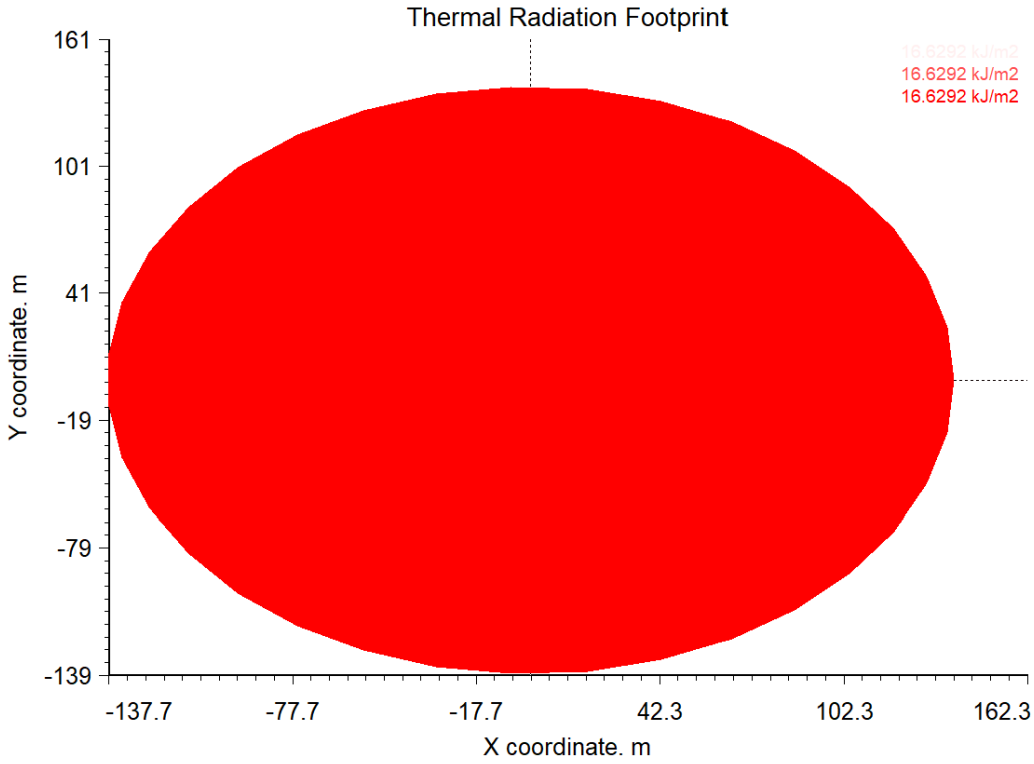


Fig. 88: Fireball Model: Gaseous Hydrogen, 25 mm orifice - Thermal Radiation Footprint



Fig. 89: Fireball Consequences - 25 mm orifice - segment H2-H3

Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle

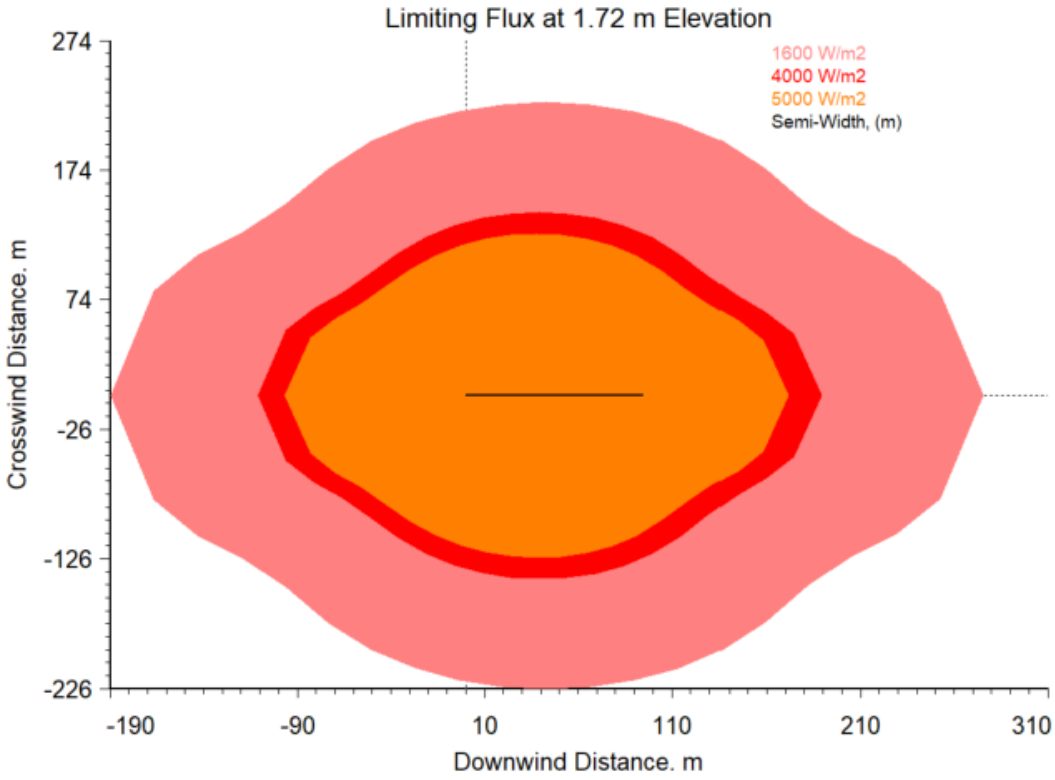


Fig. 90: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Limiting Flux at 1.72m Elevation

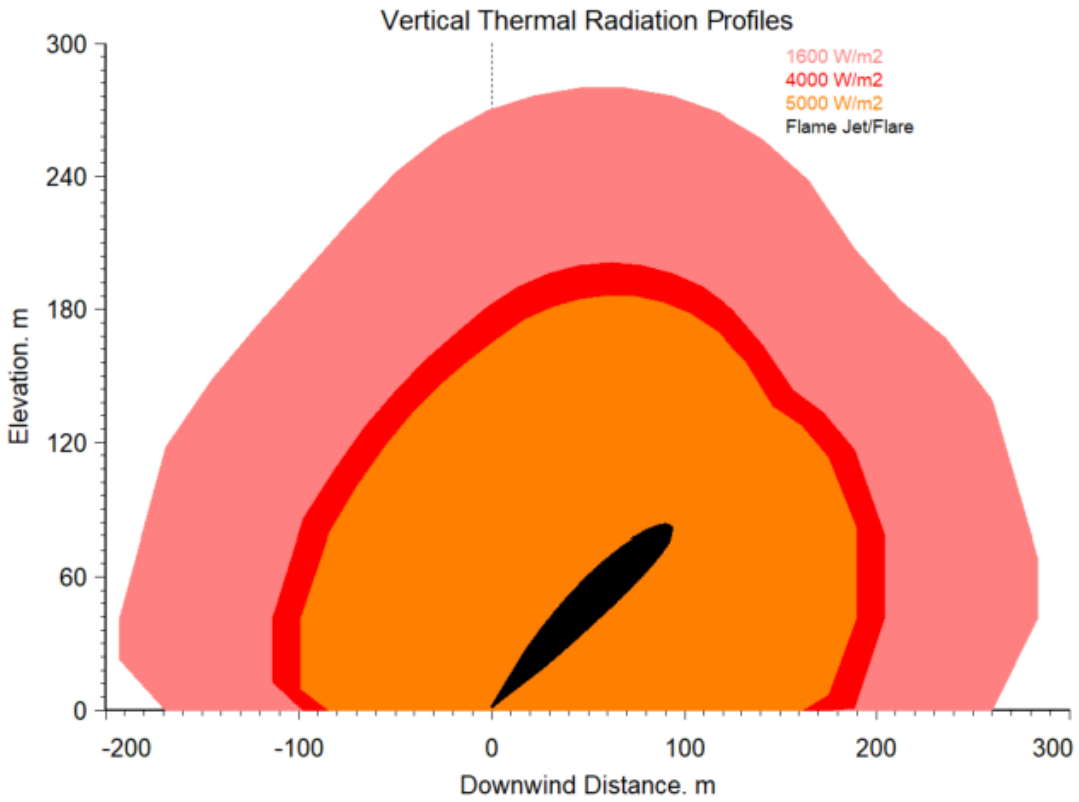


Fig. 91: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Vertical Thermal Radiation Profiles

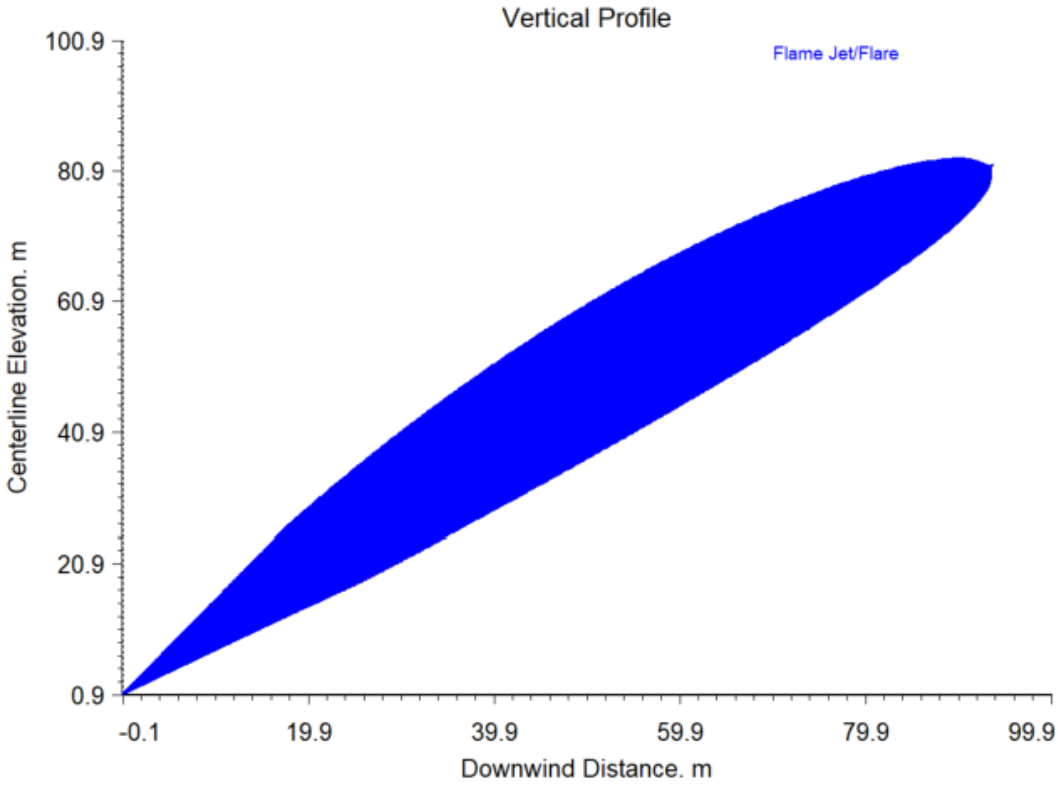


Fig. 92: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Vertical Profile

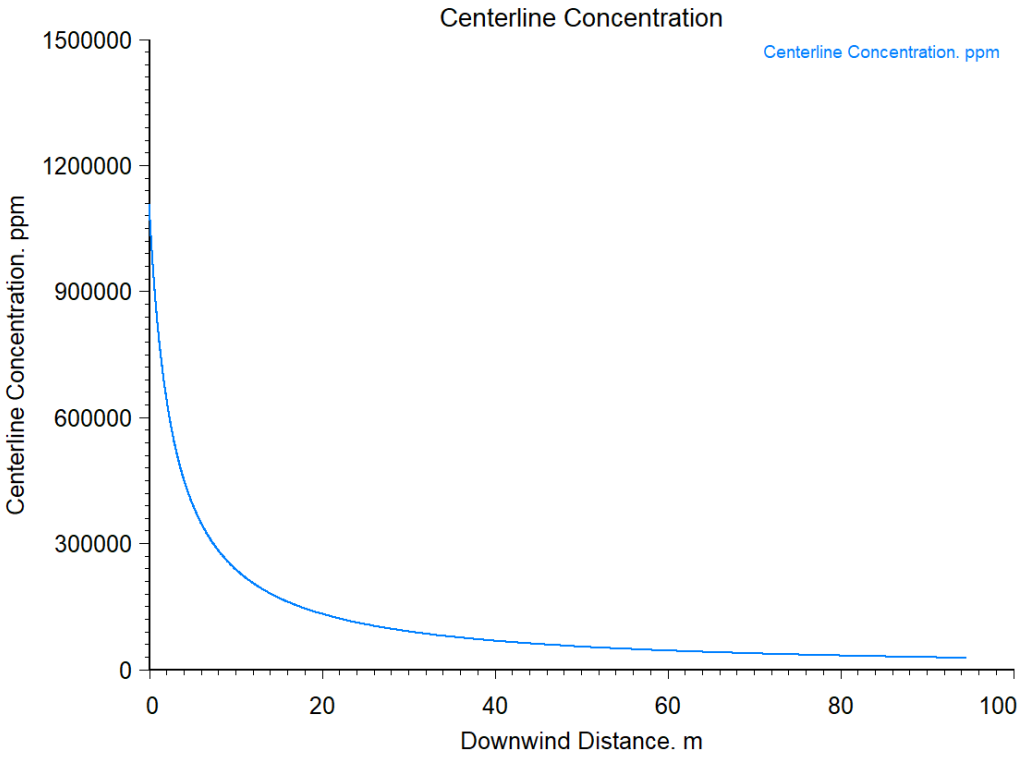


Fig. 93: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Centerline Concentration

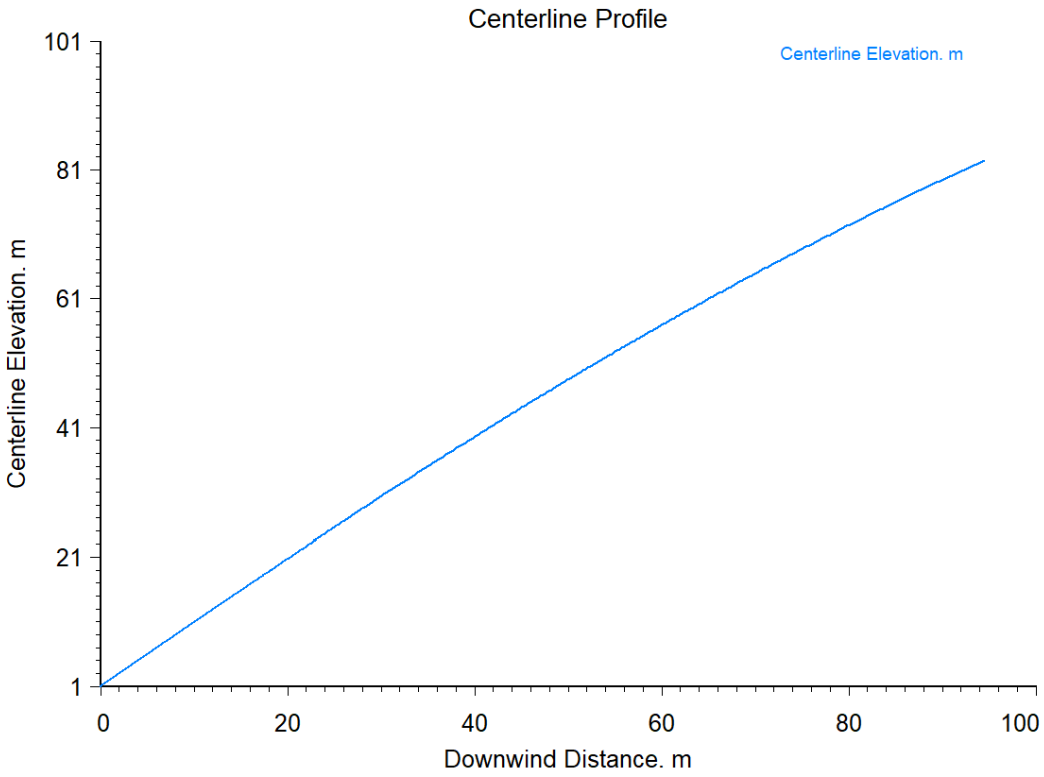


Fig. 94: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Centerline Profile

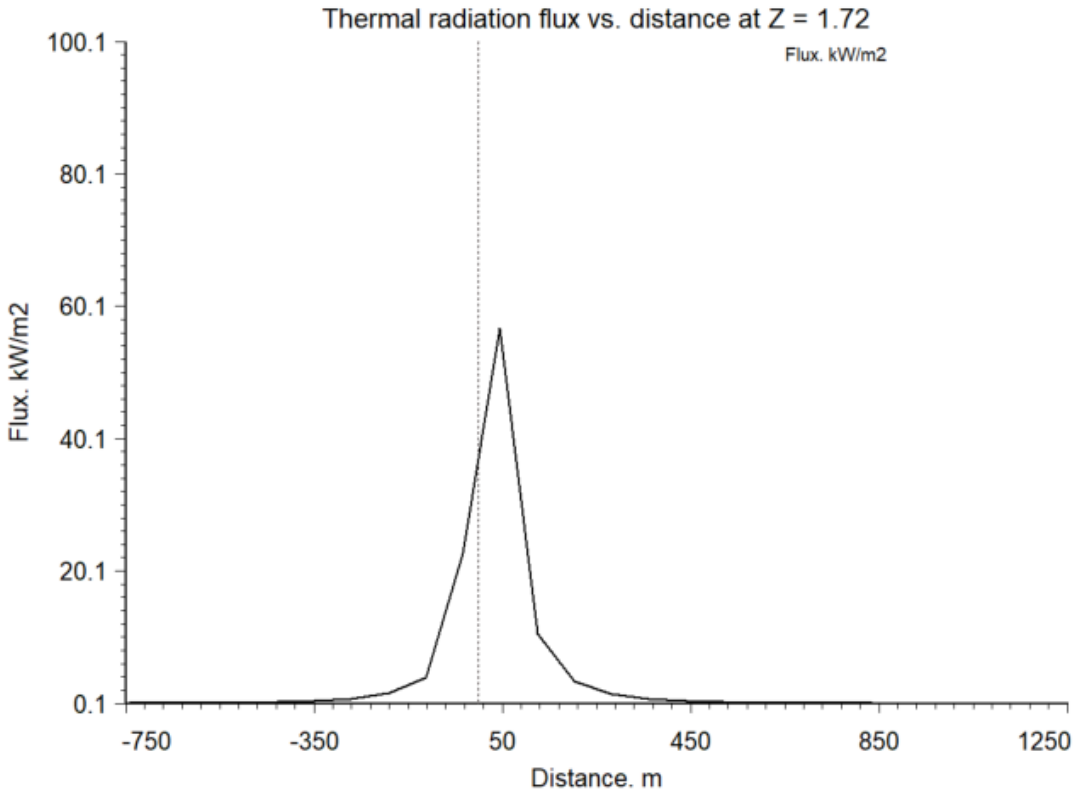


Fig. 95: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - thermal Radiation Flux vs. Distance at 1.72m



Fig. 96: Gas Flame Jet Consequences - 25 mm orifice - Segment H2-H3

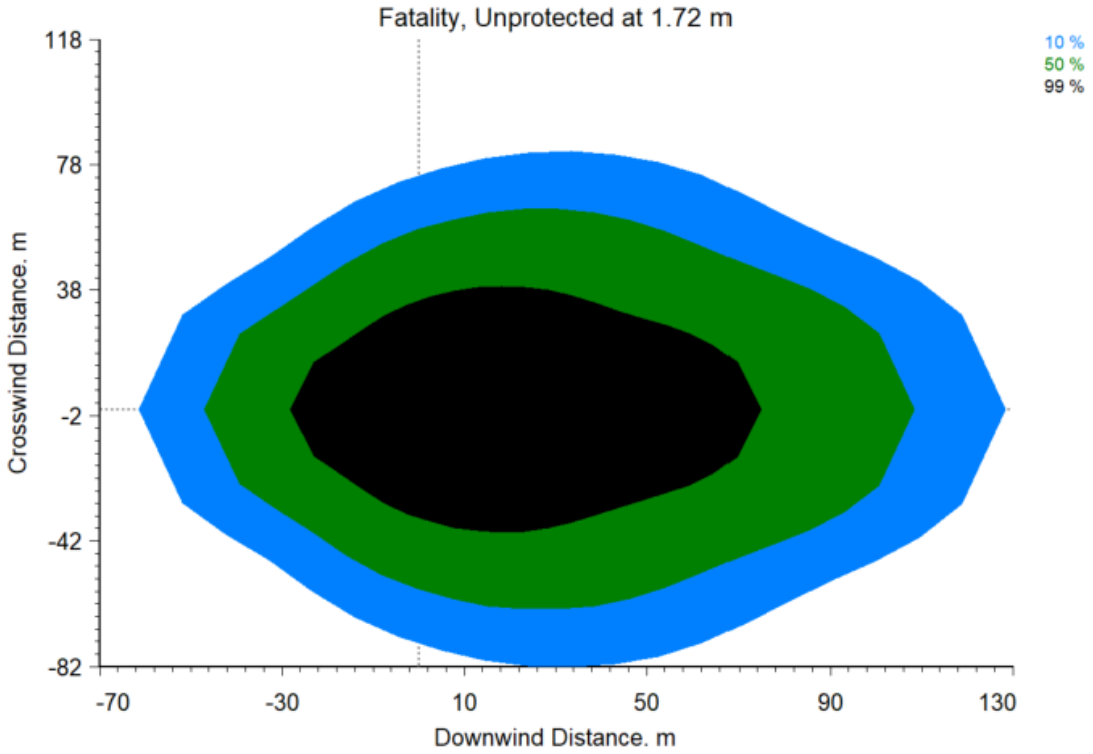


Fig. 97: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

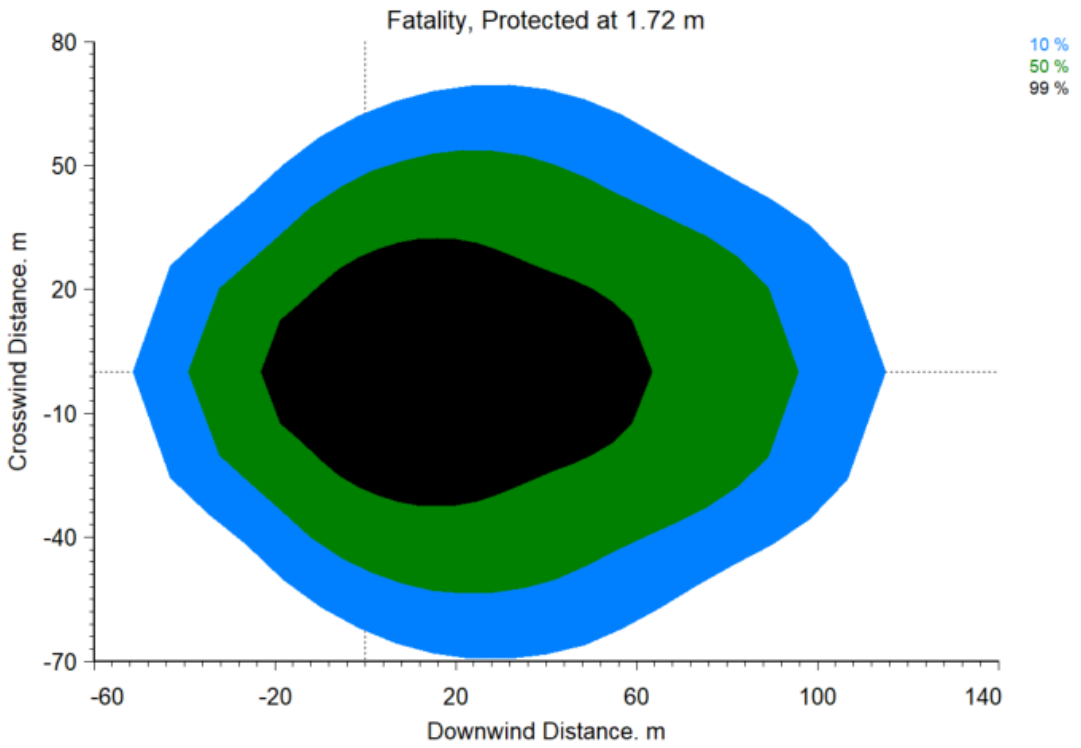


Fig. 98: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Probit Results - Fatality (Protected) at 1.72m

