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Task 19 – Hydrogen Safety

Risk Assessment Studies of Hydrogen and Hydrocarbon Fuels Fuelling Stations
Description and Review

1 INTRODUCTION

This document is the product of Subtask A “Risk Management” Activity A2 “Comparative Risk Assessments of Hydrogen and Hydrocarbon Fuelling Systems”. Once the Activities of Subtask A were fully established, the expert meetings of Task 19 started to include regular country updates on risk assessment / safety studies.

During three meetings of Task 19 experts, namely in Long Beach (March 2006), Vancouver (September 2006) and Tsukuba (January 2007) partners presented a number of risk assessment studies (or provided updates of already presented studies) of refuelling facilities that could be classified as follows:

- Planned hydrogen facilities during the design stage;
- Existing hydrocarbon (LPG) facilities to be modified or relocated due to changed risk acceptance criteria;
- Hypothetical hydrogen facility to develop generic risk mitigation measures and modify existing regulations; and
- Hydrogen and hydrocarbon (CNG) refuelling options based on an existing demonstration facility as benchmark for fuel demand.

The text below pursues three objectives.

First, to describe the available studies, thus, identifying their key elements – approaches, methodologies, methods of analysis, key results and recommendations, and post-study developments (where available). Keeping the studies’ descriptions (based on presentations) in one document is certainly a bonus, particularly when more than one presentation of a study was made. The text below arranges the slides (mostly) and text in a logical sequence, which makes studies overview much more convenient vs browsing through various presentations that are themselves contained in different folders.

Second objective is more challenging: indentify interesting findings arising from review and comparison of results. These would provide material for learning and knowledge gaps identification and closing.

Third objective is to keep the document “alive”, i.e. keep expanding it as more studies become available through the life of Task 19. This last objective constitutes part of Activity A4 of the new Subtask A scope for 2007-10 time frame.
2 RISK ASSESSMENT STUDIES PRESENTED BY PARTNERS

2.1 Case Studies Description

2.1.1 HyTrec, DNV, Norway Case Study

The HyTrec case study was presented by Norway twice:

- On March 16, 2006, in Long Beach by Angunn Engebo – this was the introduction to the study and preliminary results;

The following sequence of slides and discussion involves the combination of slides from both presentations [1, 2].

HyTrec Centre is planned to be placed in Oslo in a populated area. The current design includes hydrogen generation using water electrolysis and SMR (with prior gasification of LNG), hydrogen high pressure gaseous storage, and hydrogen use in a SOFC and / or dispensing station for vehicles fuelling.

The QRA used conventional methodology and ALARP principle approach.
HYTREC Setting

- Located in a populated area
- Centre will have no access control and is intended to have an inviting design encouraging people to walk in
- Integration with SINTEF/NTNU research activities

Production Facility

Hydrogen production

- Wind Power
- LNG Natural Gas
- Hydrogen reformer
- CO₂ Capture and storage
- Hydrogen Electrolyser
- Electricity
- Heat
- Fuel Cell (SOFC)
- Hydrogen Storage
- Fuelling Station Vehicle
HYTREC: Plant Overview

HYTREC Risk Analysis Activities

- Pre-engineering stage

- Purpose: To analyse the risk at a moment when risk reducing measures can be implemented by re-drawing rather than re-building

- Focus on identification and calculation of “worst case” scenarios for improvement of design and lay-out

- Quantitative frequency and consequence calculations based on conservative assumptions

- Recommendations are the most important results
HYTREC QRA - Methodology

- Compile and Assess data
- Hazard Identification
  - Estimation of Frequency
  - Estimation of Consequence
- Risk Calculation
- Comparison with Acceptance Criteria
- Conclusions and Recommendations

Assumptions and Study Basis

- Hole sizes: All piping valves and fittings are assumed to be of 10mm size. Experience indicates that a leak from a storage tank itself is unlikely, but is more likely to occur from the connections of piping and equipment into the tank.
  - Small: 0-5mm. Representative hole size: 1mm
  - Large: 5-10mm. Representative hole size: 10mm

- HSE leak frequency database (hcr99)

- Presence of 3rd party
  - Visitors: Present 4 hours per visit. One visit per year. Time will be spent 40% outdoors and 60% indoors. Estimated presence fraction = 2.7E-4 (indoors) and 1.8E-4 (outdoors).
  - Inhabitant (residential house): Present 20 hours per day. Every day throughout the year. Estimated presence fraction = 8.3E-1.
Assumptions and Study Basis

- Explosion design criteria:
  - With respect to the separate explosion calculations performed, it is assumed that each of the indoor modules is equipped with an explosion relief panel in the roof, designed to open at overpressures exceeding 0.05 barg. It is also assumed that the walls and entrance doors of these modules are designed to withstand more than 0.05 barg in order to protect the personnel located indoors.

- Controlled venting of unignited releases indoors

- Immediate ignition inside SOFC module

- Ignitable concentration of gas: ½ LFL

- Fatal heat radiation level: 12.5 kW/m²

- Escalation heat radiation level: 37.5 kW/m² > 10 min

Assumptions and Study Basis

- Protection of storage area: It is assumed that the area containing the H2 and LNG storage tanks are protected sufficiently in order to avoid accidental release of H2 or LNG caused by passing vehicles colliding into the structure.

- Unauthorised personnel: It is assumed that sufficient measures (e.g. fences) are implemented in order to keep unauthorised personnel away from the process area and other hazardous equipment.

- LNG spill bund: An assumption made for the assessments in this study is that there is a spill bund installed around the LNG storage tank and vaporisers, in order to collect accidental releases of LNG. Such bunds will confine and restrict the spread of a liquid LNG pool and thereby the extent of an accidental release.
Scenarios selected for QRA

<table>
<thead>
<tr>
<th>Module</th>
<th>Estimated leak frequency (per year)</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small (&lt;5mm)</td>
<td>Large (5-10mm)</td>
</tr>
<tr>
<td>Marintek line</td>
<td>4 E-4</td>
<td>8 E-5</td>
</tr>
<tr>
<td>Reformer H₂</td>
<td>1 E-2</td>
<td>2 E-3</td>
</tr>
<tr>
<td>Reformer NG</td>
<td>7 E-3</td>
<td>1 E-3</td>
</tr>
<tr>
<td>SOFC</td>
<td>1 E-2</td>
<td>2 E-3</td>
</tr>
<tr>
<td>H₂ storage</td>
<td>3 E-2</td>
<td>5 E-3</td>
</tr>
<tr>
<td>Fuel station</td>
<td>2 E-4</td>
<td>4 E-5</td>
</tr>
<tr>
<td>Electrolyser</td>
<td>4 E-3</td>
<td>7 E-4</td>
</tr>
<tr>
<td>LNG storage</td>
<td>3 E-2</td>
<td>5 E-3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.092</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Consequence Calculations

- Dispersion modelling: DNV software PHAST applied for outdoor releases from all modules.
- Fire modelling: DNV software PHAST applied for outdoor releases from all modules.

<table>
<thead>
<tr>
<th>Module</th>
<th>Leak size</th>
<th>Distance to ½ LFL (m)</th>
<th>Distance to 12.5kW/m² (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marintek line</td>
<td>Small</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>H₂ storage</td>
<td>Small</td>
<td>4.2</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>34.1</td>
<td>25</td>
</tr>
<tr>
<td>Fuel station</td>
<td>Small</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>42.1</td>
<td>35</td>
</tr>
<tr>
<td>LNG storage</td>
<td>Small</td>
<td>2.3</td>
<td>6.53</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>37</td>
<td>73</td>
</tr>
</tbody>
</table>
Initial QRA results and recommendations are listed below:

### Results and Recommendations

- The estimated risk impact to the most exposed individual 3rd party (an inhabitant) is assessed to be just below Statoil’s acceptance criteria for most exposed 3rd party (1E-5 per year).

- The main risk contributor to 3rd party is assessed to be events escalating to the storage tanks (H2 or LNG). Such escalated events could cause an impact several hundred metres away from the plant and is therefore assessed to be catastrophic. One of the main contributors to the high escalation frequency is the high probability of an ignited leak to expose one of the storage tanks, due to the short distance between leak sources and storage tanks.

- Due to the short distance between leak sources and storage tanks, even small leaks have potential of causing escalation. And as most of the leaks are assessed to be small (about 85%), the risk impact is therefore significant.

### Results and Recommendations

- Several risk reducing measures proposed
  - Increase distance between leak sources and storage tanks
  - Passive fire protection
  - Fire walls
  - Reduce number of leak sources
  - Ignition control
  - Direction of leak sources
  - Detection and shutdown systems
  - Deflective walls obstructing dispersion and jet flames
  - Alarms
  - Contingency plans

- Special focus should be made in order to reduce the potential of accidents escalating to the storage tanks.

- The effects of introducing such measures will probably be a reduction of the risk level for the most exposed 3rd party to a region of 10-6-10-7 per year.

The QRA results were reviewed and the following design changes implemented.
Changes to design from earlier rev of QRA

- Shielding walls built around and between modules in order to reduce the dispersion distance of ignitable gas as well as the jet fire length
- Building assumed not dimensioned against explosion overpressure. Low risk contribution since the cabinets and modules now are assumed designed with similar safety level as if they where ATEX zone 2

Updated main QRA results are summarized below:

Main risk results

Acceptable risk level for most exposed third party and for societal risk, as long as the ALARP principle is followed. The risk is in the lower part of the ALARP region

Most exposed third party:
The main risk contributor for an inhabitant living within 150 m from the plant. is assessed to be events escalating to storage tanks (H2, LNG, LPG). Such event may cause impact 150 meter away from the plant.

Societal risk:
- Main risk contributor to fatalities of several 3rd parties is assessed to be events escalating to storage tanks (H2, LNG, LPG). Such event may cause impact 150 meter away from the plant.
- The main contributor to the smaller number of fatalities is assessed to be large LNG leaks from the storage module. Such release could cause impact up to about 25 meters away from the plant due to heavy gas effects.

The final QRA recommendations were slightly modified to reflect new findings:
Recommendation – Risk Reducing Measures

- Reduce number of leak sources
- Ignition control
- Detection and shutdown systems
- Alarms
- Passive fire protection
- Routines for H2-filling of cars
- Emergency preparedness and contingency plans
- Safe design of ventilation system
- Establishment of Routines/Procedures for safe operation and service on the process plant.

Special focus should be made in order to reduce the potential of accidents escalating to the storage tanks and cars performing H2-filling operations.

DNV pointed out the QRA uncertainties as follows:

Uncertainties in the assessment

- Presence of third party is a very important assumption
- Leak frequencies (early design and HC-frequency database)
- Ignition probabilities
- Dispersion calculations
Some outstanding queries related to this study are as follows (as posed by Koos Ham):

- Is percentage of damage included in the acceptance criteria shown in the 1st bullet of the first slide on page 10 “Results and Recommendations”?
- Figures to support the results presented on the slide “Main risk results” on page 11 would be helpful.

The plan is to include the resolution of these and other queries in the next revision.

### 2.1.2 QRA for LPG Car Refuelling Station, TNO, Netherlands Case Study

The LPG car refuelling case study was presented by Netherlands, Koos Ham, twice:

- On March 16, 2006, in Long Beach – this was the introduction to the study and results to date pending some action from the government authorities;

The following sequence of slides and discussion involves the combination of slides from both presentations [3, 4].

#### Use of LPG as a car fuel:
**Situation in The Netherlands**

- LPG consumption as car fuel: ~1.1 million m$^3$/year (approx. 8% of car fuel consumption in the country)
- Number of car fuelling stations:
  - total: 3,600
  - of which with LPG: 2,200
- Annual throughput per LPG-station:
  - average: 500 m$^3$/year
  - variation: < 100 - ~ 5,000 m$^3$/year
- Location of installations
  - in build-up areas / inner city: 65%
  - on outskirts / highways: 35%
Safety zones around LPG refuelling stations

LPG Integral policy, 1985:

- LPG storage tanks brought underground or buried
- Storage capacity: minimum 20 m³
- Location-based risk $10^{-6}$ / year at 80 metres distance
- New situations not allowed within 80 m from tank truck unloading location / storage filling connection
- Existing situations: accepted if distance > 20 metres, with technical modifications and preventive measures

Risk policy in The Netherlands, 2004 (1)

Implementation of Decree on risk acceptance criteria for establishments:

- Location-based Risk: No dwellings within $10^{-6}$ /year risk contour
  → Limit value; Mandatory enforcement
- Societal risk: Risk of 10 fatalities < $10^{-5}$/year
  → Goal setting; Justification of accepted excess
Risk policy in The Netherlands, 2004 (2)

Seveso-2 establishments and other hazardous activities:
QRA study to be carried out: determination of LR and SR

Categories of establishments
  • chemical stores and warehouses
  • ammonia refrigeration installations
  • LPG car refuelling stations
for which special regulation applies:
  • Mandatory (technical and organisational) requirements for risk reduction (prevention and repression)
  • Land-use planning requirements through safety zoning, thus no QRA required

Risk policy in The Netherlands, Development in 2006/2007 (1)

1. Unification of risk analysis software
   • For stationary installations: Safeti-NL (DNV – UK)
   • Transport: RBM-2 (AVIV – NL)
   Schedule:
     • Roll-out of software in 2006
     • First introduction and training of users in 2006
     • Formal legislative basis in 2007 (?)