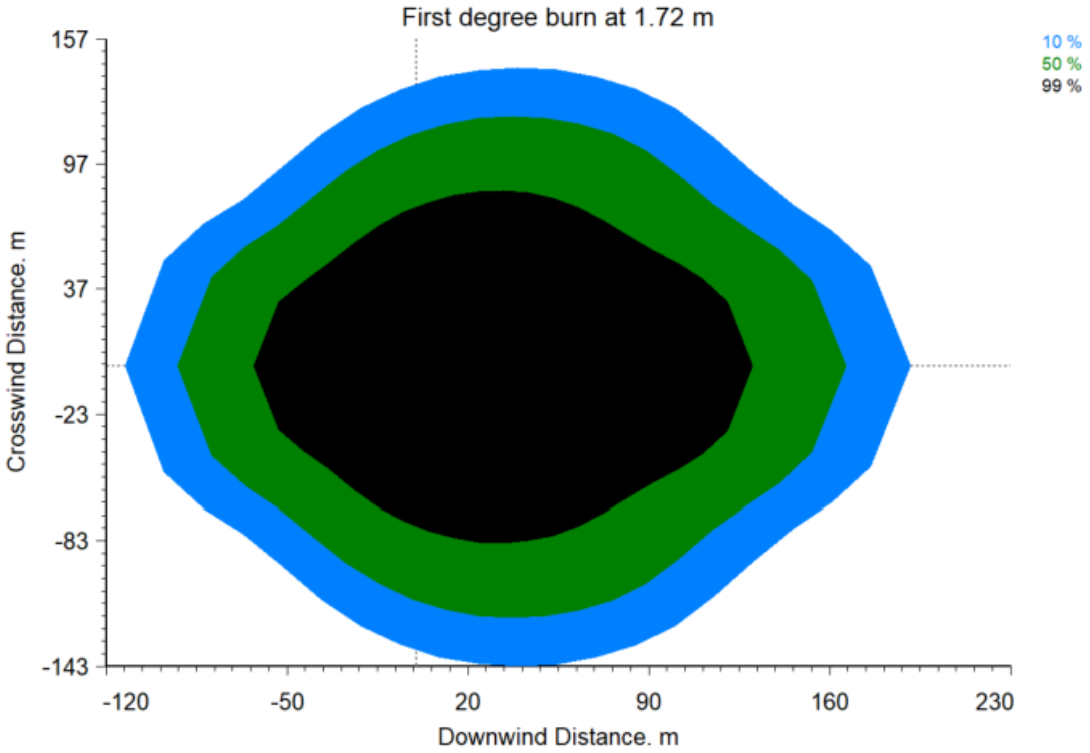


Fig. 99: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Probit Results – First Degree Burns at 1.72m

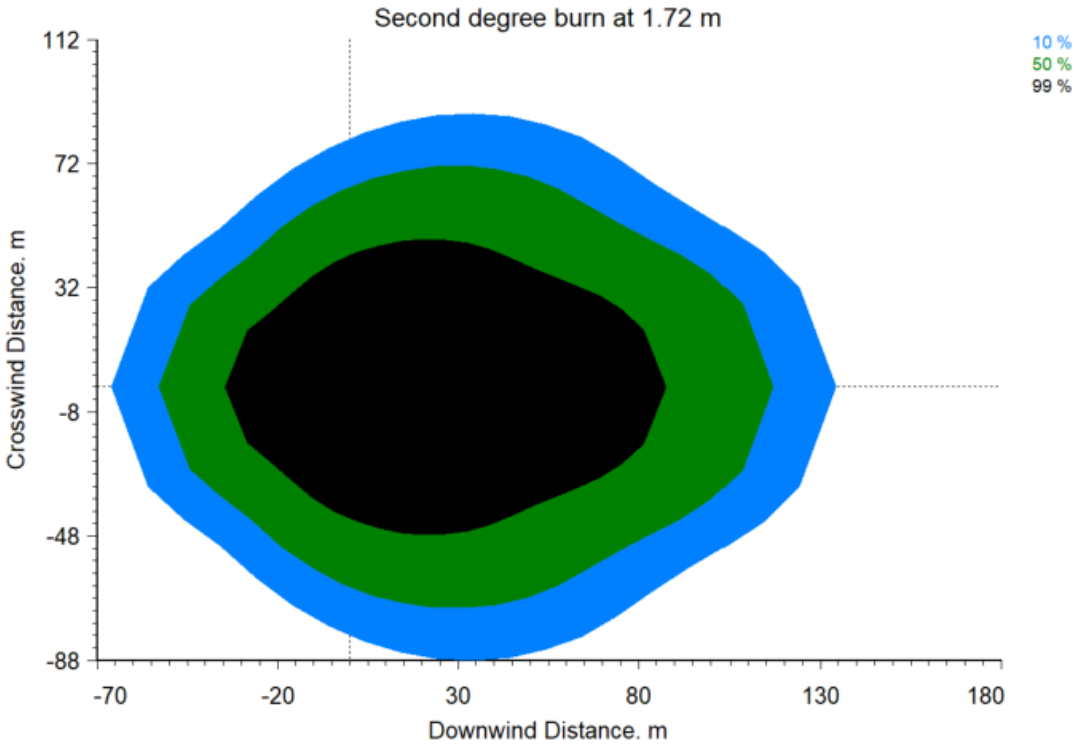


Fig. 100: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 45° Release Angle - Probit Results – Second Degree Burns at 1.72m

Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle

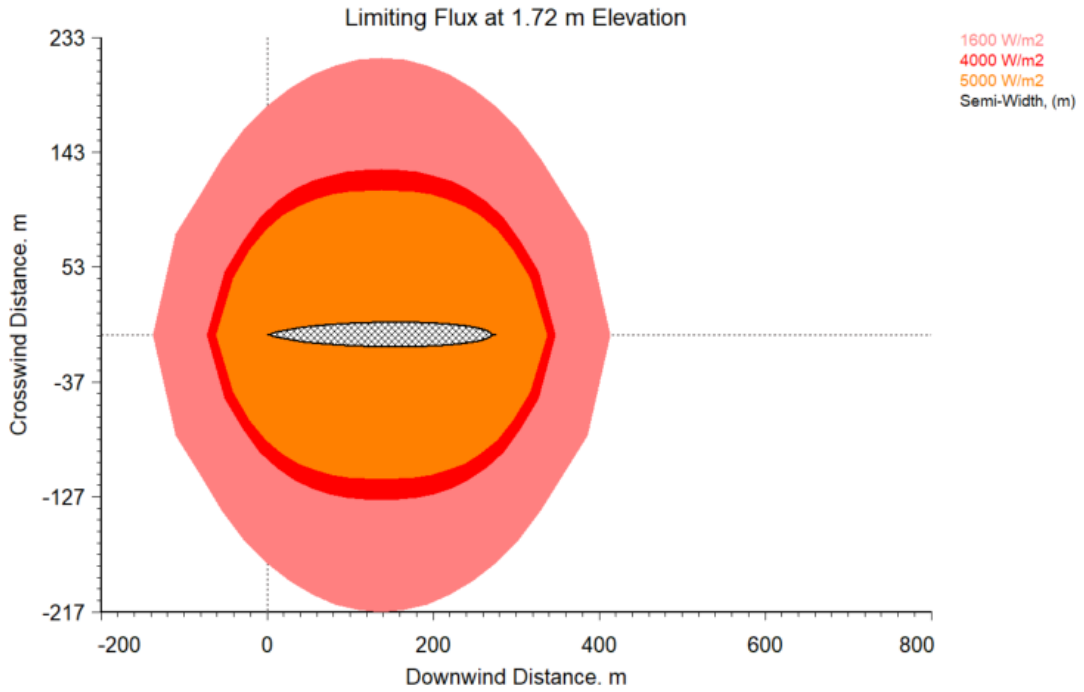


Fig. 101: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Limiting Flux at 1.72m Elevation

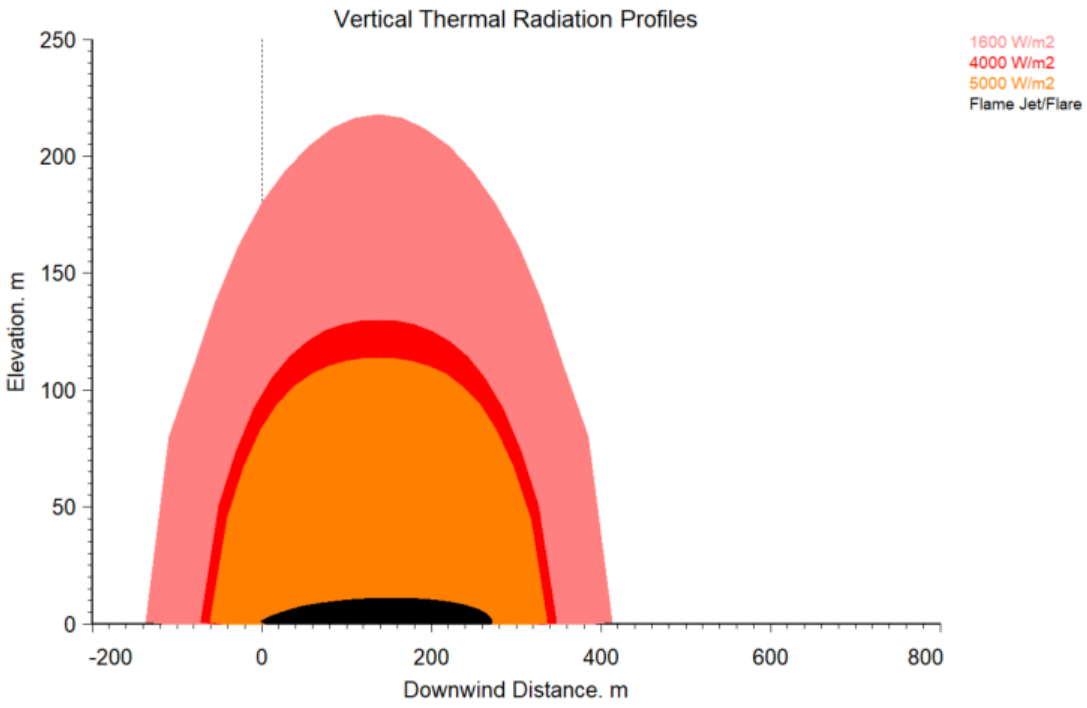


Fig. 102: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle – Vertical Thermal Radiation Proifles

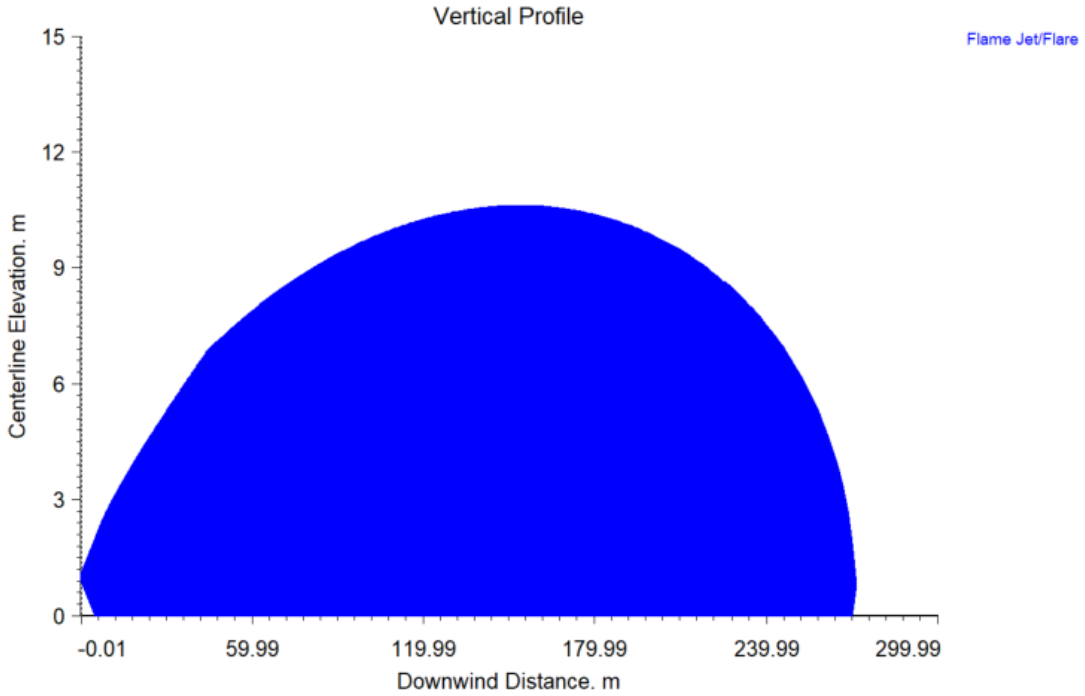


Fig. 103: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle – Vertical Profile

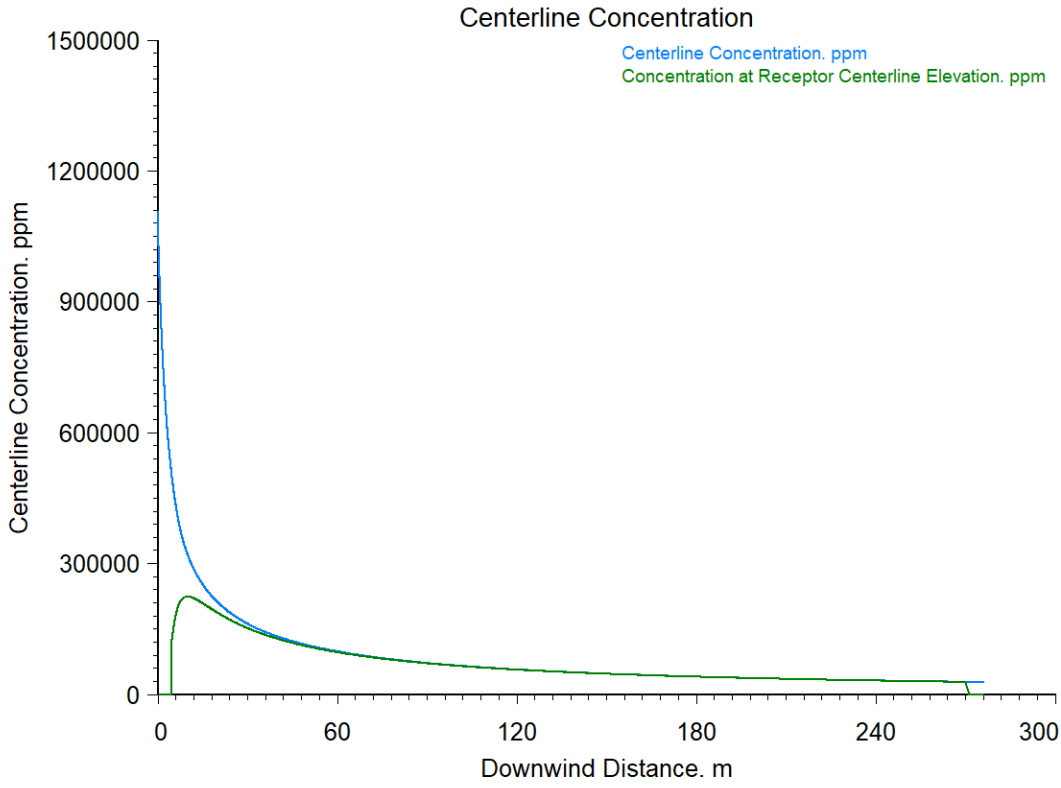


Fig. 104: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Centerline Concentration

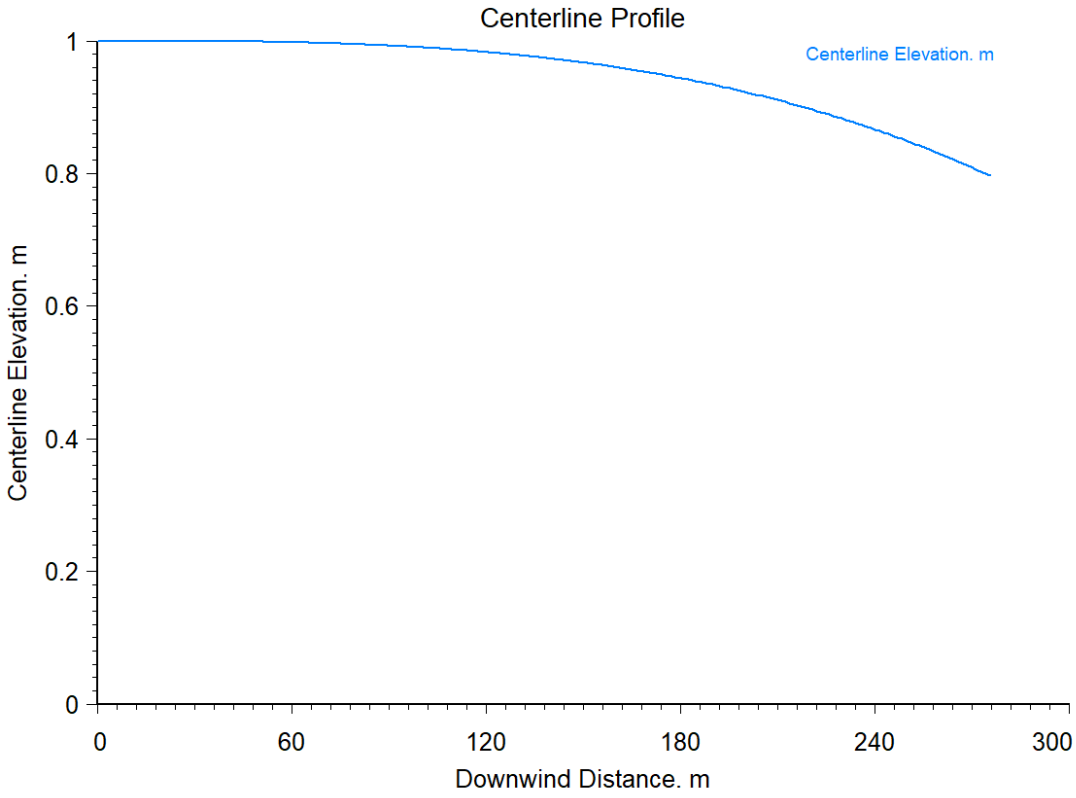


Fig. 105: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Centerline Profile

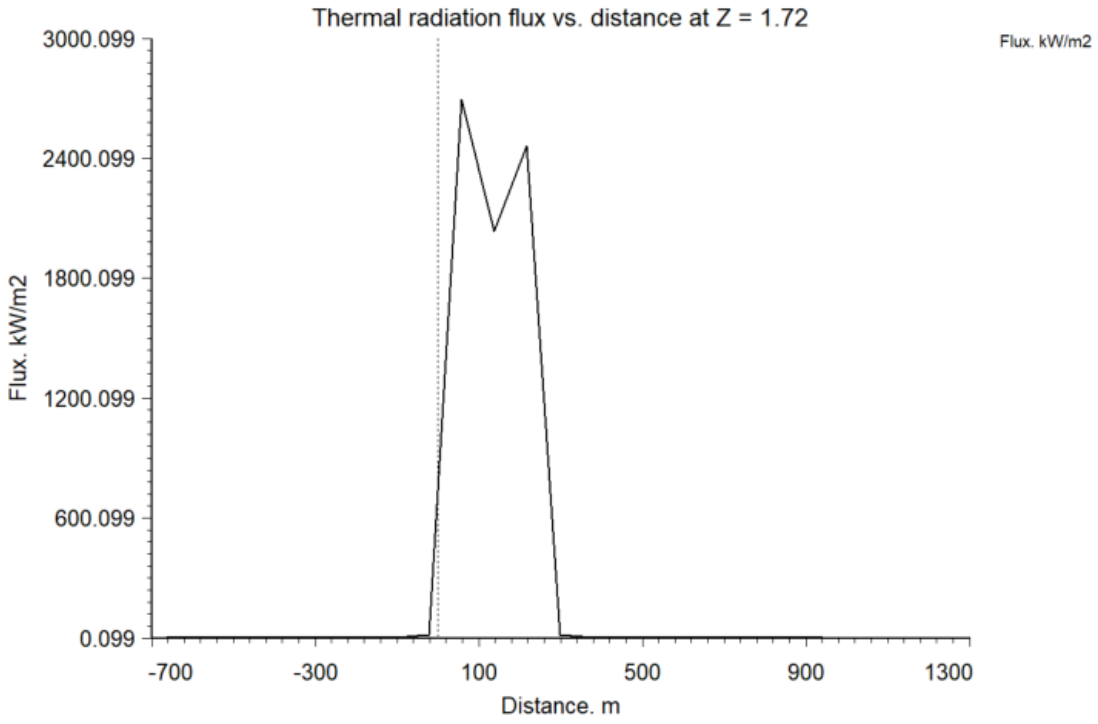


Fig. 106: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Thermal Radiation Flux vs. Distance at 1.72m

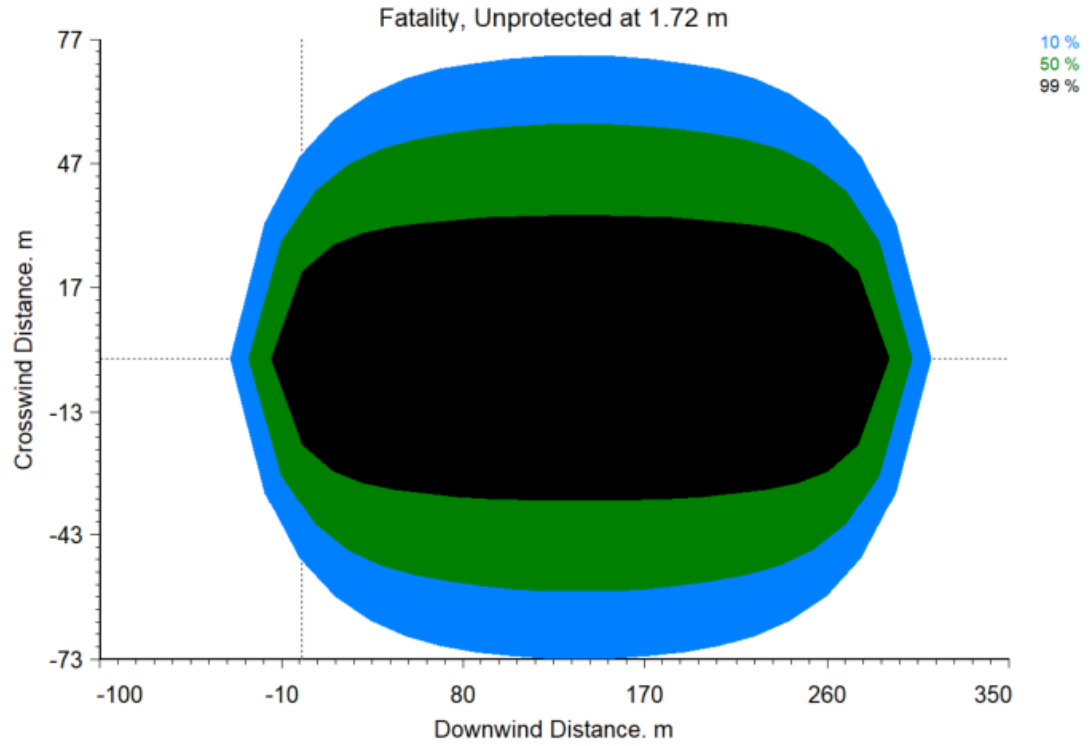


Fig. 107: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

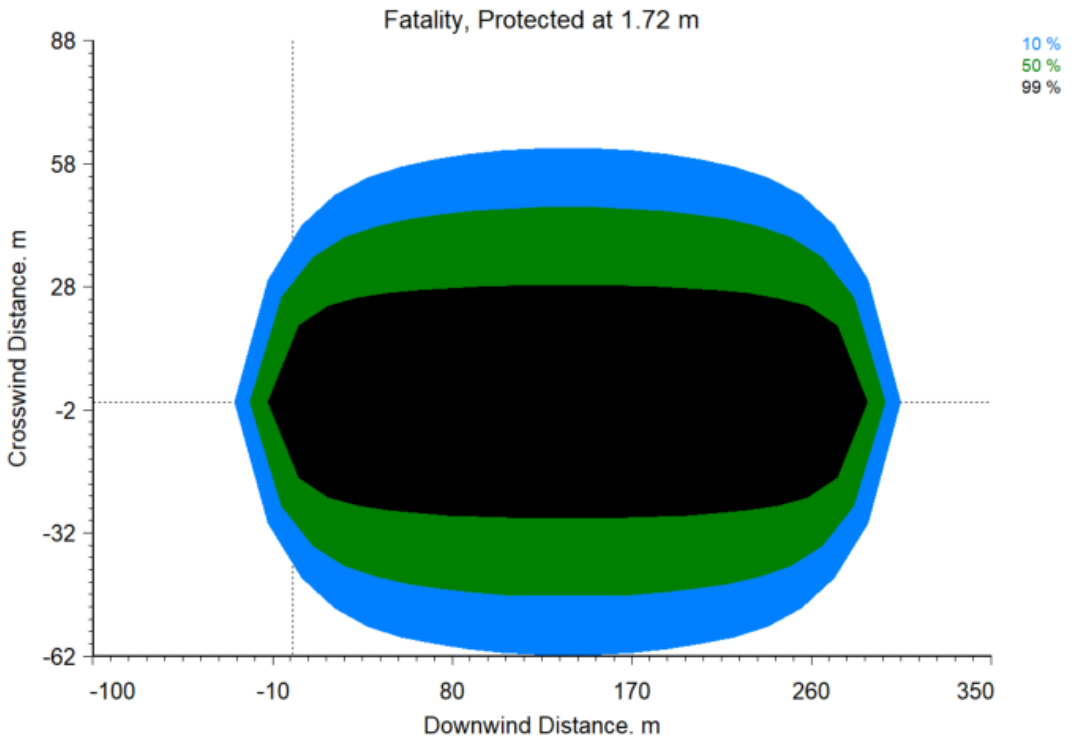


Fig. 108: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Probit Results - Fatality (Protected) at 1.72m