2. Installation of Task Force QRA – experts
   • Aim: identification of future needs and requirements
   • Prioritising these needs
   • Advisory to inter-departmental committee on 'future agenda' for QRA
Risk policy in The Netherlands, Development in 2006/2007 (2)

3. Location based societal risk tool
   • Development and feasibility analysis
   • Joint project of RIVM, TNO and Ministry of VROM
   • Three demo projects (industrial sites and complex transport areas) are ongoing

4. Implementation of ‘new evaluation / decision tool’ for societal risk responsibility:
   • Local authorities (environmental and land-use planning)
   • Emergency response organisations

QRA for generic LPG refuelling station
Scope and objectives

TNO conducted generic QRA study for typical LPG fuelling station (2000 / 2001), on instruction of Netherlands Ministry of Environment (VROM)

Scope of QRA study:
• Definition of generic / typical refuelling station
• Definition of accident scenario’s, especially for LPG delivery
• QRA to determine location-based risks, and distances of $10^{-6}$ and $10^{-5}$ contours

Ministry of VROM to define safety distances and to implement them in national regulation
QRA for generic LPG refuelling station  
System descriptions

Tank truck
- Capacity \( \sim 64 \text{ m}^3 = 26.7 \text{ ton} \)
- Unloading capacity, nominal 500 litres/min
- Unloading hose, diam. 2 inch
- Safety relief valve, setting 19.25 bar

Accident prevention:
- Two excess flow valves in unloading line
- Bottom valve air operated, with melting fuse to close
- Organisational measures: training of driver/operator, no simultaneous petrol unloading, break-away coupling, etc.

QRA for generic LPG refuelling station  
Scenarios truck unloading

Tanker
- Catastrophic rupture
- BLEVE
- Rupture or leak of largest connection

Unloading piping
- Rupture or leakage of pump
- Rupture or leakage of unloading hose
QRA for generic LPG refuelling station
Accident frequencies tank truck (1)

Basis: Purple Book
All frequencies expressed in probability per delivery

<table>
<thead>
<tr>
<th>LoC event</th>
<th>Frequency ( \times 10^{-9} ) / delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic rupture</td>
<td>0.03</td>
</tr>
<tr>
<td>BLEVE</td>
<td>13.1</td>
</tr>
<tr>
<td>Largest connection</td>
<td>5.7 (incl. pump rupture)</td>
</tr>
</tbody>
</table>

QRA for generic LPG refuelling station
Accident frequencies tank truck (2)

Basis: Purple Book
All frequencies expressed in probability per delivery

<table>
<thead>
<tr>
<th>LoC event</th>
<th>Frequency ( 10^{-9} ) / delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage pump</td>
<td>28.5</td>
</tr>
<tr>
<td>Rupture hose (2 inch, 51 mm)</td>
<td>2000 (used: 1000)</td>
</tr>
<tr>
<td>Leakage hose (5 mm)</td>
<td>20,000</td>
</tr>
</tbody>
</table>
QRA for generic LPG refuelling station
Re-assessment hose rupture frequency

Purple Book: \( F = 4 \times 10^{-6} \text{ /hr} = 2 \times 10^{-6} \text{ / delivery} \)

Reassessment RIVM + LPG Industry:

- VVG & Shell-UK: \( 0.35 \times 10^{-6} \text{ / delivery} \)
- VVG: \( 0.4 \times 10^{-6} \text{ / delivery} \), based on casuistry in The Netherlands: 2.5 million deliveries in 45 years, with ‘zero hose ruptures during operation’
- Various other sources: \( 0.07 \sim 2 \times 10^{-6} \text{ / delivery} \)
- Sources not always clear in leaks and ruptures

Conclusion: \( 1 \times 10^{-6} \text{ / delivery}, as 95\% confidence interval \)

QRA for generic LPG refuelling station
Effects and consequences

- BLEVE: Fire ball,
- Flame contact & Heat radiation

- Instantaneous release: gas cloud
- Flame contact & VCE (overpressure)

- Continuous release: torch fire or gas cloud
- Flame contact and/or VCE (overpressure)
QRA for generic LPG refuelling station
Consequence distances

BLEVE:
- Fireball radius: $R = 89$ m
- $35 \text{ kW/m}^2$: $R = 150$ m (100% fatalities)
- $\sim 14 \text{ kW/m}^2$: $R = 307$ m (1% fatalities)

Torch fire, rupture loading hose:
- Flare length: $L = 38$ m (100% fatalities)

Cloud fire, rupture loading hose
- Cloud length (LEL): $L = 43$ m (100% fatalities)
- VCE (0.1 bar): $L = 54$ m (2.5% fatalities)

QRA for generic LPG refuelling station
Risk distances; f-X curve
### QRA for generic LPG refuelling station

#### Risk distances for $10^{-5}$ and $10^{-6}$/year

<table>
<thead>
<tr>
<th>LPG sales [m$^3$/year]</th>
<th>Distance LR = $10^{-5}$ [m]</th>
<th>Distance LR = $10^{-6}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>1000</td>
<td>26</td>
<td>46</td>
</tr>
<tr>
<td>1500</td>
<td>30</td>
<td>108</td>
</tr>
</tbody>
</table>

### Fixed safety distances in legislation

Ministry of VROM defined safety distances and requirements for LPG fuelling stations as follows:

<table>
<thead>
<tr>
<th>LPG sales (actual or permitted) [m$^3$/year]</th>
<th>Distance LR = $10^{-5}$ [m]</th>
<th>Distance LR = $10^{-6}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1000</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>1000 – 1500</td>
<td>25</td>
<td>110</td>
</tr>
<tr>
<td>&gt; 1500</td>
<td>Specific QRA required</td>
<td></td>
</tr>
</tbody>
</table>
Fixed safety distances: consequences

1. Situations with houses within LR > 10^{-5}: to be solved within three years, by:
   a. Measures at source, e.g. relocation of truck unloading point
   b. Withdrawal of permit; occasionally financial compensation
   c. Removal of houses, or terminate their destination

2. Situations with houses within LR > 10^{-6}: to be solved by 1st January 2010, by:
   a. Risk reduction measures at the source
   b. Withdrawal of permit
   c. Removal of houses, or terminate their destination
   d. Limitations in land-use developments

Evaluation of consequences:
Situation for LPG fuelling stations

Inventory investigation of situations revealed:

- Urgent situations: ~ 165 stations
  LR > 10^{-5} (x = 25 m) and/or >10 houses within 80 m

- Situations requiring future modification: ~ 400 stations
  LR > 10^{-6} (x = 45 or 110 m)

- Situations with Q > 1500 m³/year: ~ 125 stations
LPG fuelling stations:
Implementation of measures (planned in 2005)

➢ Urgent situations, including situations of high societal risk:
   ➢ Clean-up and buy-out is ongoing
   ➢ Governmental budget allocated: ~ Euros 30 Million

➢ Situations to be solved before 2010:
   ➢ Formal agreement between LPG Association and Ministry of VROM, to
     investigate risk reducing measures at source, and to implement them by
     2009
   ➢ Measures specifically focussed on tank truck unloading process:
     ➢ Higher integrity of unloading hose, and its operation: \( f_{\text{refl}} = 2 \times 10^{-4} \) /delivery
     ➢ Improved heat resistance of cargo tank, to prevent (or at least delay) occurrence
       of a hot BLEVE in case of fire: \( f_{\text{BLEVE}} = 13.1 \times 10^{-3} \) /delivery
   ➢ Results of these investigations and decisions on implementation expected
     before the end of 2006

LPG fuelling stations:
Implementation of measures (realised in 2006)

➢ Most of the ‘urgent situations’ have been bought out and were
  removed.

➢ For other cases and future problems, two measures were
  investigated:

   ➢ Measure 1: Higher integrity of unloading hose

   ➢ Measure 2: Reduction of frequency of hot BLEVE of tank
     truck, by improved heat protection
Measure 1: Higher integrity of unloading hose

- Measure 1: Higher integrity of unloading hose has been proven in statistical analysis and technical evaluation:
  - Failure (rupture) frequency approx. 70x lower than average hoses; recommended for QRA factor 10x reduction.
  - Statistical evaluation based on unloading of tank truck + loading of vehicles, from three companies having 90% of the market:
    - 50 years experience (1955 – 2005): $1 \times 10^4$ transfers
    - 15 years experience (1990 – 2005): $5 \times 10^3$ transfers
- Reduction of loading hose failure will reduce distance of $IR = 10^{-6}$/year:
  - for annual sales < 1000 m$^3$, by approx. 10 – 20 m
  - for annual sales > 1000 m$^3$, depends on outcome of BLEVE reduction

Measure 2: Prevention of hot BLEVE

- Measure 2: Reduction of frequency of hot BLEVE of tank truck has proven possible by providing hot resistant coating
- Predefined conditions:
  - BLEVE will not occur at temperatures below ~400 °C
  - An unprotected tank may reach this temperature within 15 – 20 min upon exposure to fire
  - It may take fire services (at a max!) 75 min to effectively cool the tank
- Therefore the following criterion was determined:
  - The temperature of the metal body of a filled LPG tank, provided with heat resistant coating, shall not exceed $T = 300$ °C, when it is exposed to a fire with specified flame temperatures etc, during at least 75 min.
- TNO carried out BONFire tests for two tanks: $V = 3$ m$^3$, 50% and 80% filled with LPG. Tanks were protected with 10 mm layer of Chartec-7.
BONFire test 3 m³ LPG tank: experimental set-up (4)

BONFire test 3 m³ LPG tank: Results (5)
Koos Ham provided the following post-commentary regarding the age of non-compliant stations:

- Most, if not all, of the LPG stations affected by the new regulations were constructed and taken into operation before 1985. It is a fact that in 1985 a first round of modifications and removal has taken place, for stations with vulnerable objects within 80 m distance. With specific measures, several existing situations could be allowed where houses were present at a distance as short as 25 meters, but no new situations were allowed since then with distances shorter than 80 m.
- The new 'BEVI/REVI' regulations require a minimum distance of 45 m (or 110 m for annual sales > 1000 m³). Therefore, it is expected that most of the removal situations are those which were permitted to continue in 1985, but with houses closer than 45 m.
- Most of the (100 - 200) situations that required taking measures since the new requirements came into force, have been resolved by terminating the LPG sales. For these cases of termination, some compensation was paid to the station owners. In a (very) limited number of cases, removal of houses appeared a better option.
- Of course, in the two decades between 1985 and 2005 there have been many situations where requests for permission to establish vulnerable objects, like houses, within the 80 m zone from an LPG station were rejected. This had limited the number of cases that were eventually affected by the legislative criteria.
2.1.3 QRA for Gaseous Hydrogen Refuelling Station in Turin, UNIPI, Italy Case Study

This QRA case study was presented by Italy, co-authors Alessia Marangon and Marco Carcassi from University of Pisa, at the meeting in Vancouver on September 6, 2006 [5].

The study concerns the future demonstration hydrogen refuelling facility located within the Environmental Park in Turin. Slides below provide the study summary.

**Hydrogen refueling station:**

**SITE / LOCATION:**

- Within an “Energy/Environment demonstration area”- “Environment Park Turin, Italy”;
- 2 blocks of flats: 55 m - separation distance;
- Commercial center: 75m - separation distance;
- 2 bus stops: 85 m and 107 m - separation distances;
SITE / LOCATION: the characterization of the site is necessary for the determination of the:

- Impact of the station on the territory;
- Centers of vulnerability;
- Consequences of the accidental scenarios on the population and on the environment outside the fence of the plant;
- Domino effect (propagation of the accident).
**Hydrogen refueling station:**

**PLANT DESCRIPTION:** The plant includes:

- A reserve of water (500 liters) and demineralization unit;
- An electrolyser unit (4 bar; 8 - 40 Nm³/h);
- Hydrogen dryer and purification units;
- A hydrogen compression unit (280 barg; 39 Nm³/h);
- 3 horizontal cylinders for high pressure hydrogen storage (280 bar; \(C_{TOT} = 276\) liters);
- Bottles of hydrogen for emergency refueling (160 Nm³; 200 barg);
- 1 dispenser with a control's skid for the filling procedure, with an internal compression unit and an internal storage unit (420 barg for the storage and 350 barg for the refueling);
- A nitrogen storage (5,000 liters) and vaporization unit.

**PLANT DESCRIPTION:** Lay-out:
**Risk assessment methodology:**

The analysis is so organized:

1. identification of the hazards present on site;
2. selection of the most critical hazards and definition of the events that are the primary cause of an accident (initiator events);
3. analysis of the accidental sequences that can derive from the selected initiator event;
4. evaluation of the risk and of the distances of damage, as well as identification of the design & management improvements (related to each phase of the analysis) that could significantly reduce the risk.

**Identification of the hazards - HAZID methodology:**

<table>
<thead>
<tr>
<th>Functional analysis of all the units present on site</th>
<th>Identification of all the principal functions carried out by the plant. Then each principal function is decomposed in elementary functions, through a hierarchical approach (tree structure).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td>FUNCTION</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1.</td>
<td>Hydrogen production</td>
</tr>
<tr>
<td>1.1</td>
<td>Demineralization of water</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Demineralised water storage</td>
</tr>
<tr>
<td>......</td>
<td>......</td>
</tr>
<tr>
<td>1.2</td>
<td>Hydrogen generation</td>
</tr>
<tr>
<td>1.3</td>
<td>Hydrogen purification</td>
</tr>
<tr>
<td>......</td>
<td>......</td>
</tr>
<tr>
<td>2.</td>
<td>Compression and delivery of the hydrogen to the storage units</td>
</tr>
</tbody>
</table>
Identification of the hazards - HAZID methodology:

Analysis of the elementary functions

Identification of all the possible deviations

Identification of the related causes

Evaluation of the related consequences

Compilation of the HAZID chart

Identification of the hazards - HAZID chart:

<table>
<thead>
<tr>
<th>Principal function</th>
<th>Elementary function</th>
<th>Hazard / Deviations</th>
<th>Causes</th>
<th>Consequences</th>
<th>F</th>
<th>D</th>
<th>R</th>
<th>Existing Prevention / Mitigation measures</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1</td>
<td>Hydrogen storage in 3 units</td>
<td>Hydrogen release</td>
<td>Leak from valves or piping</td>
<td>Fire and/or explosion, possible domino effect</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>The storage units are separated from the other systems by a concrete wall built on 3 side. Moreover the storage units are protected from the solar radiation by a shield</td>
<td>Structural integrity verifications of piping, connections and weldings, Periodic maintenance of valves</td>
</tr>
</tbody>
</table>