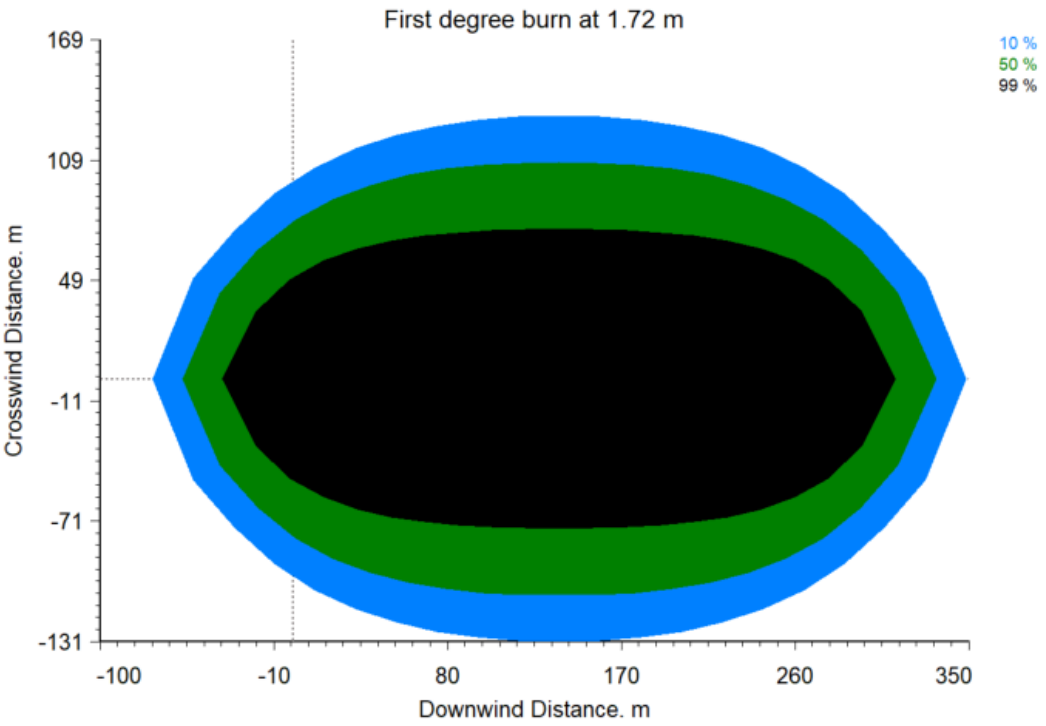


Fig. 109: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Probit Results – First Degree Burns at 1.72m

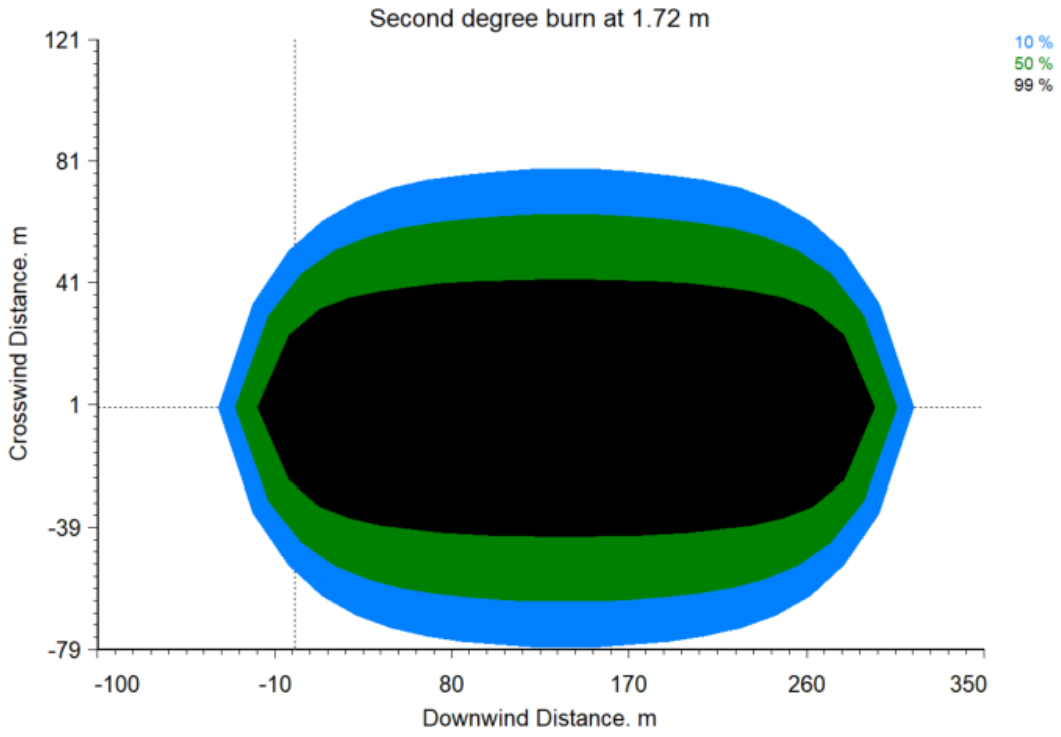


Fig. 110: Gaseous Hydrogen, 25 mm orifice, 0° Release Angle - Probit Results – Second Degree Burns at 1.72m

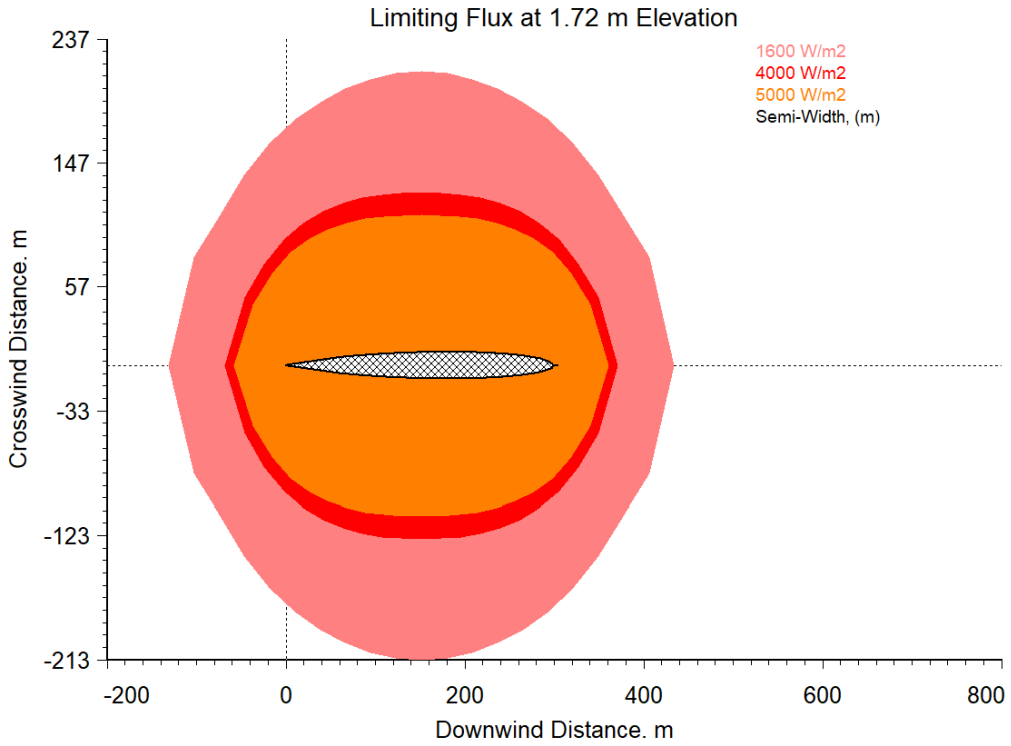


Fig. 111: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Limiting Flux at 1.72m Elevation

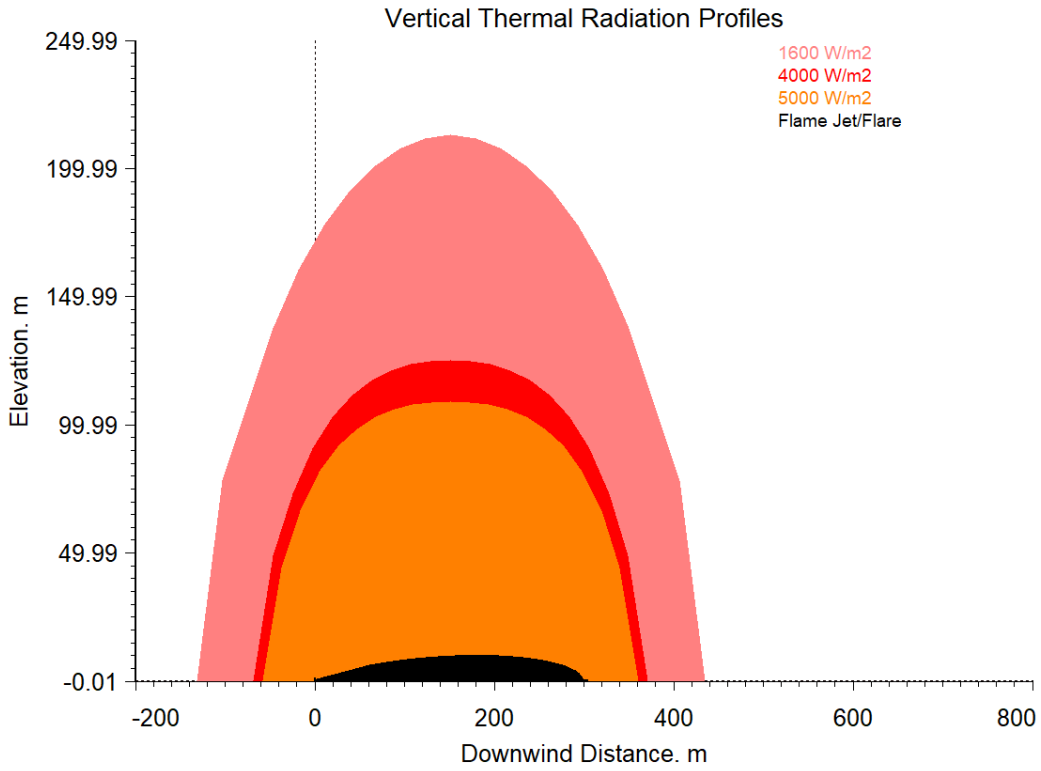


Fig. 112: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Vertical Thermal Radiation Profiles

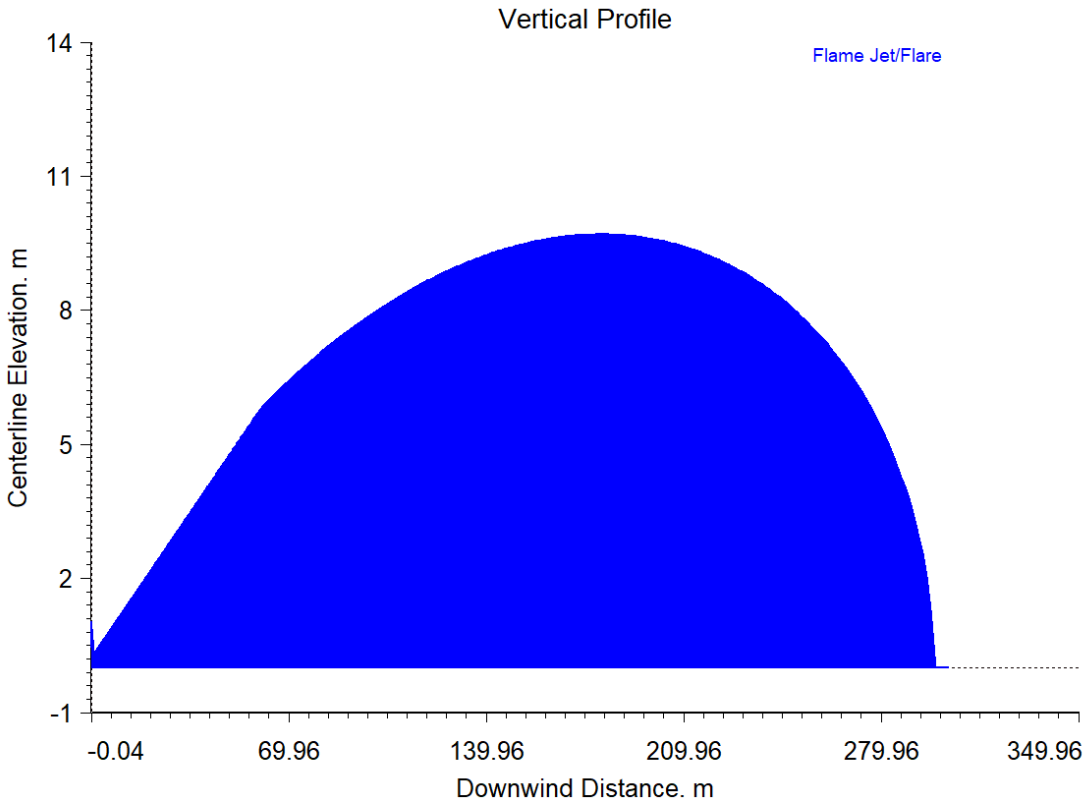


Fig. 113: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Vertical Profile

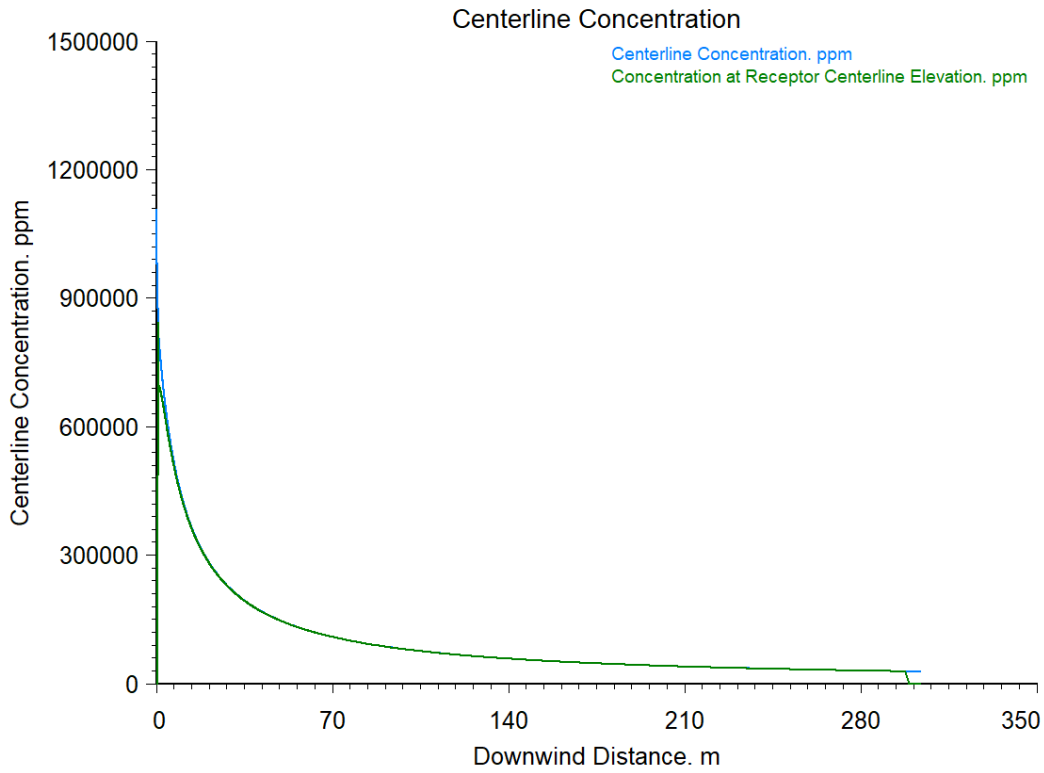


Fig. 114: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle – Centerline Concentration

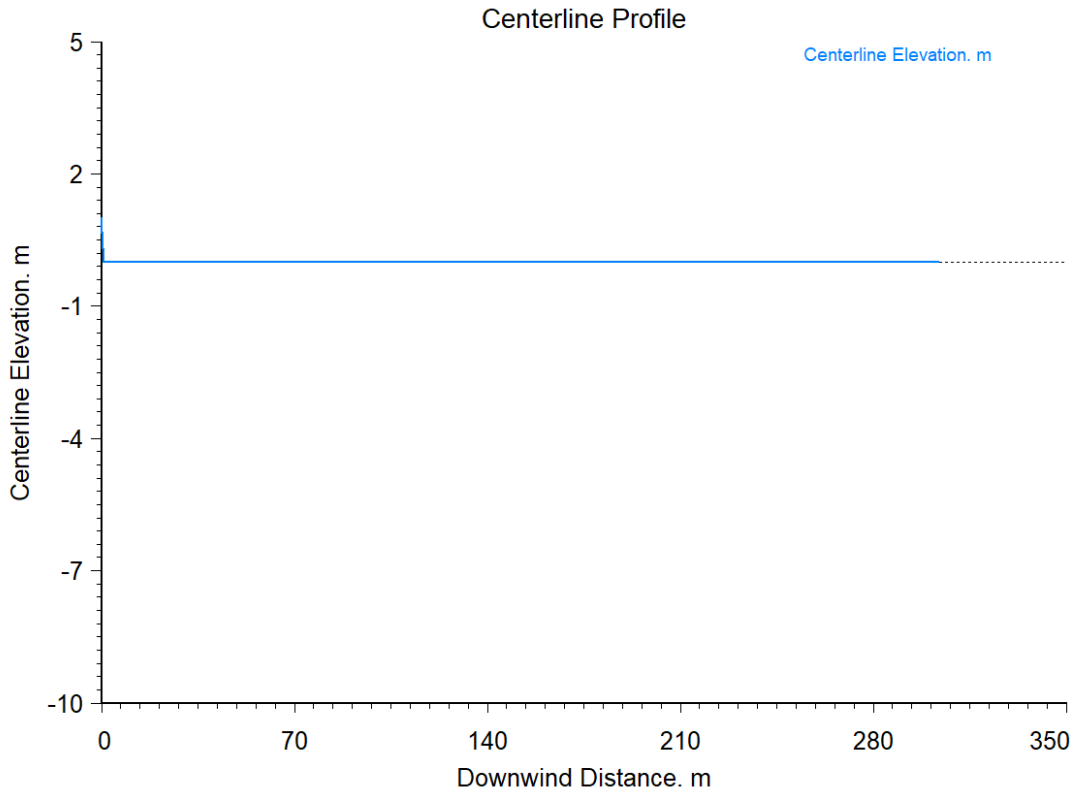


Fig. 115: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle – Centerline Profile

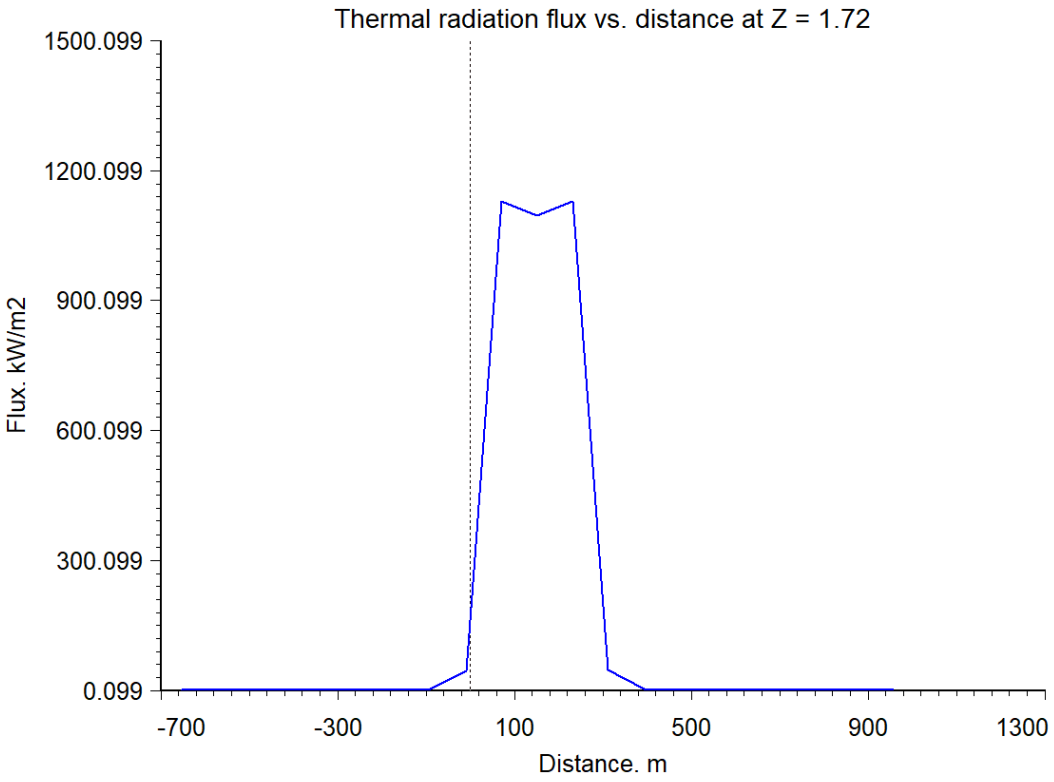


Fig. 116: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Thermal Radiation Flux vs. Distance at 1.72m