Identification of the hazards

The Frequency (F), Damage (D) and Risk (R) indexes are estimated on the basis of a qualitative judgment with reference to the following classification.
Frequency (F) Classification

<table>
<thead>
<tr>
<th>F</th>
<th>Time between two events / Annual Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highly improbable: non expected during the plant life</td>
</tr>
<tr>
<td>2</td>
<td>Improbable: it should not occur during the plant life</td>
</tr>
<tr>
<td>3</td>
<td>Not very probable: expected at maximum once during the plant life</td>
</tr>
<tr>
<td>4</td>
<td>Probable: expected few times during the plant life</td>
</tr>
<tr>
<td>5</td>
<td>Occasional: expected several times during the plant life</td>
</tr>
</tbody>
</table>

Damage (D) Classification

<table>
<thead>
<tr>
<th>$D_A$</th>
<th>Entity</th>
<th>Damage description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Negligible</td>
<td>No damage to people and/or safety functions</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>Slight injury to people and/or partial loss of safety functions</td>
</tr>
<tr>
<td>3</td>
<td>Severe</td>
<td>Severe injury to people and/or total loss of safety functions</td>
</tr>
<tr>
<td>4</td>
<td>Critical</td>
<td>Death of operators</td>
</tr>
<tr>
<td>5</td>
<td>Catastrophic</td>
<td>Many death, also between external people, and/or plant destruction</td>
</tr>
</tbody>
</table>

The association of the frequency and of the damage index to the single event is carried out with the following hypothesis:

Operational functions:

- the frequency is estimated in relation to the cause of greater frequency enable to produce a deviation of the operational function;
- the damage is estimated in the hypothesis that the present safeguards work correctly.

Protective/Safety functions:

- the frequency is estimated taking into account the simultaneous verification of the two events here listed:
  - the frequency related to the cause of greater frequency able to produce the loss of the protective/safety function and contemporarily,
  - the verification of an anomaly in the system that asks for the intervention of the protective/safety function.
- the damage is estimated keeping in mind that the protective/safety function is not available.
Selection of the most critical hazards and definition of the initiator events:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Risk matrix (Risk acceptance criteria)**

- **Unacceptable**: more detailed studies are recommended together with design and/or managerial modifications.
- **ALARP (As Low As Reasonably Practicable)**: design and/or managerial modifications are suggested to keep the risk as low as reasonable practicable with respect to the economic point of view.
- **Acceptable**: the design and the management of the plant guarantee an adequate control of the risk.

So the most critical events are selected and collected in a Matrix of Risk that allows to classify all the events in three great categories:

- **Non acceptable risk**: more detailed analysis are recommended together with design and/or managerial improvements.
- **ALARP (As Low As Reasonably Practicable) region** (Almost acceptable risks): design and/or managerial modifications are suggested to keep the risk as low as reasonable practicable with respect to the economic point of view.
- **Acceptable risk**: the design and the management of the plant guarantee an adequate control of the risk.

**QUANTITATIVE ANALYSIS:**

Then the most critical hazards and also the ones in the ALARP region have been analyzed in a quantitative way:

- **EVENT TREE METHODOLOGY** for the frequencies
- **CFD simulations (PHAST code)** for the consequences
**Event tree - Example:**

<table>
<thead>
<tr>
<th>Initiator event</th>
<th>Immediate ignition</th>
<th>Delayed ignition</th>
<th>N° Seq</th>
<th>Incidental sequence</th>
<th>Frequency ev./year</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,08 $10^{-5}$ ev/year</td>
<td>0,50</td>
<td>0,45</td>
<td>1</td>
<td>Jet-fire</td>
<td>1,54 $10^{-5}$</td>
</tr>
<tr>
<td>Pipeline rupture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>2</td>
<td>VCE or Flash fire</td>
<td></td>
<td></td>
<td>6,93 $10^{-6}$</td>
</tr>
<tr>
<td>No</td>
<td></td>
<td></td>
<td></td>
<td>Dispersion in atmosphere of the inventory of the 3 storage units</td>
<td>8,47 $10^{-6}$</td>
</tr>
</tbody>
</table>

Event tree data references:

➢ IGC Doc 75/01/E/rev, “Determination of Safety Distances,” EIGA (European Industrial Gases Association):

<table>
<thead>
<tr>
<th>Rupture type</th>
<th>Frequency (ev. / year *meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small break</td>
<td>7.50 E-06</td>
</tr>
<tr>
<td>Large break</td>
<td>2.00 E-06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Small Spill</th>
<th>Large Spill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.15</td>
<td>0.50</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.50</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Immediate ignition

Note: small spills involve 10% of tank inventory, large spills involve 100% of tank inventory.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Small Spill</th>
<th>Large Spill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>0.68</td>
<td>0.23</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.45</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Delayed ignition

Note: small spills involve 10% of tank inventory, large spills involve 100% of tank inventory. For propane and hydrogen, these probabilities are the total contribution from scenarios involving: a) ignition when the vapor cloud edge is over the population edge, and b) ignition when the vapor cloud center is over the population center.

- EGIG 1997, Gas pipeline incidents, 1998;
- Saffioti, Merendino, I rischi di incendio nelle procedure per le autocisterne, Antincendio, Marzo 1996;
- OREDA 1992, Offshore Reliability Data, 1992
- OREDA 1984, Offshore Reliability Data, 1984
- AIChE, Guidelines for process equipment reliability data, 1989
Consequence evaluation: Targets / Vulnerabilities definition

<table>
<thead>
<tr>
<th>Criteria for harm potential Reference damage limit values</th>
<th>Seveso directive as it is in force in Italy through the Ministerial Decree of 9th May 2001 Mandatory</th>
<th>IGC Doc 75/01/E/rev Not mandatory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fires (stationary thermal load)</strong></td>
<td>Minor harm to people: 3 kW/m² High harm to people: 5 kW/m² Start value for lethal effect: 7 kW/m² High lethality: 12.5 kW/m² Damage to equipment / domino effect: 12.5 kW/m²</td>
<td>No harm: 1.6 kW/m² Harm to people: 9.5 kW/m² (pain threshold reached after 8s; second decade burns after 20s) Damage to equipment: 37.5 kW/m²</td>
</tr>
<tr>
<td><strong>Bleve / fireball (variable thermal load)</strong></td>
<td>Minor harm to people: 125 kJ/m³ High harm to people: 200 kJ/m³ Start value for lethal effect: 359 kJ/m³ High lethality: fireball radius Damage to equipment / domino effect: 200-800 m (*)</td>
<td></td>
</tr>
<tr>
<td><strong>Flash-fire (instantaneous thermal load)</strong></td>
<td>Start value for lethal effect: ½ LFL High lethality: LFL</td>
<td>No harm: ½ LFL Harm to people: LFL</td>
</tr>
<tr>
<td><strong>Explosions (peak overpressure)</strong></td>
<td>Minor harm to people: 0.03 bar High harm to people: 0.07 bar Start value for lethal effect: 0.14 bar High lethality: 0.3 bar (0.6 bar in open spaces) Damage to equipment / domino effect: 0.3 bar</td>
<td>No harm: 0.02 bar Harm to people: 0.07 bar Damage to equipment: 0.2 bar</td>
</tr>
</tbody>
</table>

(*) Depending on the size and type of the storage system

- **Explosion**: death of 5% of people within the area characterized by an overpressure equal or greater than 0.3 bar (Conservative assumption: Lees suggested a probability of death lower than 1% for overpressure lower than 1 bar (Loss Prevention in the Process Industries, Butterworth, 1983, page 599);

- **Jet-fire**: death of 100% of people within the flame area and of 5% of people exposed to thermal radiation of 12.5 kW/m² (Conservative assumption: Lees suggested a probability of death equal to 1% for a thermal radiation of 10.2 kW/m² that lasts for 45.2 seconds (Loss Prevention in the Process Industries, Butterworth, 1983, page 526).

- **Flash fire**: death of 100% of people within the area characterized by a hydrogen concentration in air equal to or greater than LFL. No injuries to people outside that area.
Some results: Large break of the high pressure connection pipe between the 3 storage units and the dispenser

Input Data

- Pipe length: 0.5 m
- Diameter: 8.5 mm
- Hydrogen inventory: 75.5 kg
- Initial pressure: 300 bar
- Initial temperature: 15 °C
- Diameter of the rupture: 8.5 mm at 0 m (ground level)
- Angle of output of the jet: 20°

<table>
<thead>
<tr>
<th>Atmospheric data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability Class</td>
</tr>
<tr>
<td>Ambient temperature [°C]</td>
</tr>
<tr>
<td>Relative humidity</td>
</tr>
</tbody>
</table>

Dispersion (simulation with PHAST_ “Line Rupture”)

<table>
<thead>
<tr>
<th>Dispersion results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability class</td>
</tr>
<tr>
<td>Average flow [kg/s]</td>
</tr>
<tr>
<td>Duration of the release [s]</td>
</tr>
<tr>
<td>Maximum distance on the ground (LEL concentration) [m]</td>
</tr>
<tr>
<td>Maximum distance of the center of the cloud (LEL concentration) [m]</td>
</tr>
<tr>
<td>Maximum height of the center of the cloud (LEL concentration) [m]</td>
</tr>
<tr>
<td>Maximum width of the cloud (LEL concentration) [m]</td>
</tr>
<tr>
<td>Area with hydrogen concentration in air equal or greater than LEL (damage area) [m²]</td>
</tr>
</tbody>
</table>
Dispersion: simulation with PHAST—"Line Rupture"

Study Field: explosion hydrogen
Audit No. 0884
Model: EHP-1A Abortive de 300 bar
Material: HYDROGEN
Average Time: 100 s
Flammable (10,75 s)
Legend: North

Category 1/F 6,805 s
Category 2/F 4,139 s
Category 5/D 1,942 s

Dispersion: simulation with PHAST—"Line Rupture"

Study Field: explosion hydrogen
Audit No. 0884
Model: EHP-1A Abortive de 300 bar
Material: HYDROGEN
Average Time: 100 s
C/L Offset 0 m
Concentration 40000 ppm
Legend: North

Category 1/F 6,805 s
Category 2/F 4,139 s
Category 5/D 1,942 s
### Jet-Fire results

<table>
<thead>
<tr>
<th>Jet orientation</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal radiation of the hydrogen flame kW/m²</td>
<td>109,3</td>
</tr>
<tr>
<td>Length of the jet-fire along the flame axis [m]</td>
<td>13,3</td>
</tr>
<tr>
<td>Maximum radius of the flame [m]</td>
<td>0,8</td>
</tr>
<tr>
<td>Maximum distance from the release point at which the thermal radiation is equal to 12.5 kW/m² [m]</td>
<td>13,4</td>
</tr>
<tr>
<td>Damage area (elliptical shape) [m²]</td>
<td>107,1</td>
</tr>
</tbody>
</table>

---

Jet-Fire (simulation with PHAST_“Line Rupture”)

![Diagram showing the results of the Jet-Fire simulation](image)

**Legend**
- **Red**: Area of fire
- **Green**: Area of radiation 12.5 kW/m²
- **Black**: Area potentially affected

---

Andrei V. Tchouvelev

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RI_Jan-08
VCE (simulation with PHAST - confinement grade of 75% and 85%)

<table>
<thead>
<tr>
<th>VCE Results</th>
<th>Confinement grade = 75%</th>
<th>Confinement grade = 85%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total hydrogen inventory [kg]</td>
<td></td>
<td>5.75</td>
</tr>
<tr>
<td>Distance from the release point at which the overpressure is equal to 0.3 bar [m]</td>
<td>21</td>
<td>26</td>
</tr>
</tbody>
</table>

VCE (simulation with PHAST - confinement grade of 75% and 85%)
Flash fire – delayed ignition (simulation with PHAST)

<table>
<thead>
<tr>
<th>Stability Class</th>
<th>1F</th>
<th>2F</th>
<th>5D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum distance on the ground (LEL concentration) [m]</td>
<td>0,20</td>
<td>0,20</td>
<td>0,34</td>
</tr>
<tr>
<td>Maximum distance of the center of the cloud (LEL concentration) [m]</td>
<td>20,1</td>
<td>16,9</td>
<td>11,6</td>
</tr>
<tr>
<td>Maximum height of the center of the cloud (LEL concentration) [m]</td>
<td>10,5</td>
<td>7,2</td>
<td>2,8</td>
</tr>
<tr>
<td>Area characterized by a concentration equal or greater than LEL (damage area) [m²]</td>
<td>64</td>
<td>54</td>
<td>28</td>
</tr>
</tbody>
</table>

Flash fire – delayed ignition (simulation with PHAST)
**Conclusion:**

- All the results of the event frequencies and consequences analysis have been related to the acceptability criteria proposed by the “European Integrated Hydrogen Project (EIHP)” for hydrogen systems.

![Graph showing event frequencies and consequences](image)

All the events are in the acceptability region

**Conclusion – New approach in Italy:**

**Deterministic approach**

Why?

- Because in Italy we don’t have any official “Risk Acceptance Criteria”

- The judgment on the acceptability of an installation can be different from authorities to authorities;

- The Government with the help of the local interested Fire Brigades and with the help of Universities and Industries has elaborated a draft regulation for the “Construction and exercise of hydrogen and multifuel refueling station”.