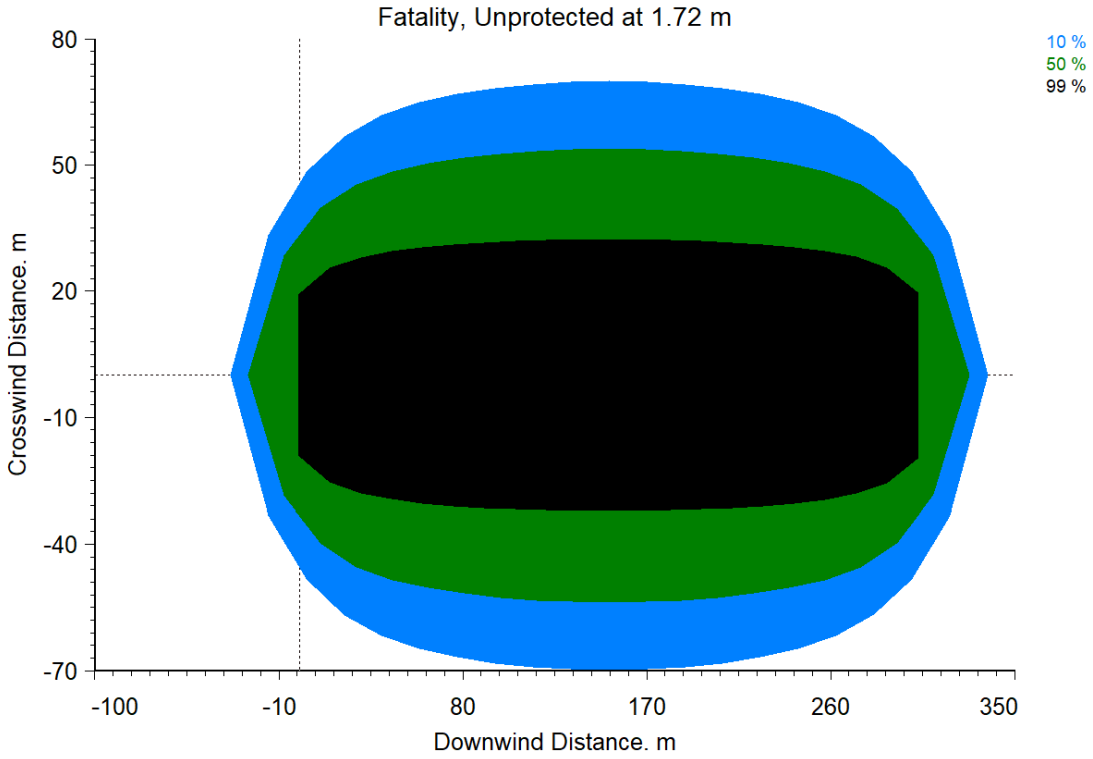


Fig. 117: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Probit Results - Fatality (Unprotected) at 1.72m

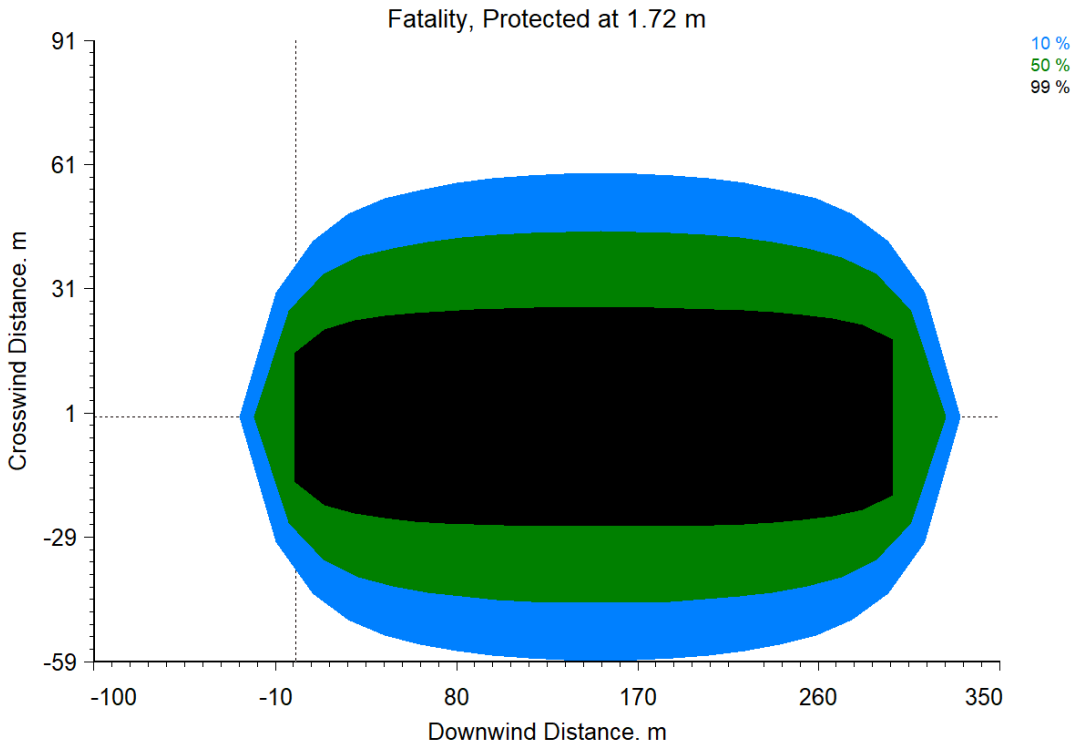


Fig. 118: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Probit Results - Fatality (Protected) at 1.72m

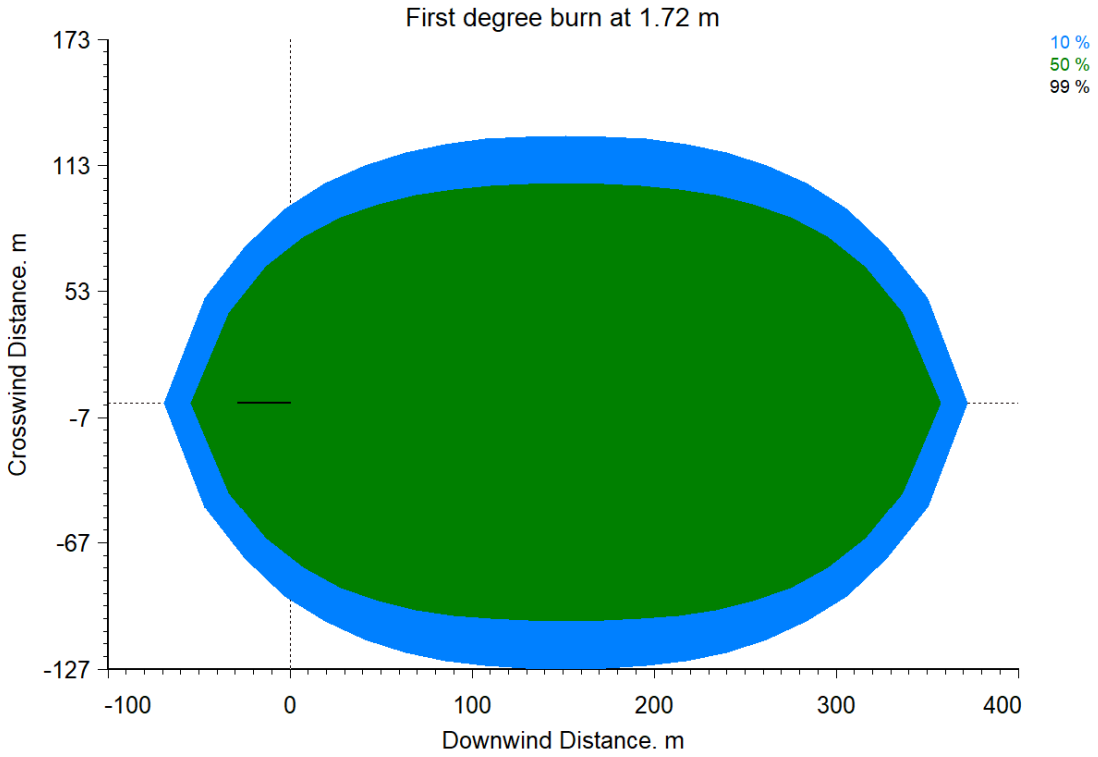


Fig. 119: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Probit Results – First Degree Burns at 1.72m

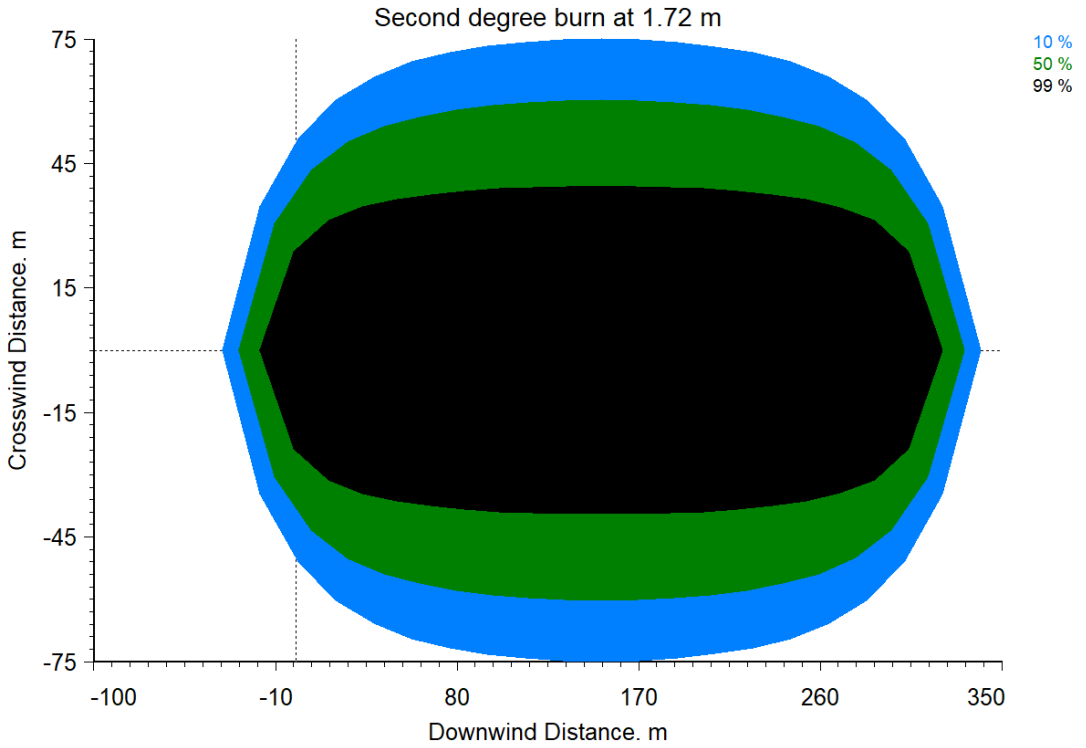


Fig. 120: Gas Flame Jet: Gaseous Hydrogen, 25 mm orifice, -45° Release Angle - Probit Results – Second Degree Burns at 1.72m

Two Phase Jet model: Liquid Hydrogen, 45° Release Angle

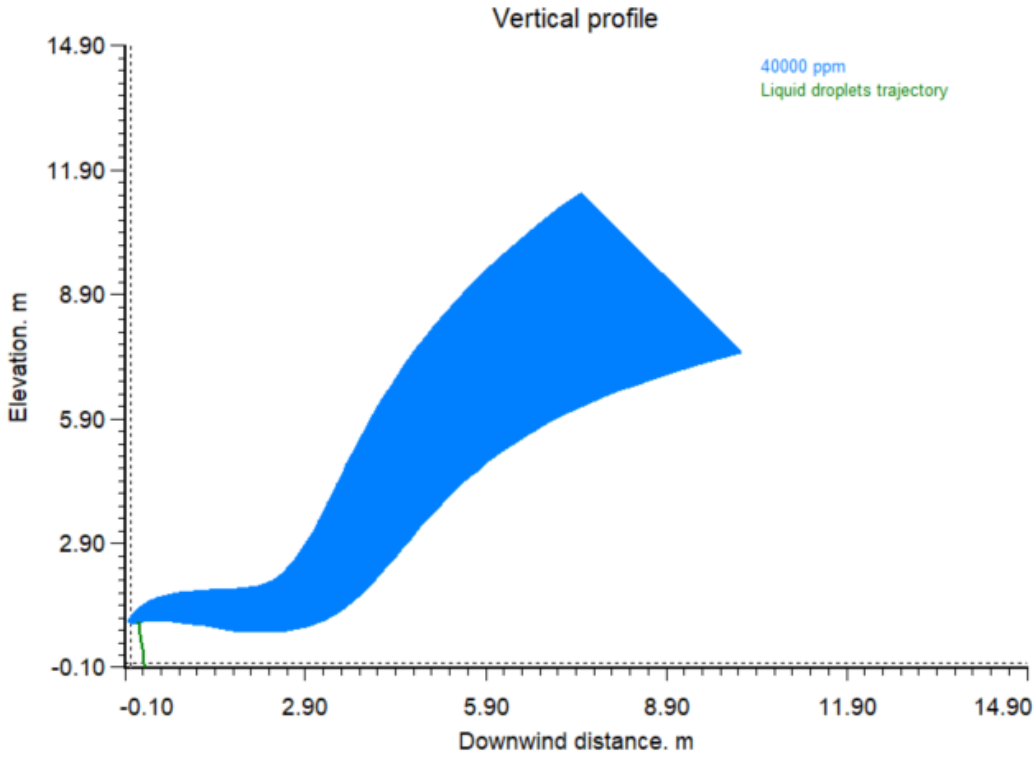


Fig. 121: Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm orifice, 45° Release Angle – Vertical Profile

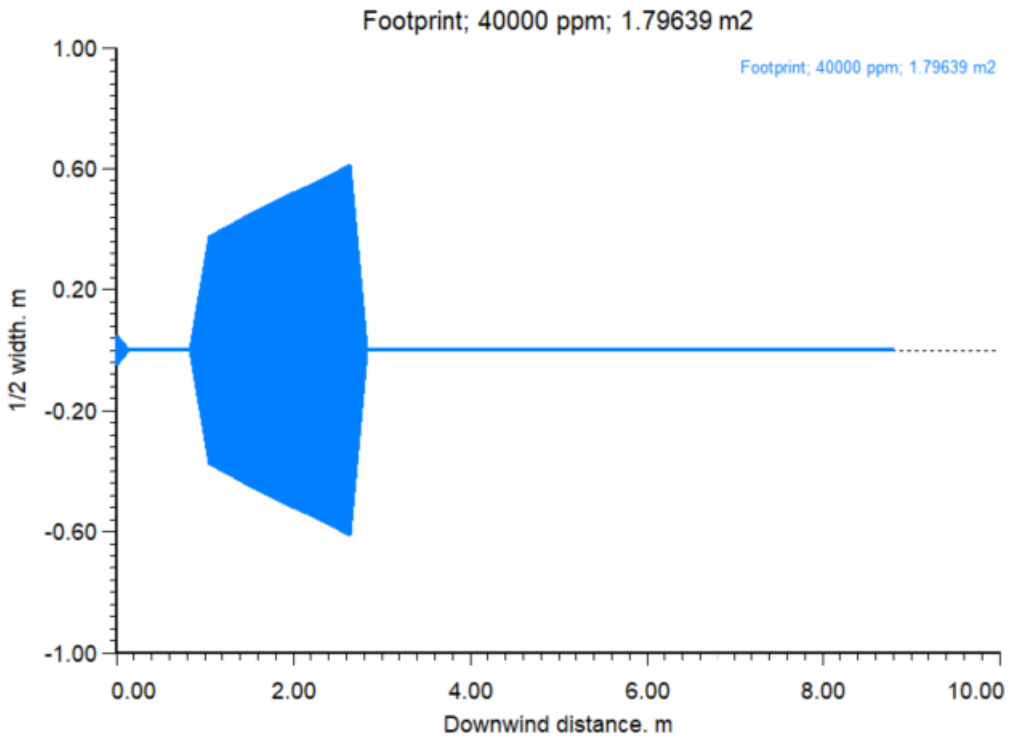


Fig. 122: Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm orifice, 45° Release Angle – Footprint

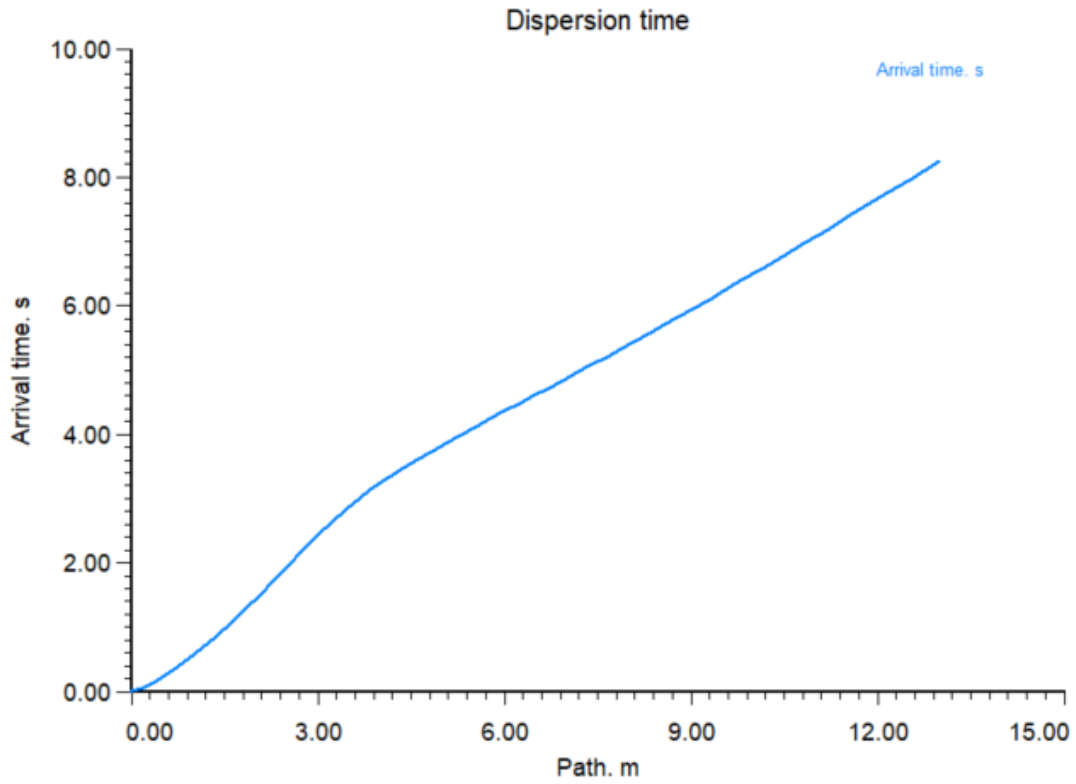


Fig. 123: Two-Phase Jet Model: Liquid Hydrogen, 100 mm orifice or 25 mm orifice, 45° Release Angle – Dispersion Time

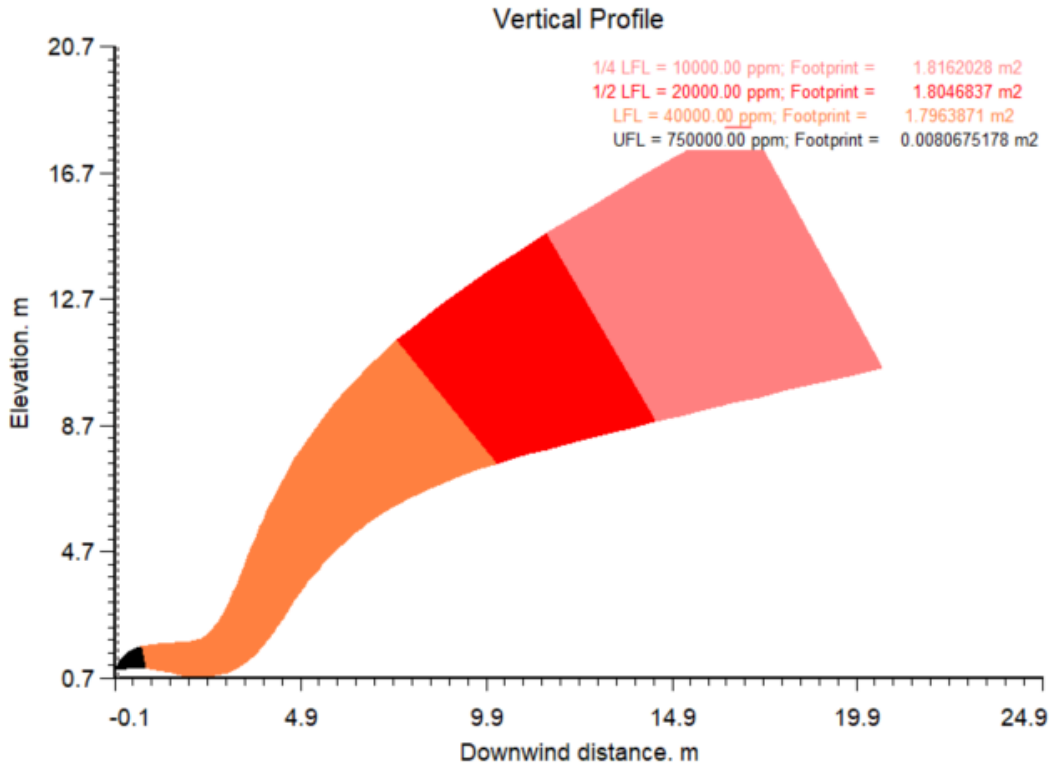


Fig. 124: Two-Phase Jet Model: Liquid Hydrogen, 25 mm orifice, 45° Release Angle - Flammable Contours Vertical Profile

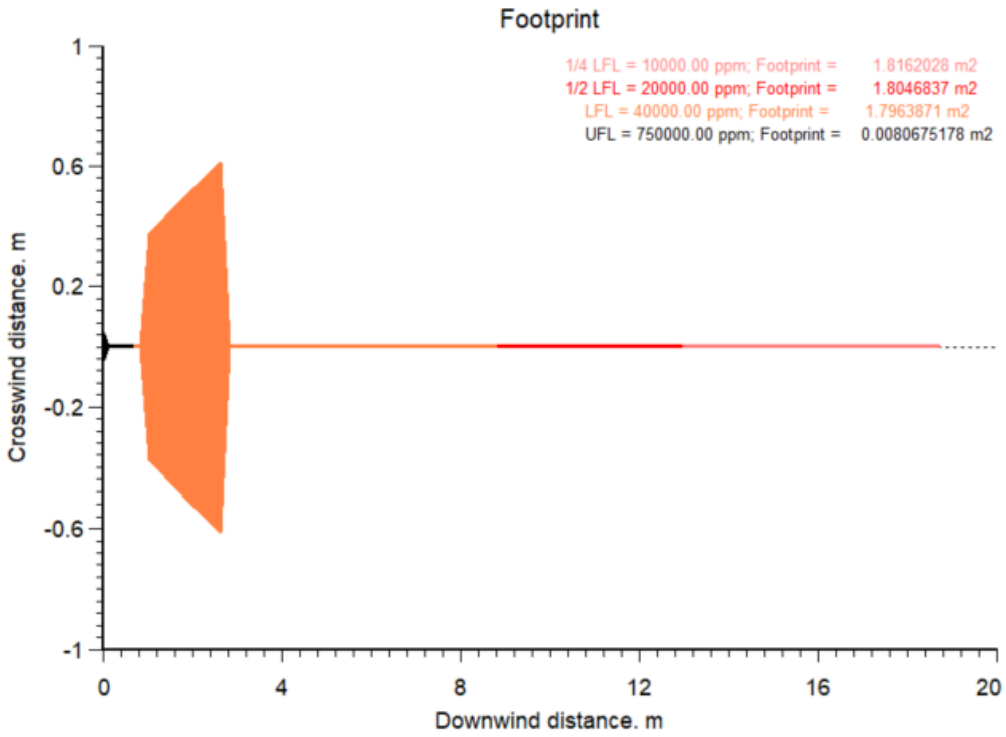


Fig. 125: Two-Phase Jet Model: Liquid Hydrogen, 25 mm orifice, 45° Release Angle - Flammable Contours Footprint