*The regulation is a living document*, periodically reviewed on the basis of the results of demonstrative projects and on the basis of the further understanding of the phenomena related to hydrogen (Knowledge gap);
Some features:

- The regulation has been elaborated on the basis of the one in force in Italy for natural gas refueling stations.
- The safety distances have been incremented with respect to the ones in force for natural gas, especially for the storage systems and for the external safety distances.
- In Italy these distances (both for natural gas and hydrogen) are larger than in USA (NFPA) and Europe (IGC, TUV) and they are also larger than the ones recommended by the ISO/TS 20012 Technical Specification for Gaseous hydrogen – fuelling stations.

2.1.4 Safety Study of Gaseous Hydrogen Supply Stations, JPEC, Japan Case Study

This safety case study was presented by Japan, main author Shigeki Kikukawa from Japan Petroleum Energy Centre, at the meeting in Vancouver on September 6, 2006 [6].

The study was first presented at the 1st ICHS in Pisa in September 2005 and was published in the Conference proceedings [7]. There was a desire, however, expressed by the Task 19 participants to have a more detailed discussion on the study as well as to hear an update on further developments that happened after the study has been concluded. The study description below is based both on the original published text and the presentation at the Vancouver Task 19 meeting.

The driving force for the study was the concern with existing High Pressure Gas Law: it was feared that prescribed minimum distance of 11.3 m between a pressurized gas storage over 10 MPa and dwellings will hinder commercial roll out of hydrogen infrastructure for vehicle fuelling.

In 2003, in accordance with the government’s plan to address the above concerns, JPEC initiated a safety study that included other partners such as Mitsubishi Heavy Industries (H2 diffusion and explosion experiments, and CFD modeling), The Japan Steel Works (materials compatibility and compressor reliability), Japan Industrial Gas Association (reliability of piping and valves), Iwatani Corp. (reliability of LH2 systems) and Tatsuno Corp. (reliability of dispensing equipment). JPEC assumed project management and risk assessment.

The main objective of the study was to develop safety measures allowing reducing prescribed safety distances for hydrogen supply stations and allowing those stations to be co-located with gasoline stations as well as located in urban areas.
Concerns with Regulation

  - Released the Road Map.
  - Identified 28 concerns with regulation which should be reviewed for market introduction of Fuel Cells.

<table>
<thead>
<tr>
<th>Items</th>
<th>Description</th>
<th>Clarification Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 items</td>
<td></td>
<td>To be clarified before Dec. 2002</td>
</tr>
<tr>
<td>3 items</td>
<td>FCV</td>
<td></td>
</tr>
<tr>
<td>4 items</td>
<td>High Pressure H2 Tank of FCV</td>
<td>To be clarified before FY2005</td>
</tr>
<tr>
<td>7 items</td>
<td>H2 Infrastructure</td>
<td></td>
</tr>
<tr>
<td>Setback distance etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 items</td>
<td>Stationary FC</td>
<td></td>
</tr>
</tbody>
</table>
First key issue is to resolve restrictions on safety (setback) distances:

**High Pressure Gas Safety Law**

Setback distance for general high pressured equipment:

- 17m: Hospital, school, etc.
- 11.3m: Dwellings
- 8m: Fire sources

Hydrogen stations must FREE from DANGER!

We have to add some safety requirements to reduce the setback distance.

**Key Issue 2:**
Permission to set up H2 stations with Gasoline stations

**Fire Protection Law**

**Key Issue 3:**
Permission to build in an urban area

**Building Standard Law**
A basic quantitative risk assessment methodology was selected for this study:

Selected risk acceptance criteria as shown in the risk matrix below. JPEC used risk acceptance criteria established with EIHP2 project [x].

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Likelihood</th>
<th>Likelihood</th>
<th>Likelihood</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Extremely Severe Damage</td>
<td>Improbable</td>
<td>Remote</td>
<td>Occasional</td>
<td>Probable</td>
</tr>
<tr>
<td>1</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Severe Damage</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Damage</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Small Damage</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>Minor Damage</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>M</td>
</tr>
</tbody>
</table>
Risk levels, likelihood levels and consequence levels were selected as follows:

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (High)</td>
<td>Risk is not acceptable. Remedial actions should be considered to reduce the risk to an acceptable level.</td>
</tr>
<tr>
<td>M (Medium)</td>
<td>In principle, risk cannot be acceptable. It can be accepted only when risk reduction cannot be achieved by reasonably practical action.</td>
</tr>
<tr>
<td>L (Low)</td>
<td>Acceptable. Further risk reduction is not necessarily required.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Likelihood Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Improbable</td>
</tr>
<tr>
<td>B</td>
<td>Remote</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
</tr>
<tr>
<td>D</td>
<td>Probable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Level</th>
<th>Asset Damage</th>
<th>Human Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extremely Severe Damage</td>
<td>Collapse of nearby dwelling houses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>One or more fatalities of pedestrians or dwellers</td>
</tr>
<tr>
<td>2</td>
<td>Severe Damage</td>
<td>Major damage of nearby dwelling houses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>One or more fatalities of customers or station workers</td>
</tr>
<tr>
<td>3</td>
<td>Damage</td>
<td>Minor damage of nearby dwelling houses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Injury and hospitalization</td>
</tr>
<tr>
<td>4</td>
<td>Small Damage</td>
<td>Windows broken</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Injury and medical treatment</td>
</tr>
<tr>
<td>5</td>
<td>Minor Damage</td>
<td>No damage to nearby dwelling houses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minor injury</td>
</tr>
</tbody>
</table>
Definition of H2 Station model

The model should be concrete enough for risk assessment. The model should keep generality to be used for the review of C&S.

- On-site type H2 station
  - H2 Demand: 300Nm³/hr (30Nm³/vehicle * 10vehicles/hr)
  - H2 Generation: 300Nm³/hr
  - Compressor: 300Nm³/hr, 40MPa
  - H2 Cylinders: 250L * 14 = 3500L (40MPa, 1400Nm³)
  - Dispenser: 35MPa (supply pressure)

Types of H2 Stations

1) On-site type

2) Off-site type

3) Liquid hydrogen type

Study was finished

Study is on progress
Hazard Identification

- **Applied Methods**:  
  - HAZOP (Hazard and Operability Studies)  
  - FMEA (Failure Mode and Effect Analysis)

- **233 accident scenarios were identified for the on-site type H2 station model**  
  - Failure and deterioration  
  - Human Error  
  - Natural Disasters

Consequence Analysis

The consequences of an explosion or jet fire are assessed in this study based on three key parameters: leak size, hydrogen pressure and hydrogen inventory. The identified accident scenarios are investigated and classified into four groups depending on the leak size as follows:

<table>
<thead>
<tr>
<th>Hole Size Class</th>
<th>Representative Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>-</td>
<td>Rupture of a storage vessel. Stored hydrogen is released instantly and it explodes, if ignited.</td>
</tr>
<tr>
<td>Medium</td>
<td>10mmΦ</td>
<td>Rupture of pipe or filling hose. Massive discharge of hydrogen leads to explosion or jet fire, depending on ignition timing, if ignited.</td>
</tr>
<tr>
<td>Small</td>
<td>1mmΦ</td>
<td>Relatively small opening such as crack and pinhole on piping and filling hose. Leakage is continuous and it leads to explosion or jet fire, depending on ignition timing, if ignited.</td>
</tr>
<tr>
<td>Very Small</td>
<td>-</td>
<td>Very small opening such as leakage from gland packing of valves.</td>
</tr>
</tbody>
</table>

The following is an example of consequence analysis supported by experiments performed by Mitsubishi.