Two Phase Jet model: Liquid Hydrogen, 0° Release Angle

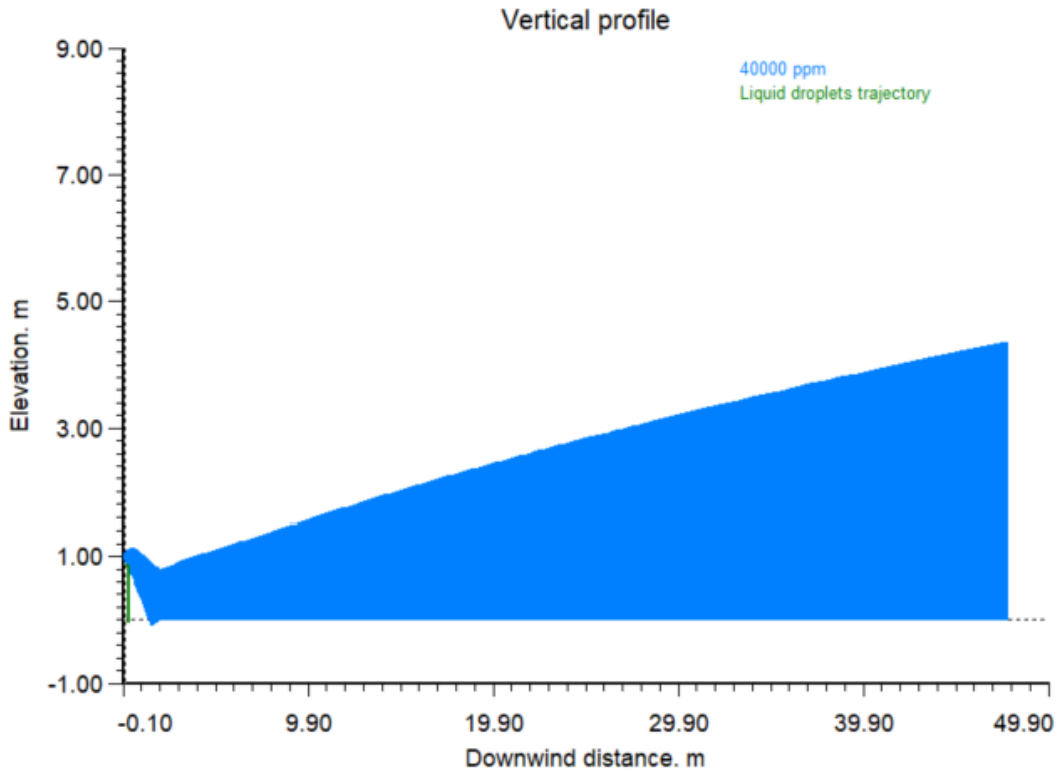


Fig. 126: Two-Phase Jet Model: Liquid Hydrogen, 0° Release Angle – Vertical Profile

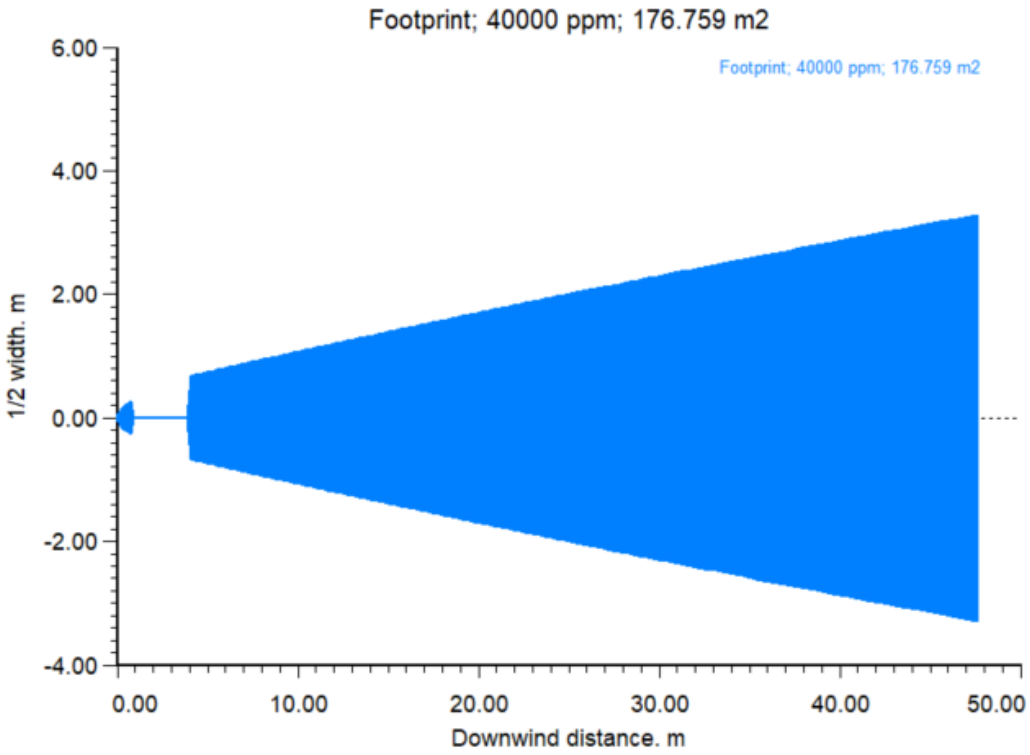


Fig. 127: Two-Phase Jet Model: Liquid Hydrogen, 0° Release Angle - Footprint

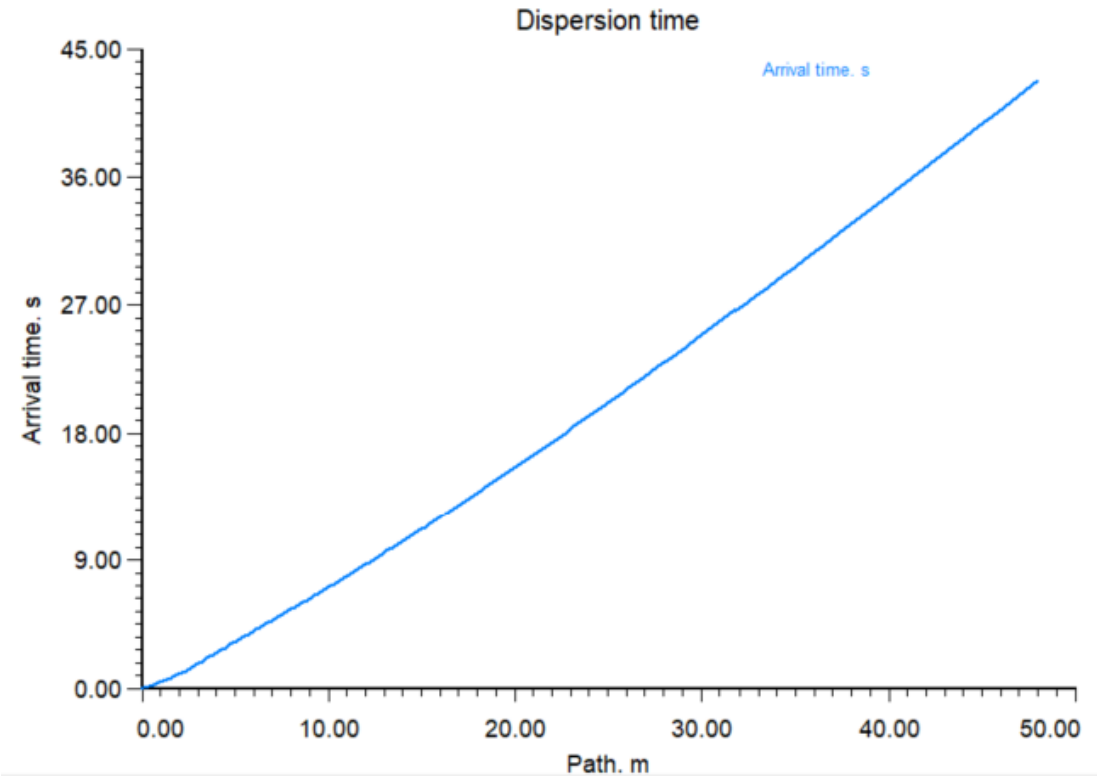


Fig. 128: Two-Phase Jet Model: Liquid Hydrogen, 0° Release Angle – Dispersion Time

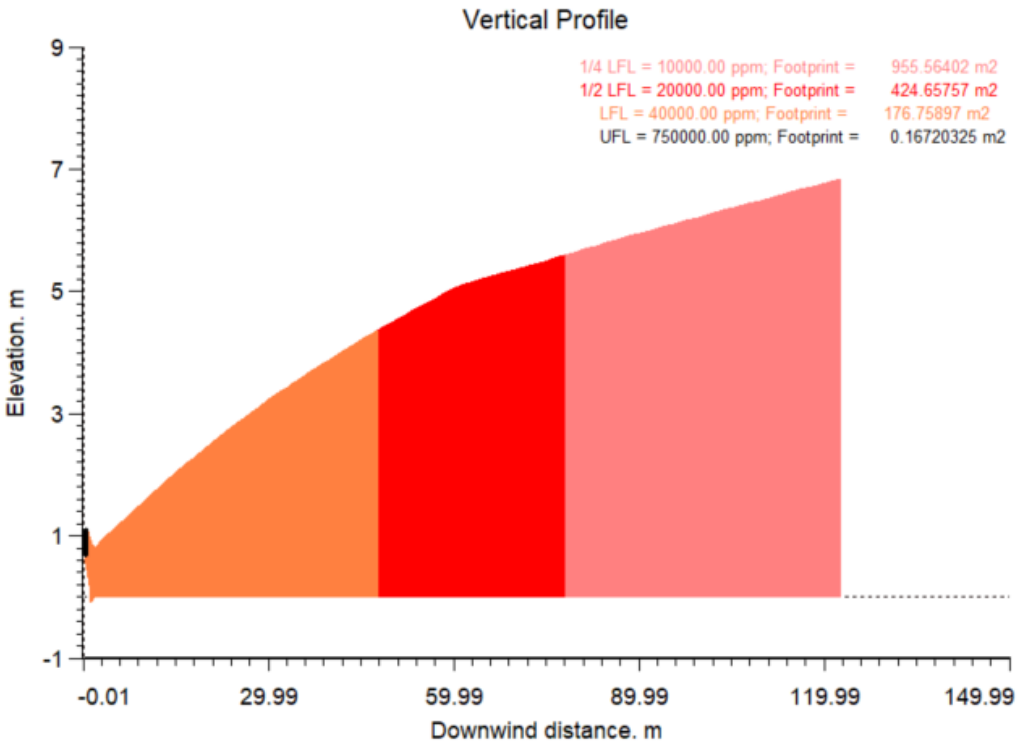


Fig. 129: Two-Phase Jet Model: Liquid Hydrogen, 0° Release Angle - Flammable Contours Vertical Profile

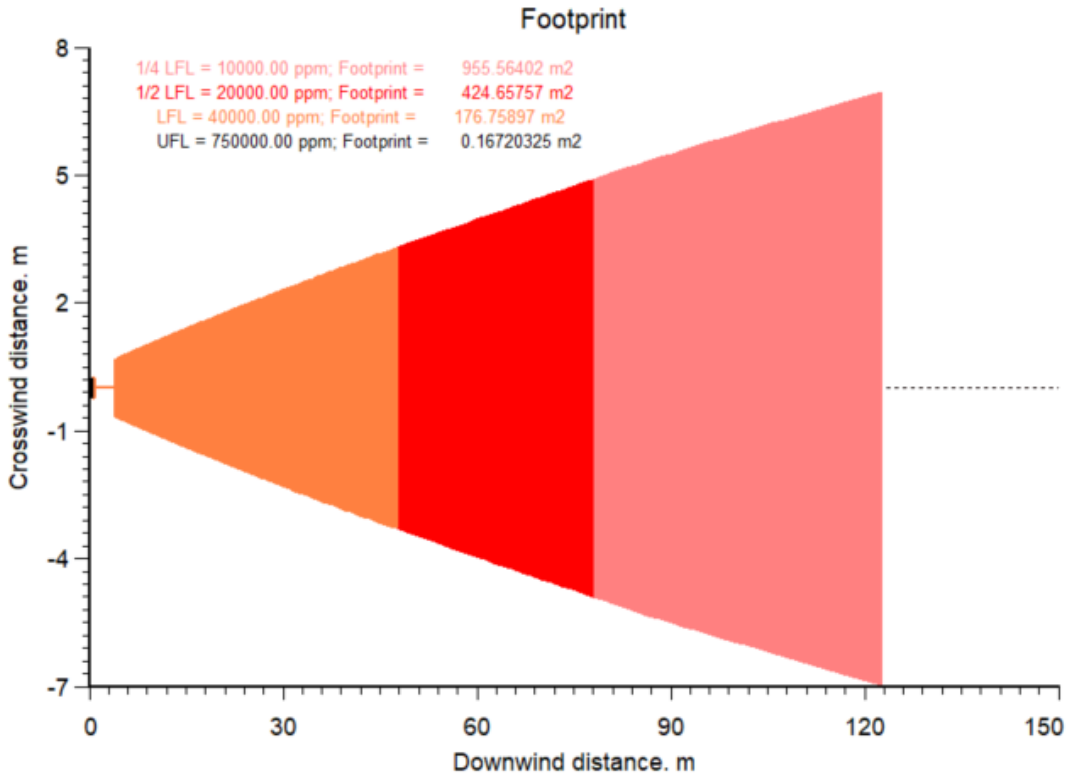


Fig. 130: Two-Phase Jet Model: Liquid Hydrogen, 0° Release Angle - Flammable Contours Footprint at 1.72m

Two Phase Jet model: Liquid Hydrogen, -45° Release Angle

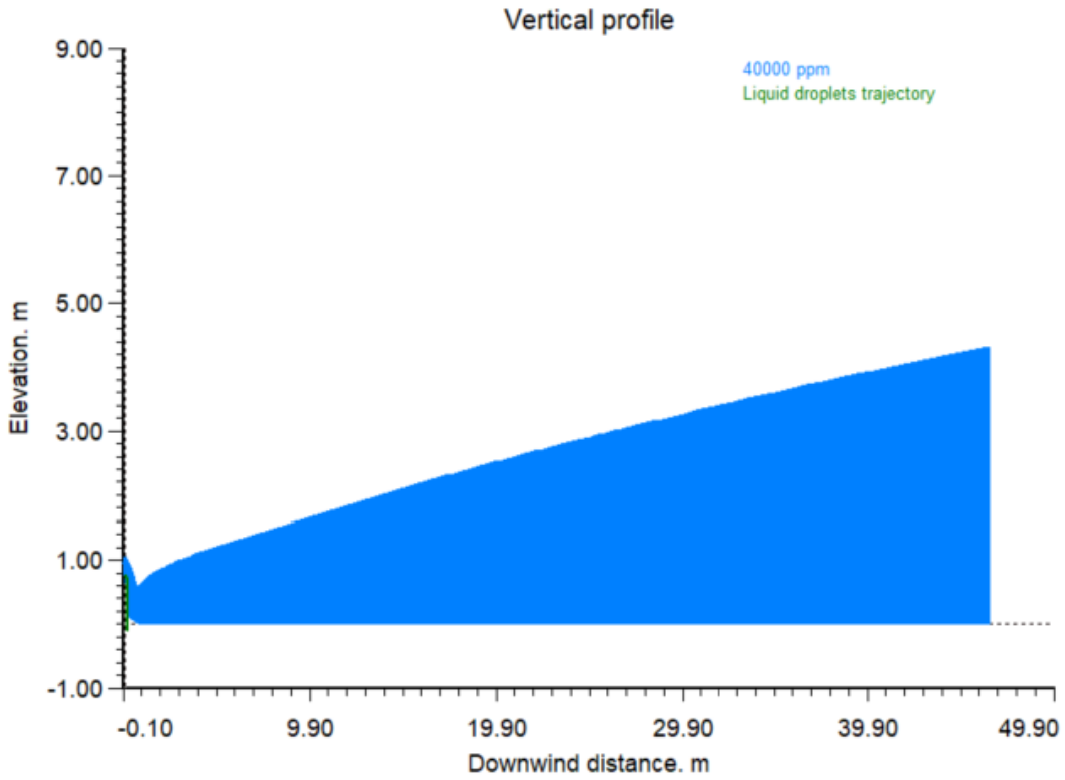


Fig. 131: Two-Phase Jet Model: Liquid Hydrogen, -45° Release Angle – Vertical Profile

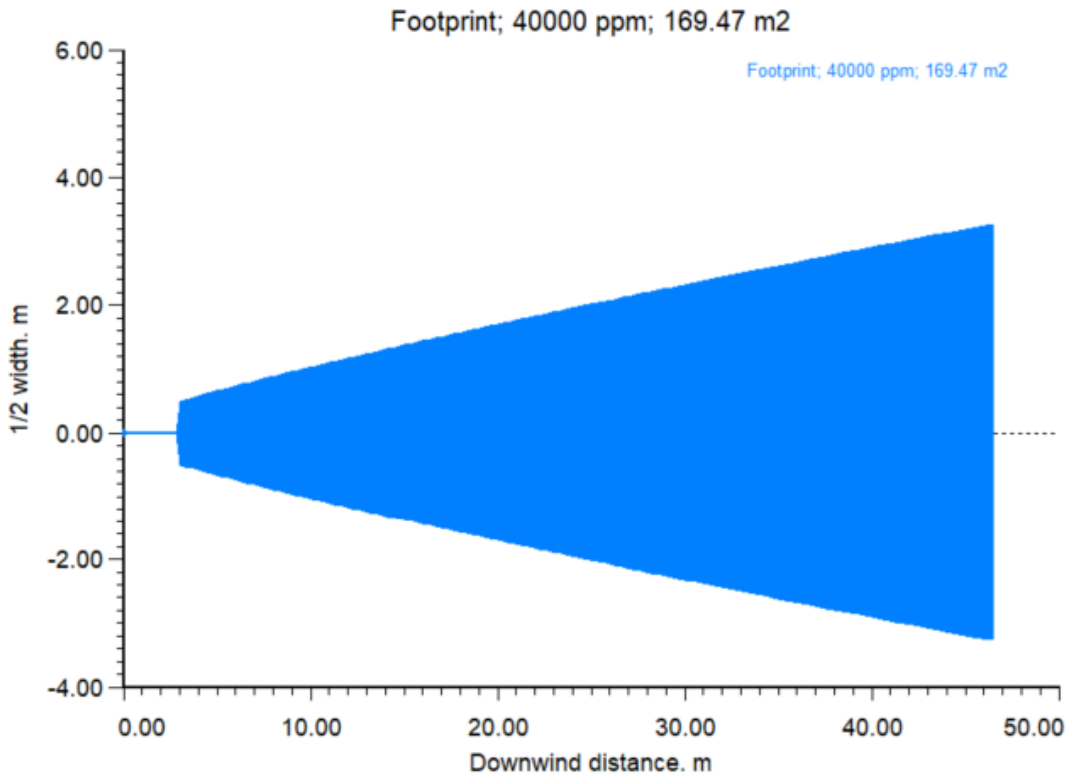


Fig. 132: Two-Phase Jet Model: Liquid Hydrogen, -45° Release Angle – Footprint

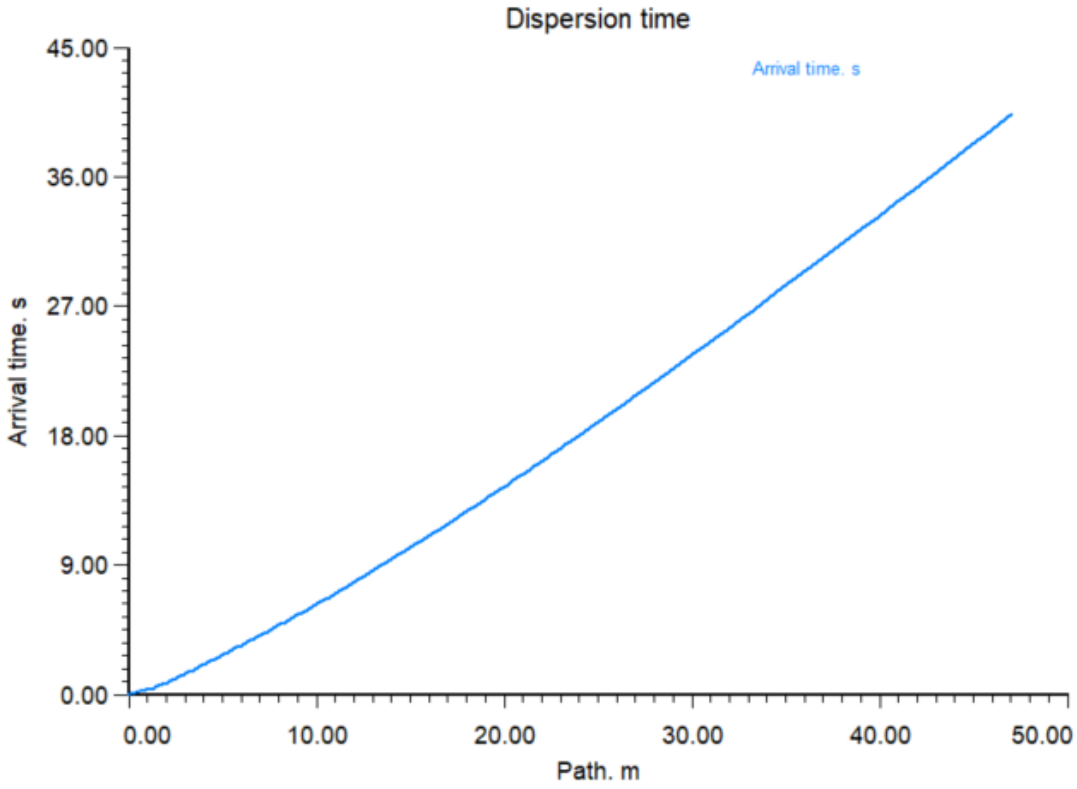


Fig. 133: Two-Phase Jet Model: Liquid Hydrogen, -45° Release Angle – Dispersion Time

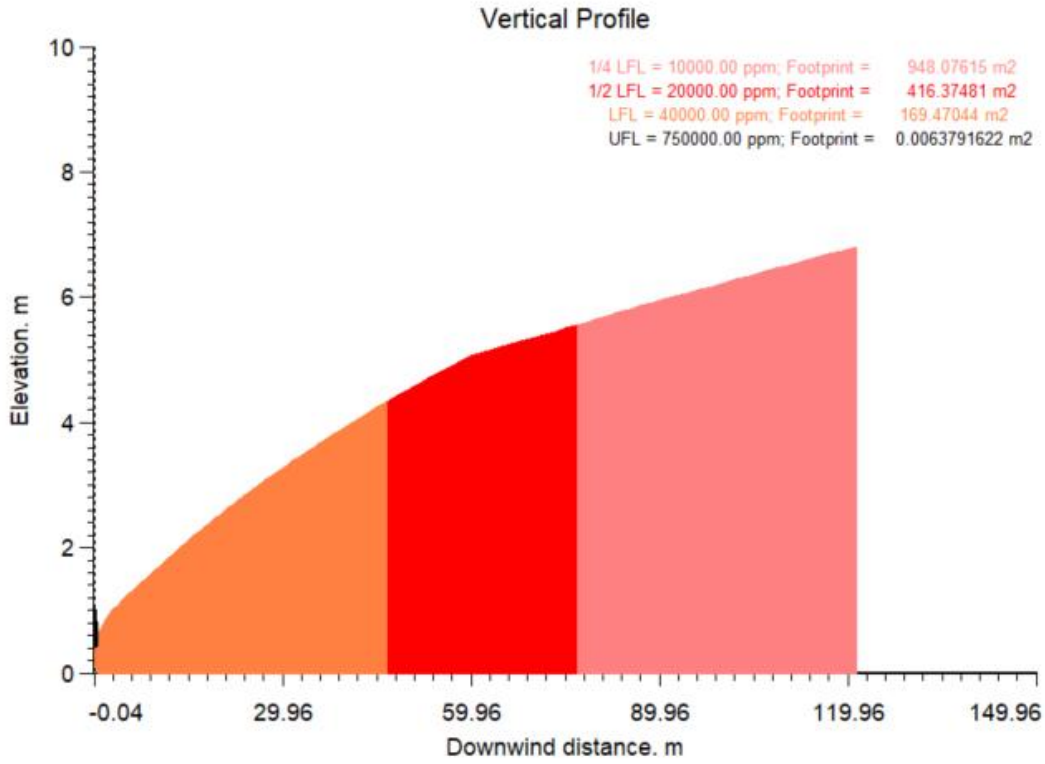


Fig. 134: Two-Phase Jet Model: Liquid Hydrogen, -45° Release Angle - Flammable Contours Vertical Profile

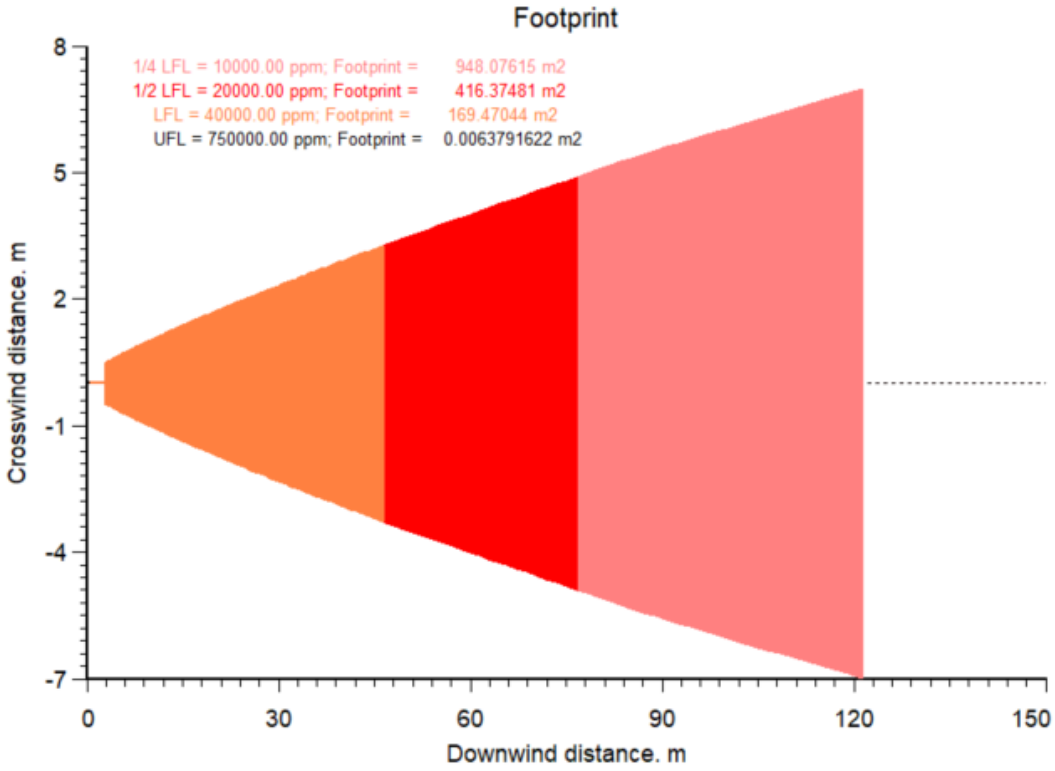


Fig. 135: Two-Phase Jet Model: Liquid Hydrogen, -45° Release Angle - Flammable Contours Footprint

Heavy Gas: Instantaneous

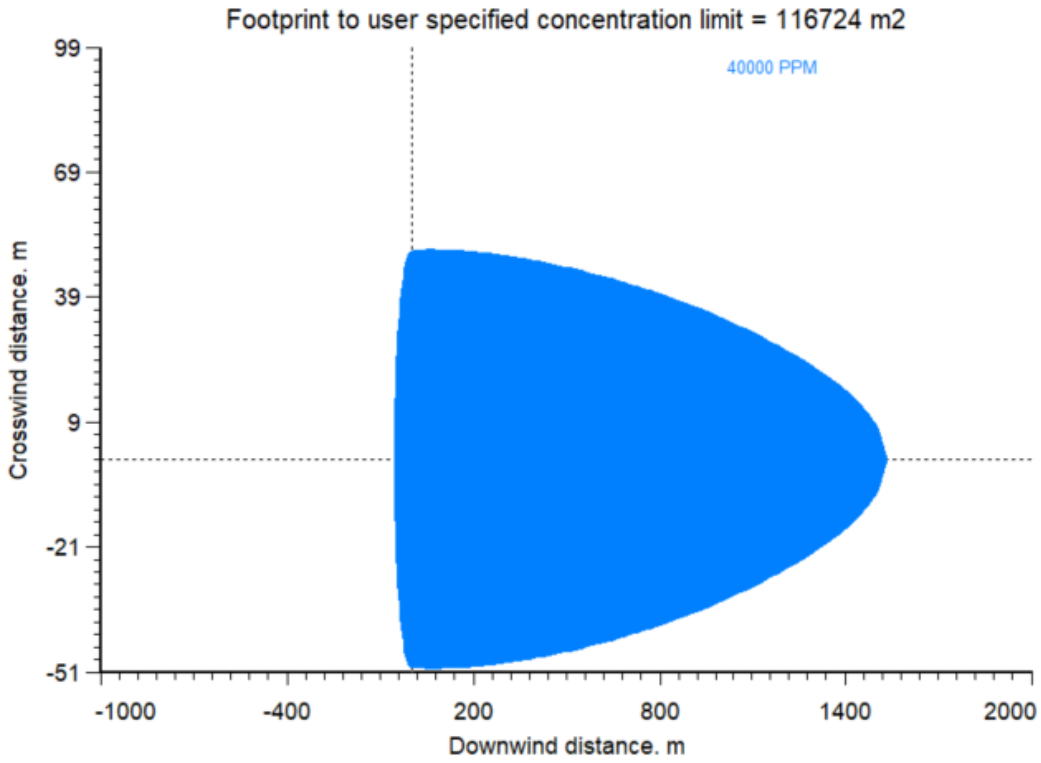


Fig. 136: Heavy Gas: Instantaneous, Liquid Hydrogen – Footprint to 40,000 ppm

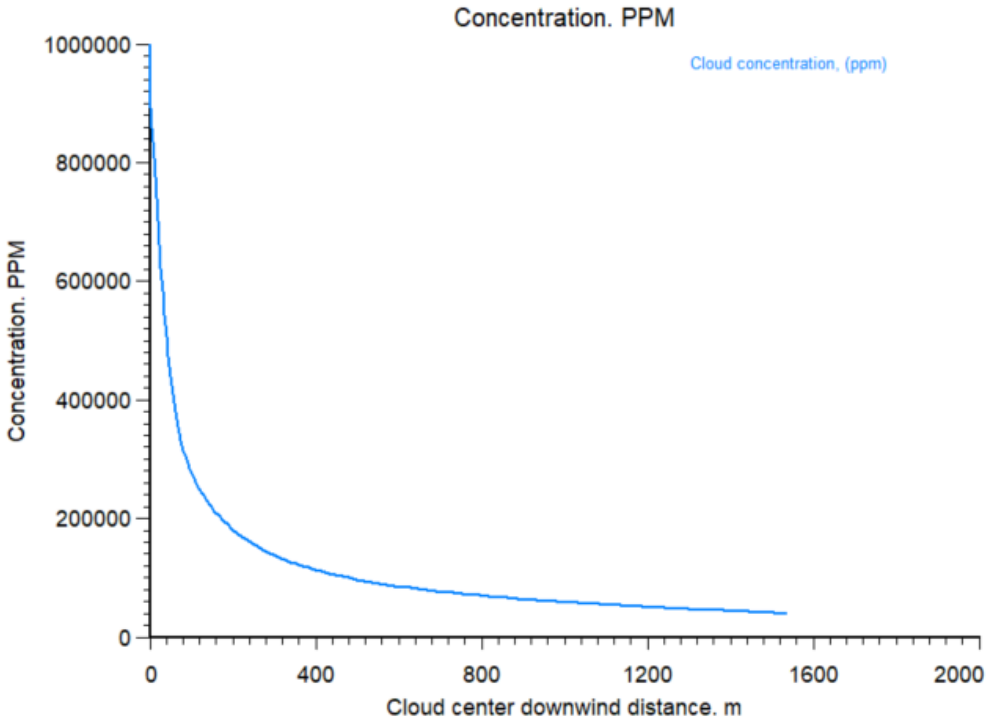


Fig. 137: Heavy Gas: Instantaneous, Liquid Hydrogen – Cloud Concentration

Fireball Model: Liquid Hydrogen

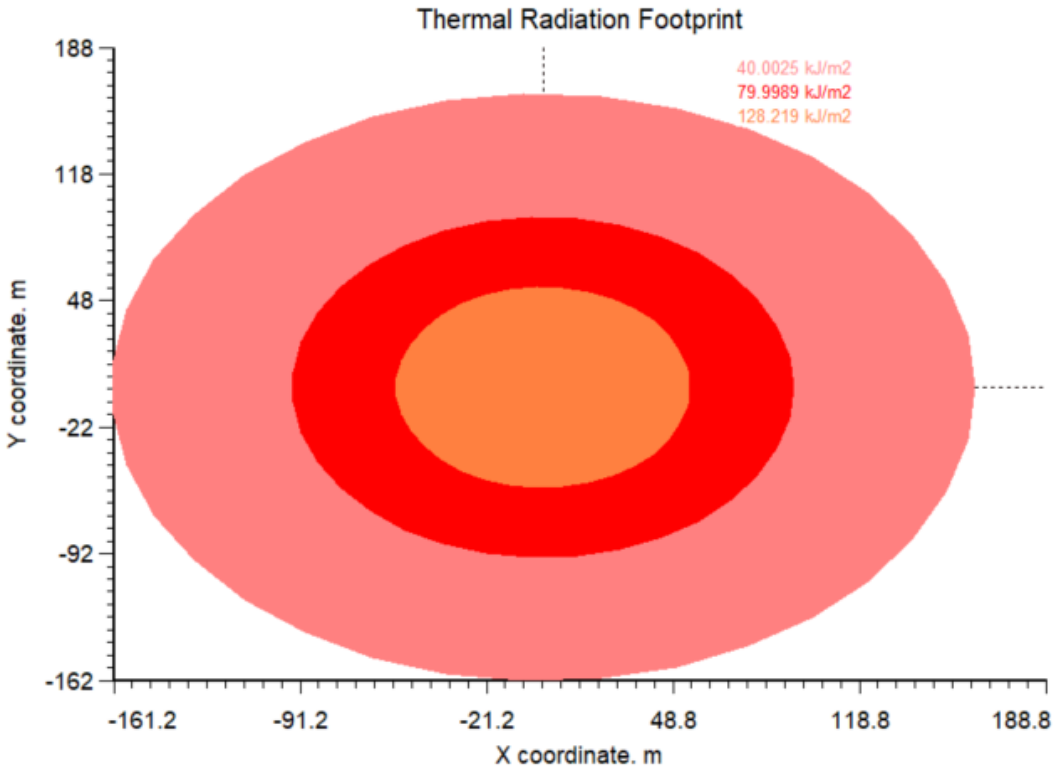


Fig. 138: Fireball Model: Liquid Hydrogen – Thermal Radiation Footprint

Two Phase Flame Jet model: Liquid Hydrogen, 45° Release Angle

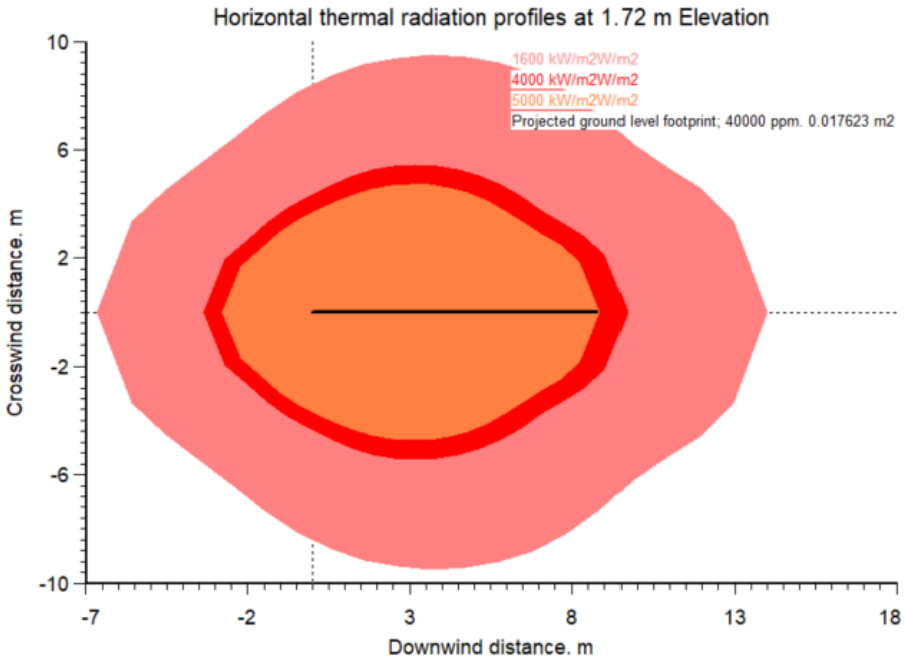


Fig. 139: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Horizontal Thermal Radiation Profiles at 1.72m

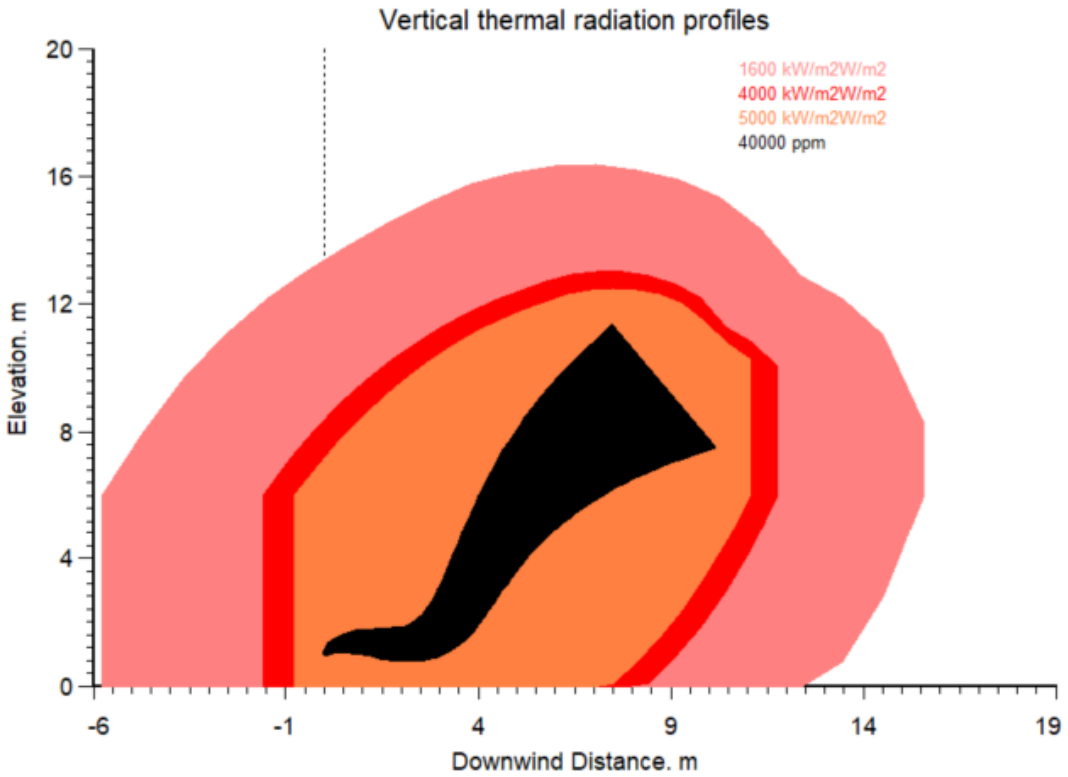


Fig. 140: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Vertical Thermal Radiation Profiles

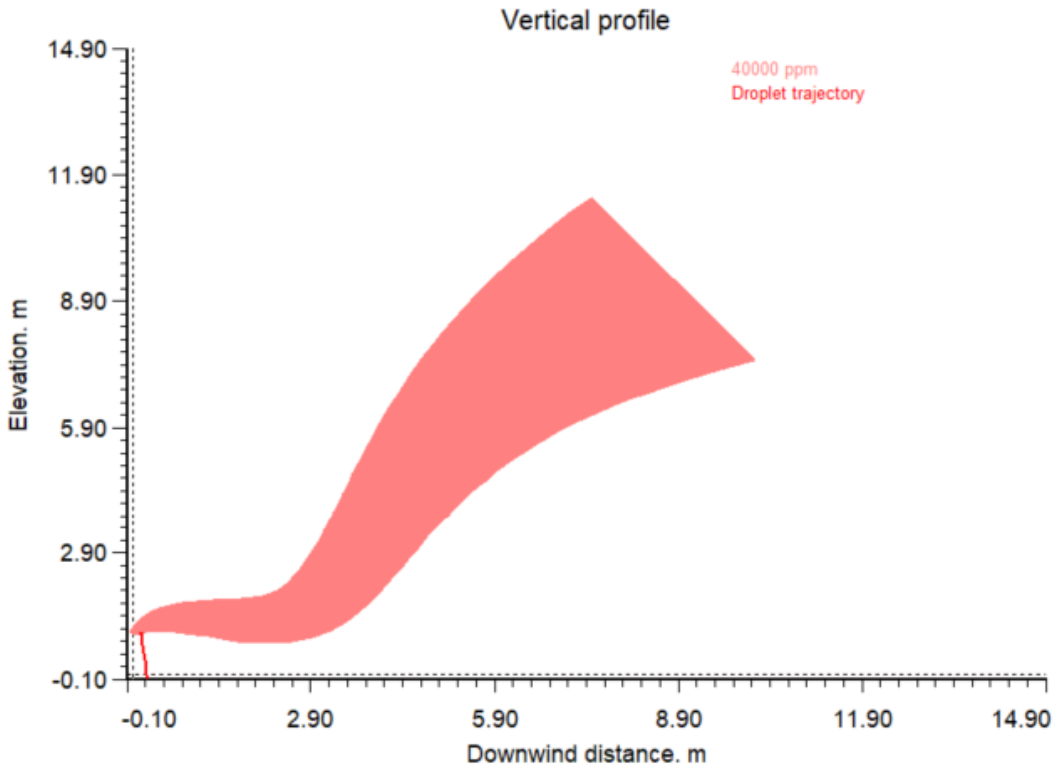


Fig. 141: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Vertical Profile

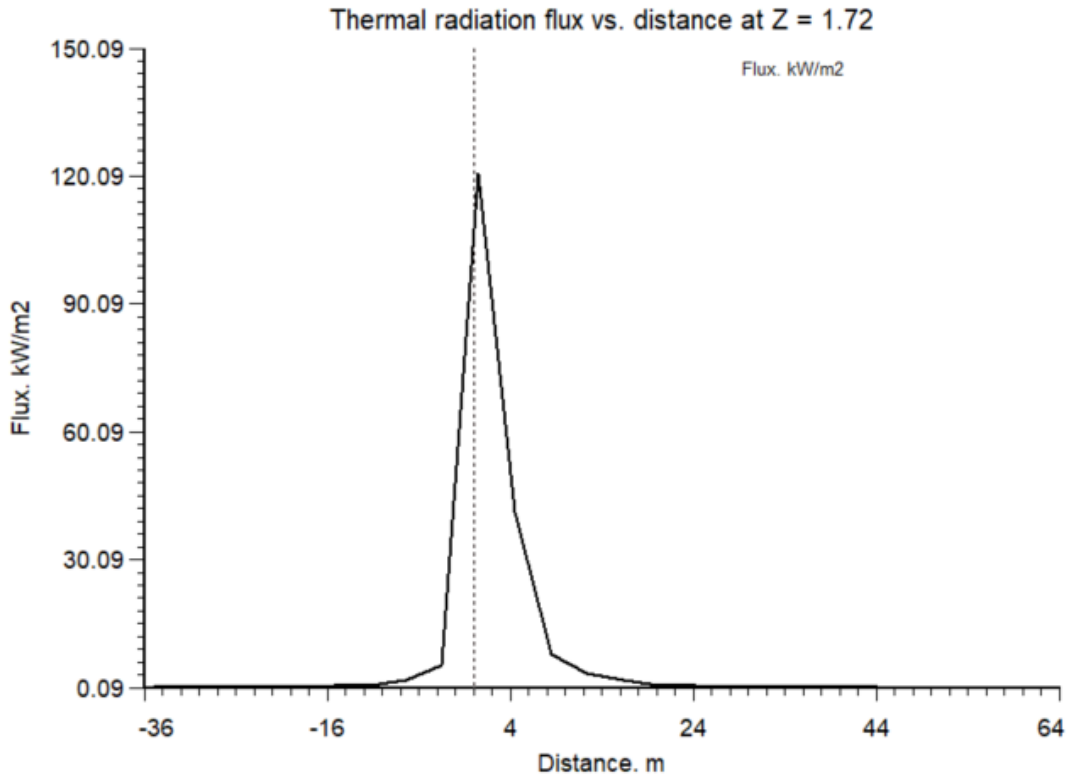


Fig. 142: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Thermal Radiation Flux vs. Distance at 1.72m

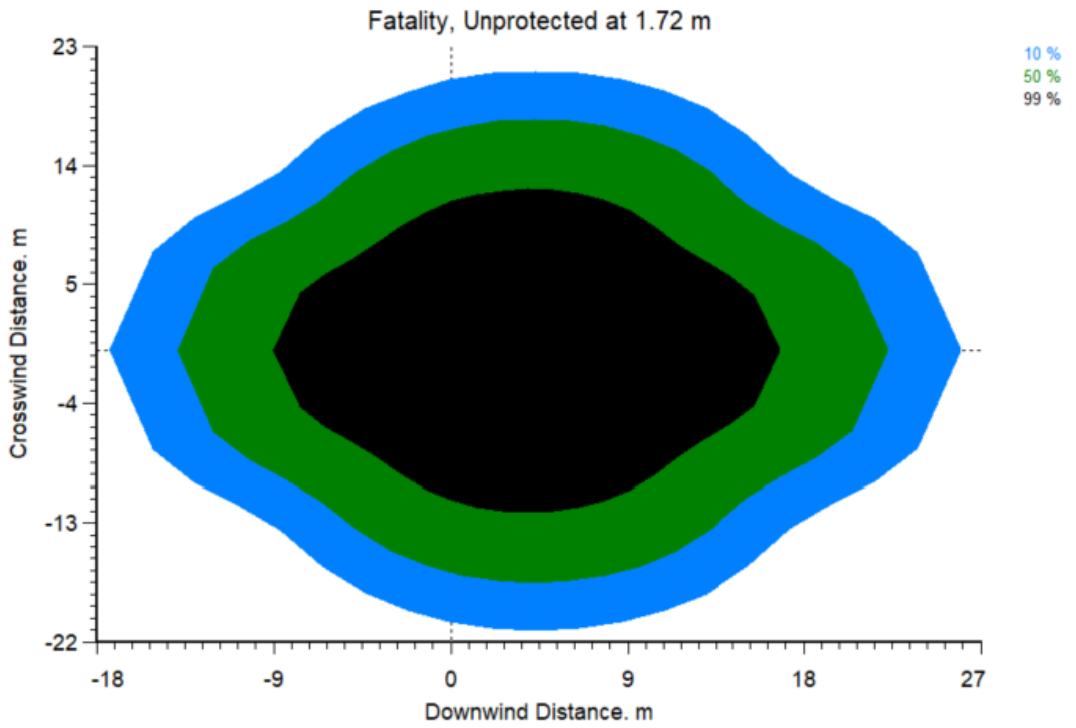


Fig. 143: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Probit Results – Fatality (Unprotected) at 1.72m

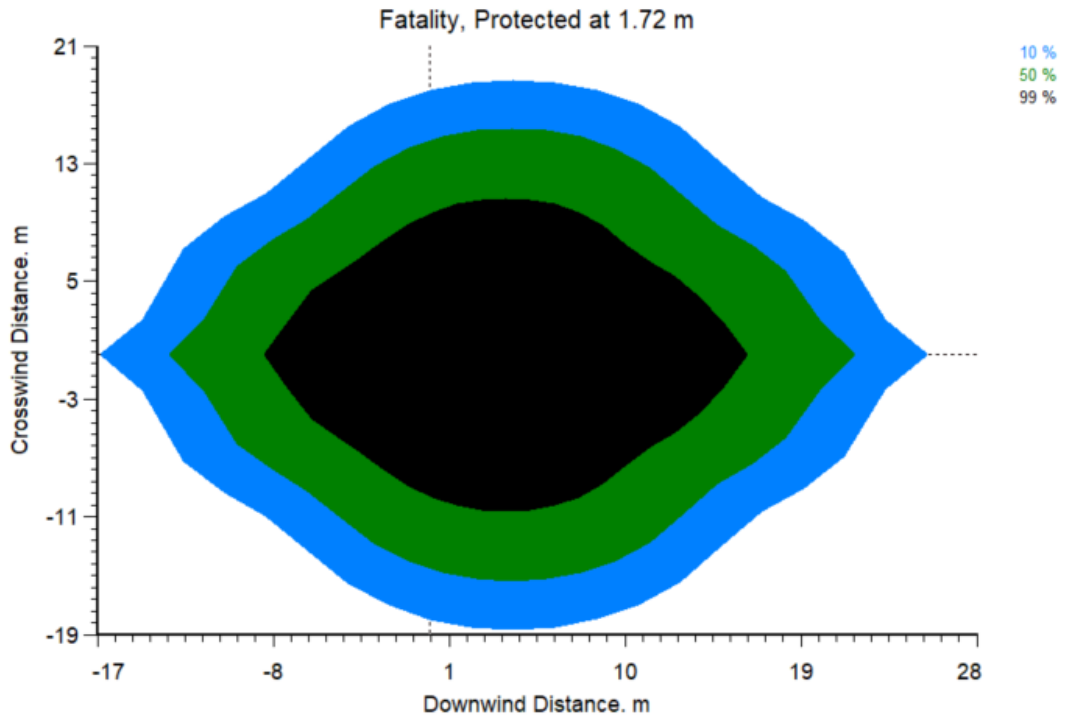


Fig. 144: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Probit Results – Fatality (Protected) at 1.72m

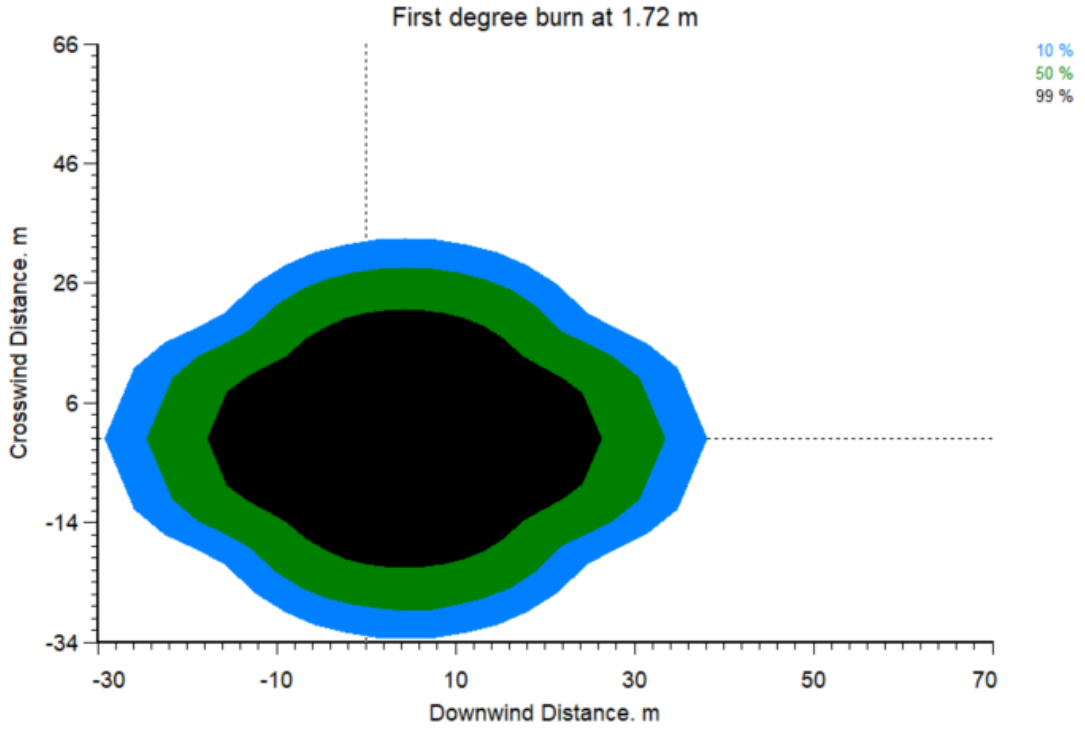


Fig. 145: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Probit Results – First Degree Burns at 1.72m

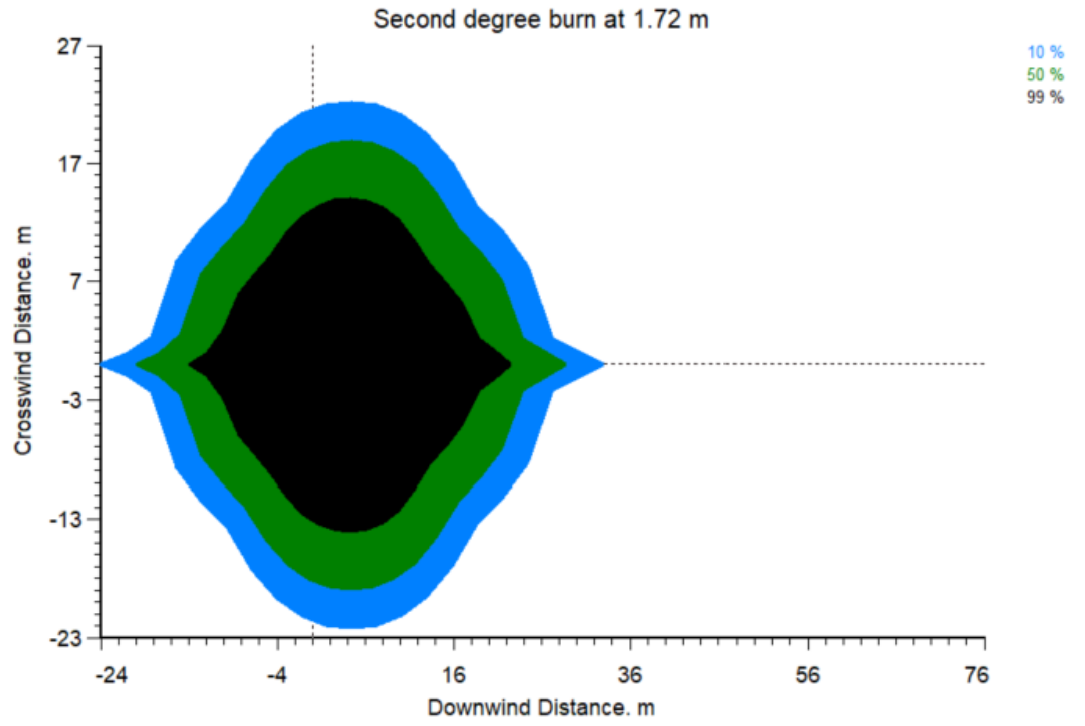


Fig. 146: Two-Phase Flame Jet: Liquid Hydrogen, 45° Release Angle – Probit Results – Second Degree Burns at 1.72m

Two Phase Flame Jet model: Liquid Hydrogen, 0° Release Angle

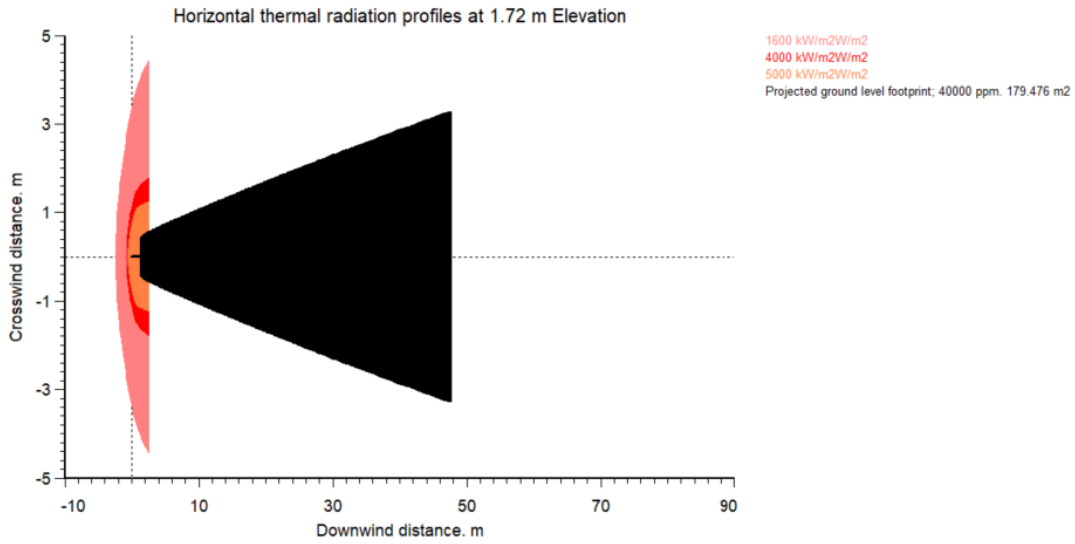


Fig. 147: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Horizontal Thermal Radiation Profiles at 1.72m

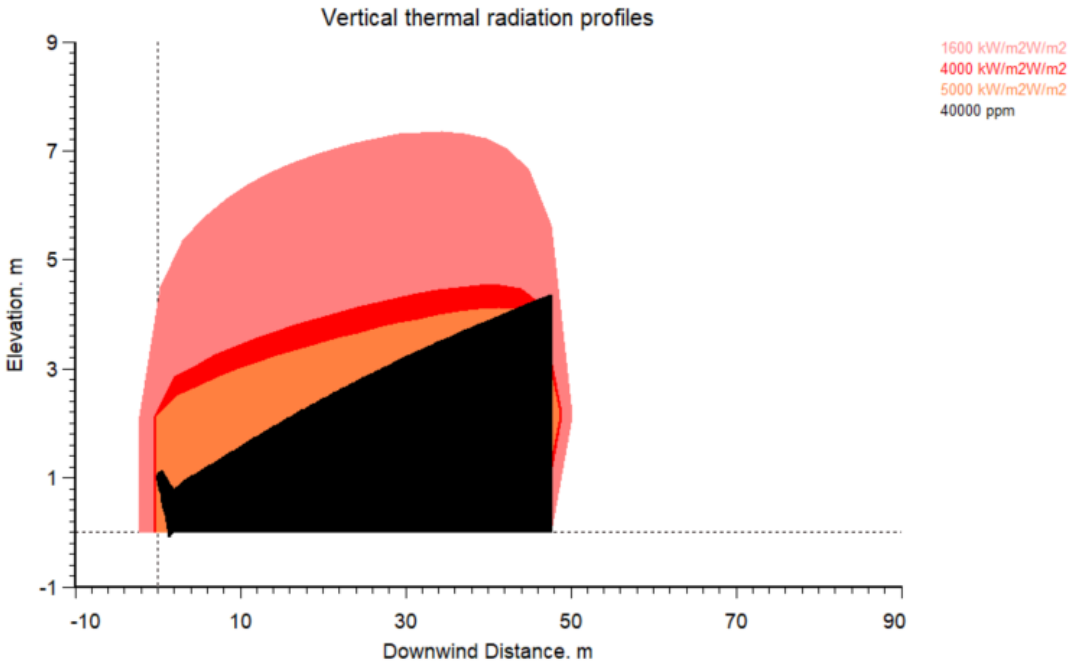


Fig. 148: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Vertical Thermal Radiation Profiles

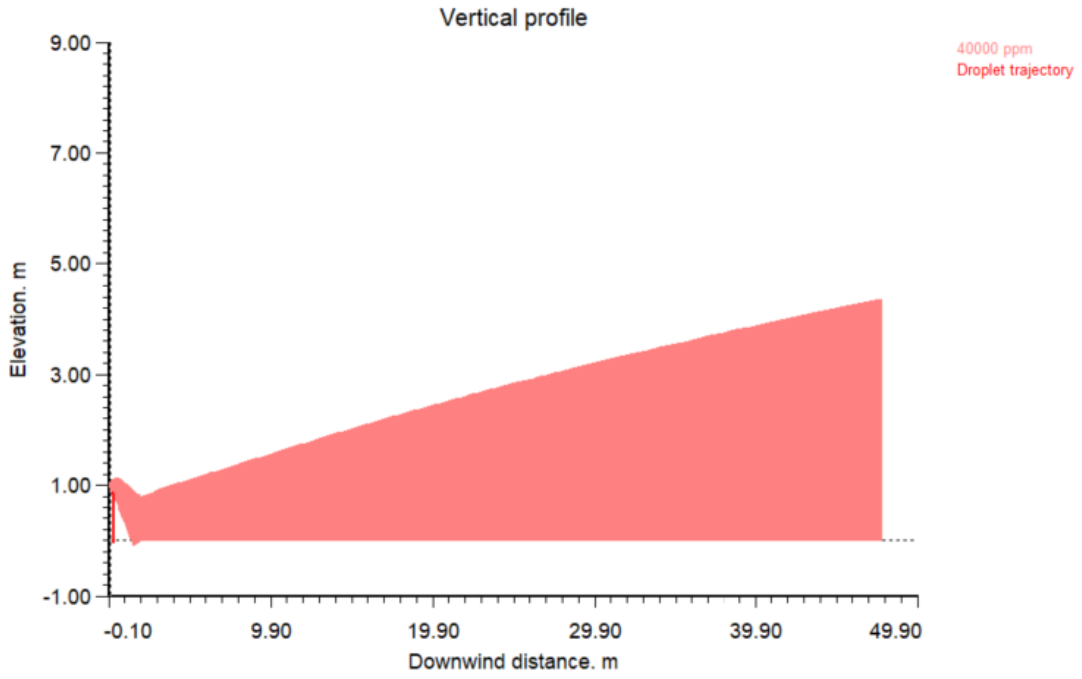


Fig. 149: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Vertical Profile

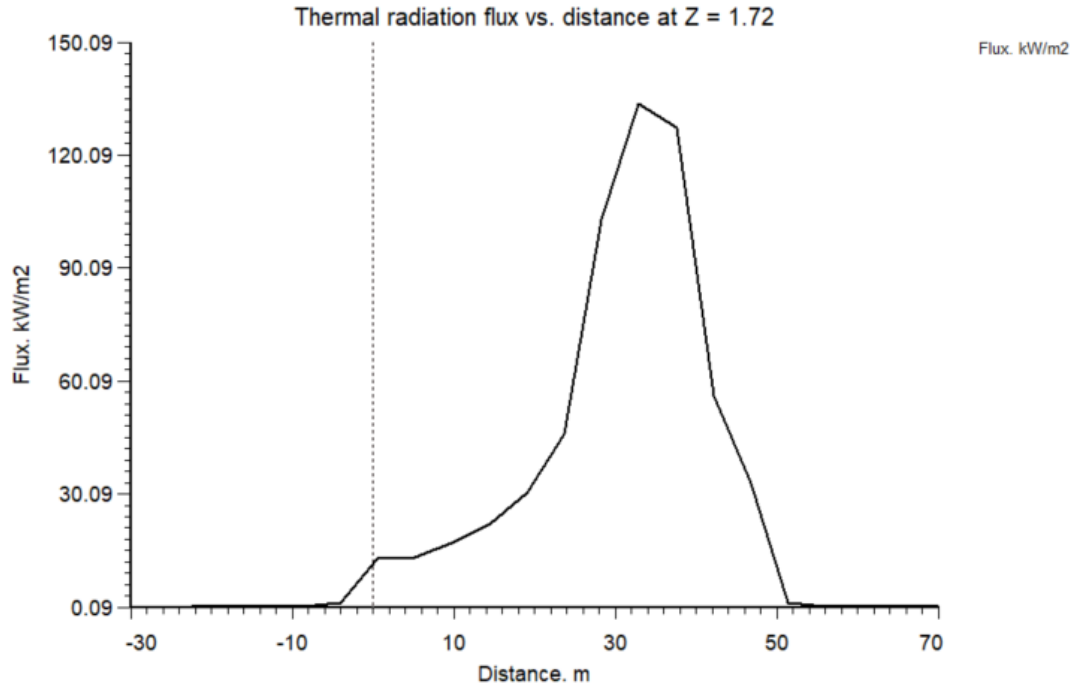


Fig. 150: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Thermal Radiation Flux vs. Distance at 1.72m

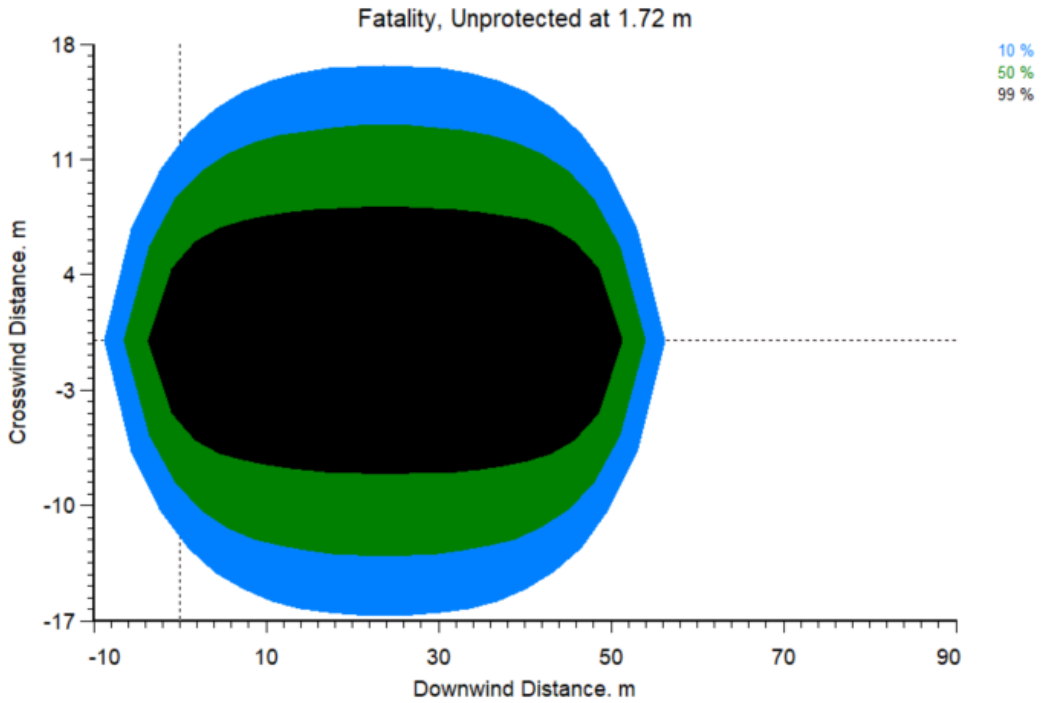


Fig. 151: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Probit Results – Fatality (Unprotected) at 1.72m

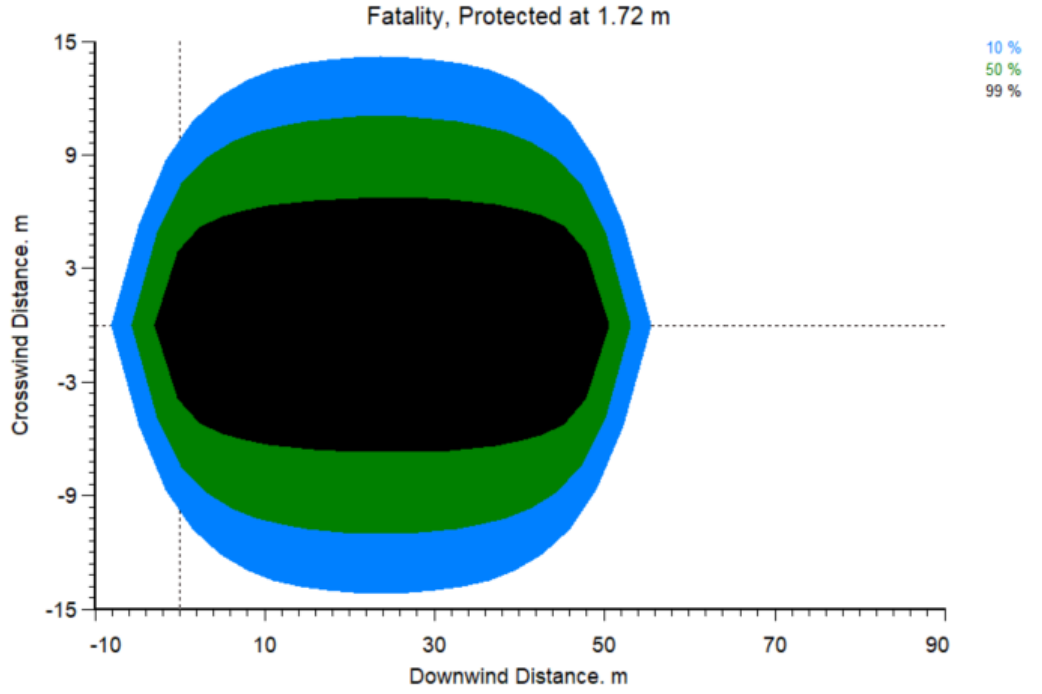


Fig. 152: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Probit Results – Fatality (Protected) at 1.72m

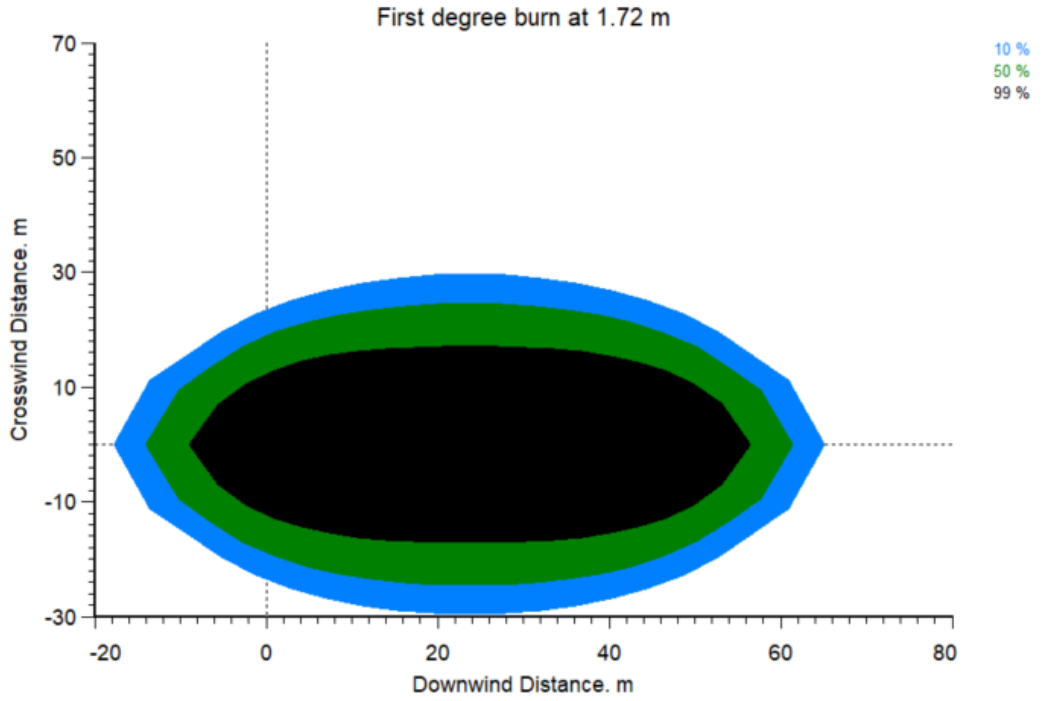


Fig. 153: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Probit Results – First Degree Burns at 1.72m

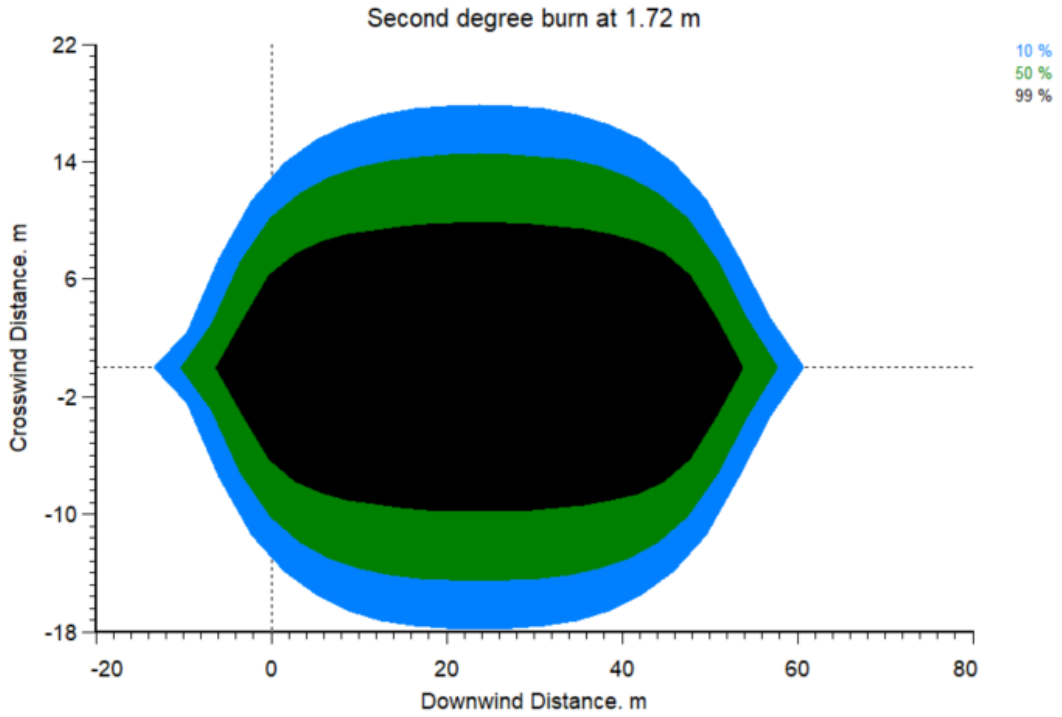


Fig. 154: Two-Phase Flame Jet: Liquid Hydrogen, 0° Release Angle – Probit Results – Second Degree Burns at 1.72m

Two Phase Flame Jet model: Liquid Hydrogen, -45° Release Angle

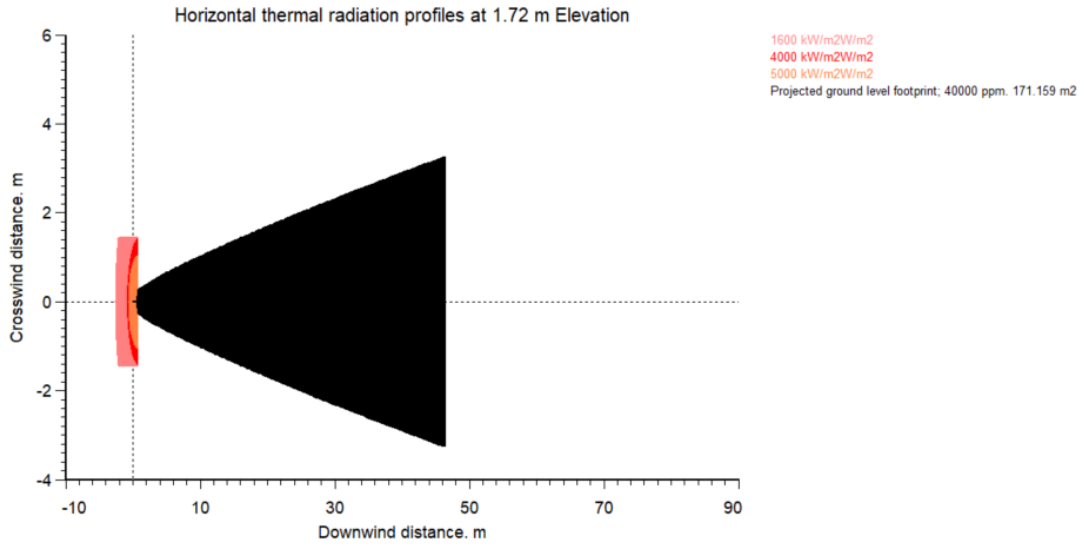


Fig. 155: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Horizontal Thermal Radiation Profiles at 1.72m

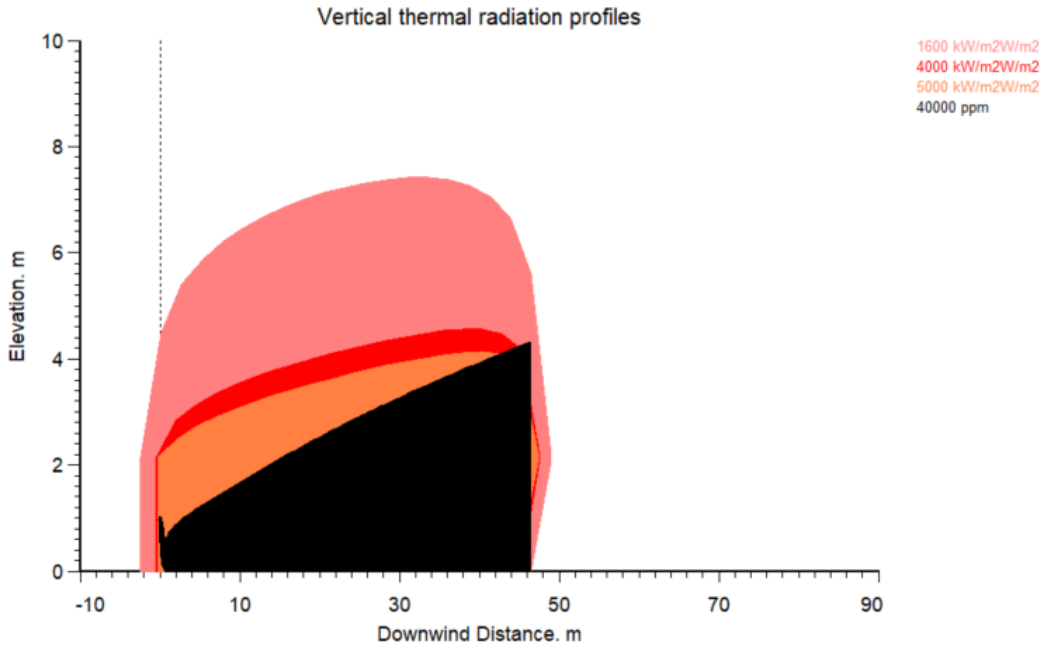


Fig. 156: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Vertical Thermal Radiation Profiles

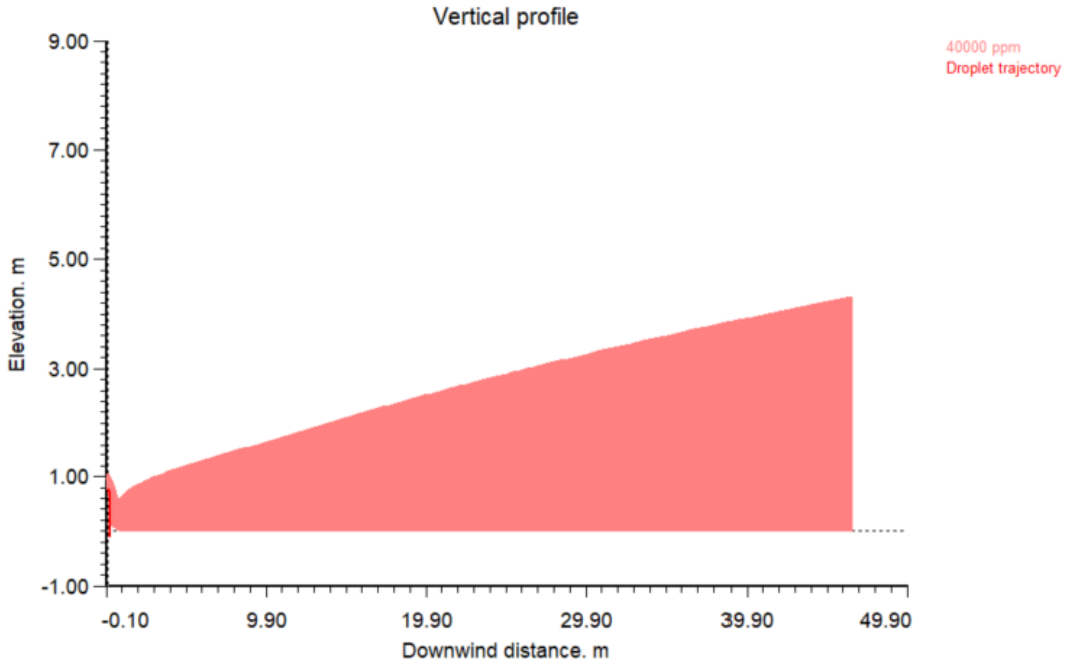


Fig. 157: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Vertical Profile

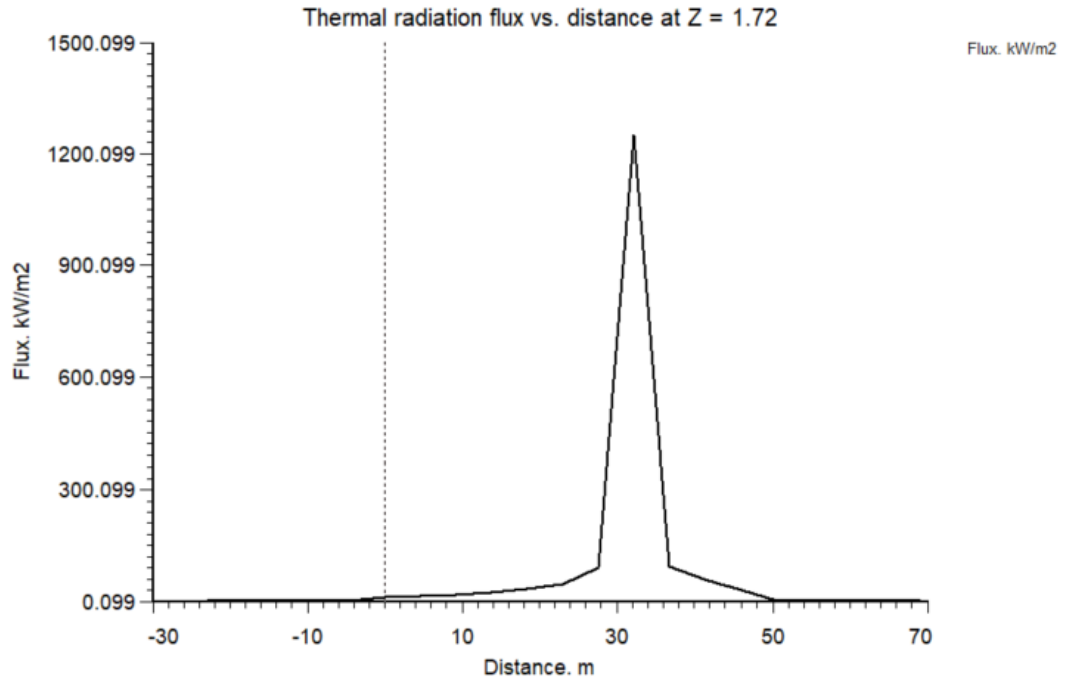


Fig. 158: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Thermal Radiation Flux vs. Distance at 1.72m

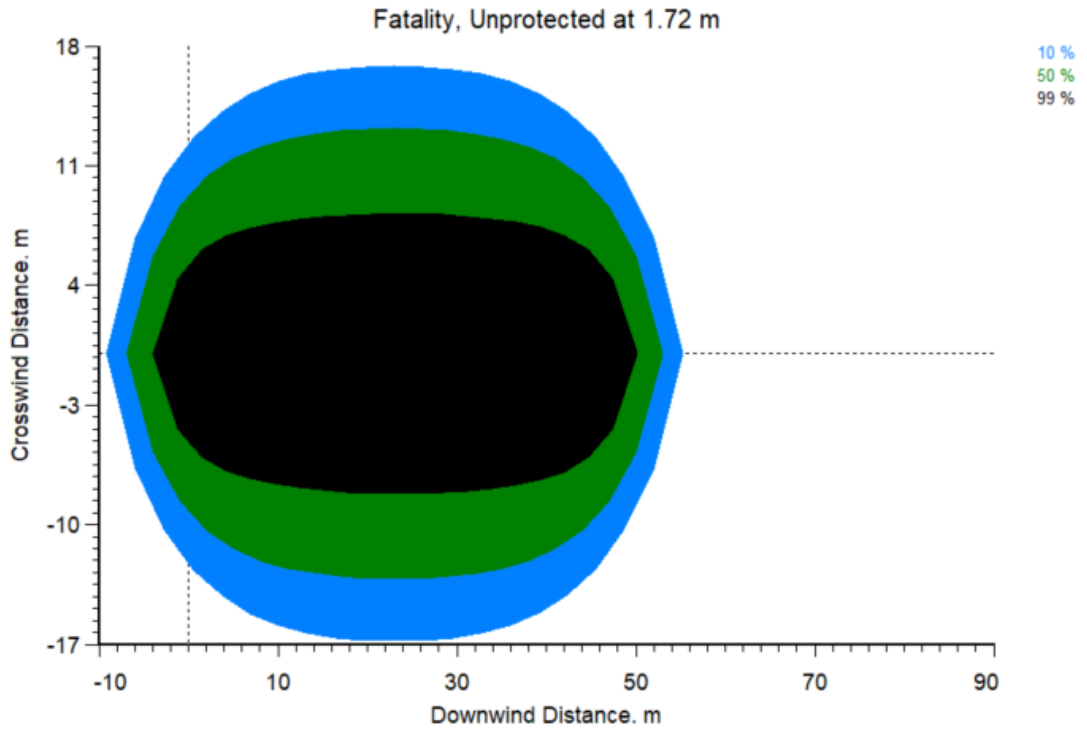


Fig. 159: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Probit Results – Fatality (Unprotected) at 1.72m

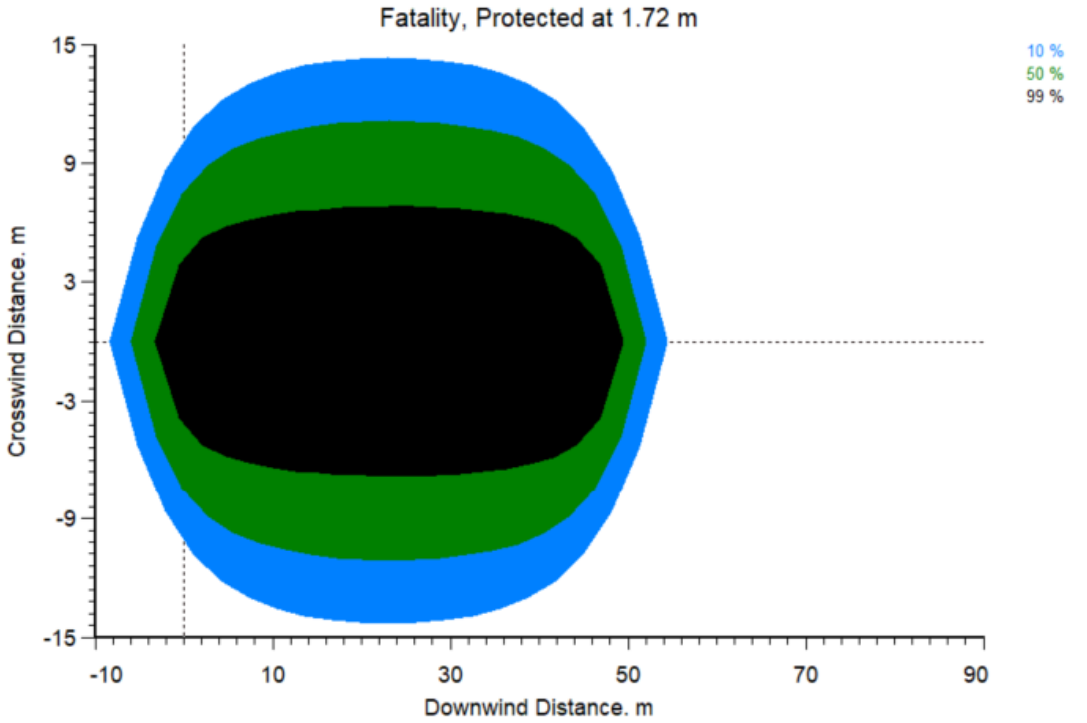


Fig. 160: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Probit Results – Fatality (Protected) at 1.72m

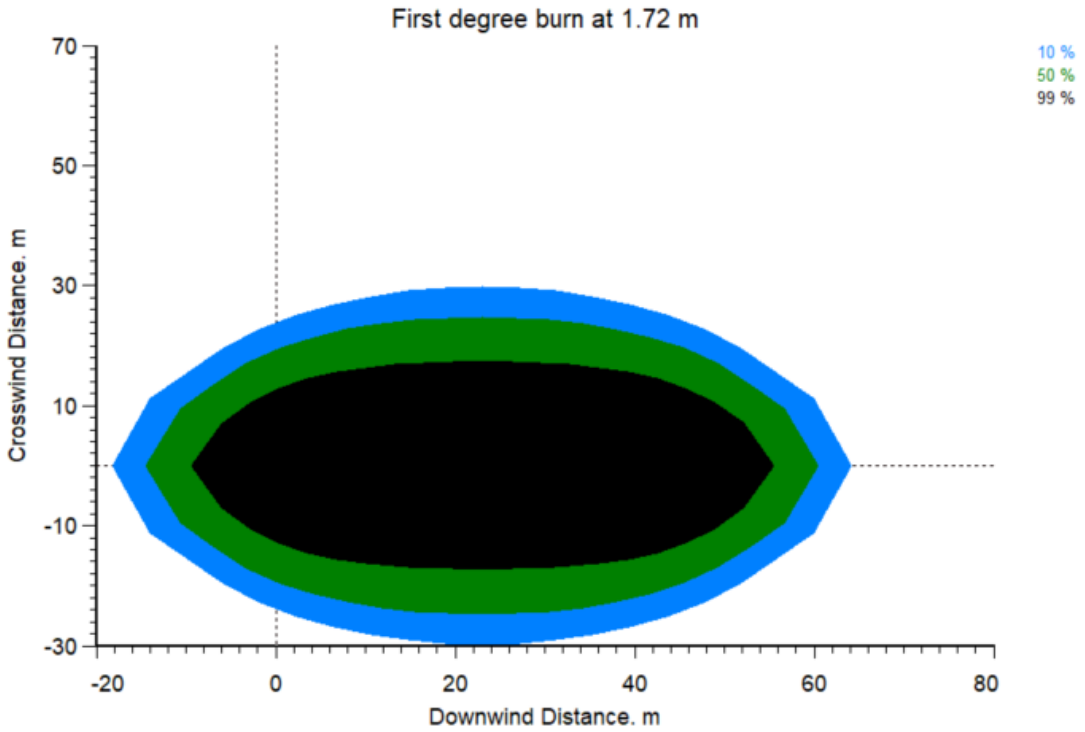


Fig. 161: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Probit Results – First Degree Burns at 1.72m

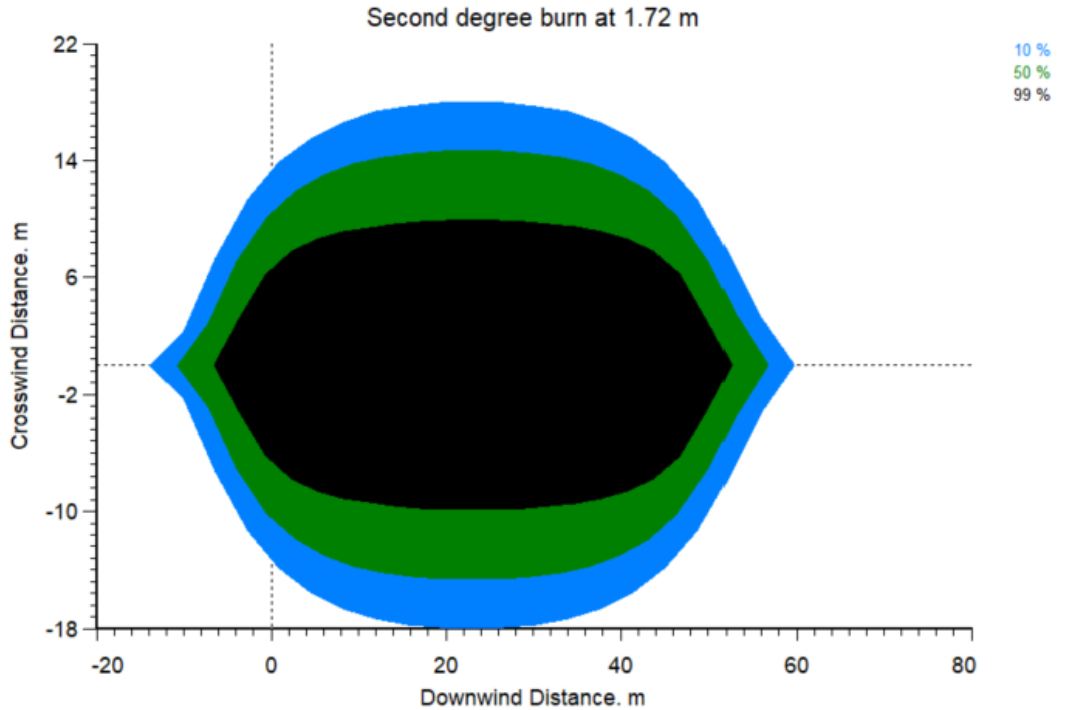


Fig. 162: Two-Phase Flame Jet: Liquid Hydrogen, -45° Release Angle – Probit Results – Second Degree Burns at 1.72m

الملخص

يُعد الوصول إلى صافي انبعاثات صفرية هدفًا عالميًا تسعى جميع الدول لتحقيقه، وقد التزمت مملكة البحرين بتحقيق هذا الهدف بحلول عام 2060. و يُقترح لتحقيق ذلك استبدال البنزين والوقود الأحفوري بمصادر مستدامة وصديقة للبيئة مثل الهيدروجين الأخضر لتشغيل المركبات بخلايا الوقود. تستعرض هذه الدراسة تقنيات مركبات خلايا وقود الهيدروجين من خلال مراجعة أدبيات شاملة توضح أهداف البحرين في هذا المجال. تقدم الدراسة بالإضافة إلى ذلك المعايير المتاحة لنقل المواد الخطرة، ونقل الهيدروجين، وتقييمات المخاطر الكمية للنقل. تضع هذه الدراسة إطارًا لتقييم مخاطر النقل بافتراض أن الهيدروجين الأخضر سيكون الوقود الرئيسي للمركبات في المملكة. تحدد الدراسة علاوة على ذلك الكميات الأساسية للمخاطر بافتراض شبكة الطرق الحالية، وموقع محطة التوزيع الحالية، ومواقع محطات التزود بالوقود القائمة.

تتوافق منهجية البحث بشكل أساسي مع الأساليب الموصى بها في "الإرشادات الخاصة بالتقييم الكمي للمخاطر – الكتاب الأرجواني"(CPR 18E) ، كما تم إجراء تحليل إحصائي لبيانات الحوادث الصادرة عن الإدارة العامة للمرور (GDOT) لبناء تحليل إحصائي. وتُستخدم نتائج التحليل الإحصائي للتنبؤ باحتمالية وقوع الحوادث المستقبلية من خلال تحليل الاحتمالية. يتم بعد ذلك إجراء تحليل العواقب لتقييم شدة أحداث فقدان الاحتواء (LOC) وتداعياتها. وأخيرًا، يتم دمج نتائج شدة العواقب مع احتمالية وقوع الحوادث لتحديد القيم الأساسية للمخاطر.

الكلمات المفتاحية :تحليل مخاطر النقل؛ التحليل الكمي للمخاطر؛ صافي الانبعاثات الصفري؛ الهيدروجين الأخضر؛ مركبات خلايا وقود الهيدروجين؛ الكتاب الأرجواني CPR 18E

جامعة البحرين

كلية الهندسة

قسم الهندسة الميكانيكية

دراسة أساس كمية لمخاطر (QRA) نقل الهيدروجين المستخدم كوقود للمركبات عبر الطرق في مملكة البحرين – إطار لدراسات تحليل المخاطر المستقبلية

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في الإدارة الهندسية

إعـــداد

حامد محمد النحوي

الرقم الجامعي: ٢٠٢٠٠٠١٣٧

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مملكة البحرين

سبتمبر 2025م