**Case 1**

Applicable accident scenario: \{false start of FCV – rupture of filling hose – leakage – ignition – jet fire or explosion\}
The opening is ‘Medium’ and the hole size is regarded 10mmØ. Even though the pressure at storage is 40MPa, the pressure at the opening is reduced to 10MPa considering pressure loss of 30MPa caused by the piping between cylinders and dispenser. In the calculation of pressure loss, it is assumed the connection piping with inner diameter 10mm is 10m long, and straight with no bending and valves. It is experimentally examined that the length of jet fire reaches to 12m at the beginning of the leakage. It implicates that pedestrians and dwellers outside a station would be fatally injured. The consequence level of the accident scenario is graded as level 1 which is ‘Extremely Severe Damage’.

![Image of hydrogen jet fire](image)

**10mmØ  40→1MPa**

**Likelihood Analysis**

Likelihood analysis is undertaken for each identified accident scenario under the assumptions stated below.

- The probability of ignition is not considered, and regarded as 1. It means that released hydrogen always ignites regardless of ignition sources.

- The probability of presence of human beings is assumed as follows. There are always station workers or customers around the equipment of a hydrogen supply station. There are always pedestrians or dwellers beyond the site borders of a hydrogen supply station.
Likelihood Estimation

- Experiments & Surveys by our Project Partners
  - Material : The Japan Steel Works
  - Compressor : The Japan Steel Works
  - Dispenser : Tatsuno Corporation
  - General piping materials & instrument:
    Japan Industrial Gas Association

Risk Evaluation

The following risk matrix was obtained after the initial risk evaluation, i.e. implementation of risk reduction measures. The matrix shows numbers of considered accident scenarios that were assessed to a relevant risk level.

<table>
<thead>
<tr>
<th>Consequence Level</th>
<th>Likelihood Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

The following risk reduction measures were suggested to reduce the number of unacceptable scenarios (those that are in the red zone):
<table>
<thead>
<tr>
<th>Applied Area</th>
<th>Safety Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>6m of clearance distance between pressurized equipment and site borders</td>
</tr>
<tr>
<td></td>
<td>Fire protection wall (h=2m) on site borders which do not face a road</td>
</tr>
<tr>
<td></td>
<td>Seismometer and interlock system</td>
</tr>
<tr>
<td>Material Selection</td>
<td>SCM435 for cylinder material</td>
</tr>
<tr>
<td></td>
<td>SUS316L for piping material</td>
</tr>
<tr>
<td>Compressor Unit</td>
<td>Hydrogen leak detector in an enclosure of a compressor</td>
</tr>
<tr>
<td></td>
<td>Ventilation system in an enclosure of a compressor and interlock system</td>
</tr>
<tr>
<td></td>
<td>Monitoring of temperature and flow rate of cooling water</td>
</tr>
<tr>
<td>Dispenser Unit</td>
<td>Breakaway device in the middle of a filling hose</td>
</tr>
<tr>
<td></td>
<td>Shock sensor and interlock system</td>
</tr>
<tr>
<td></td>
<td>Hydrogen leak detector in a body of a dispenser and interlock system</td>
</tr>
<tr>
<td></td>
<td>Hydrogen leak detector at a dispensing nozzle and interlock</td>
</tr>
<tr>
<td></td>
<td>Flame detector in dispensing area</td>
</tr>
<tr>
<td></td>
<td>Guardrail in front of a dispenser</td>
</tr>
<tr>
<td></td>
<td>Piping in trench around a dispenser</td>
</tr>
<tr>
<td>Storage Unit</td>
<td>Water sprinkler and thermal sensor</td>
</tr>
<tr>
<td></td>
<td>Flame detector at header of storage unit</td>
</tr>
<tr>
<td></td>
<td>Excess flow valve in an exit pipe of cylinder</td>
</tr>
</tbody>
</table>

Below is an illustration of implementation of one risk reducing measure related to a pipe rupture scenario:
The result of risk evaluation after the appropriate safety measures have been implemented is summarized in the risk matrix below:
Study Conclusions

The following conclusions are derived from the safety study of a gaseous hydrogen supply station.

- Risks of gaseous hydrogen supply stations can be mitigated to acceptable level, with 9 exceptional accident scenarios remaining.
- Risks of the 9 accident scenarios are assessed to be unacceptable. Their likelihood is ‘extremely low’, while the consequence is ‘extremely severe’.
- Safety measures necessary for gaseous hydrogen supply stations are specified.
- Clearance distance is proposed to be 6m between pressurized equipment and site borders.

The result of the study was reported to METI and the High Pressure Gas Safety Institute of Japan, with our recommendation to retain risks of the 9 accident scenarios and not to expand clearance distance further than 6m.

A review of existing regulations was conducted by the government based on the study conclusions:

- The result of the study was reported to the competent authorities, then examined, and basically accepted by them.
- The competent authorities revised relevant regulations.
- The new regulations have been effective since April 2005.
  - High Pressure Gas Safety Law
  - Fire Protection Law
  - Building Standard Law
Below is the summary of approved changes:

**Safety Requirements**
for High Pressure Gas Safety Law

- Setback Distance can be shortened with appropriate fire protection wall
- Wall h=2m
- Setback Distance 6 m
- H2 leak detector
- Earthquake detector
- Flame detector

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• Compressor should be placed in an enclosure.
• Ventilation with Interlock System
Conclusions

- We made drafts of revised safety codes and standards of Hydrogen supply stations.
- Government reviewed the regulations based on our drafts and new regulations have been in force now.
  - High pressure gas safety law
  - Fire Protection Law
  - Building Standard Law
- It was permitted to build H2 supply station in an urban area and to install them in the premise of a gasoline station.

2.1.5 Comparative Risk Estimation of Compressed Hydrogen and CNG Refuelling Options, CTFCA, Canada Case Study

This QRA case study was presented by Canada, main authors Andrei V. Tchouvelev (AVT), D. Robert Hay (TISEC) and Pierre Benard (HRI), at the meeting in Vancouver on September 6, 2006 [8].

The study was part of a project conducted within the Canadian Hydrogen Safety Program. It was later presented at a number of workshops and conferences including NHA Conference in San Antonio in March 2007 [9]. The description of the study below largely uses text prepared for these events.

The project comprised a comprehensive analysis of several hydrogen sourcing and refueling site configurations of which only a few representative examples of the analysis are described here for reasonable space use.

Engineering analysis and public perception of risk require both quantitative and qualitative assessments to assist in design and public acceptance of hydrogen refuelling stations. Quantitative risk assessment methodologies were applied to several safety-critical issues in hydrogen refuelling stations to generate design criteria and metrics for codes and standards development. To position the hydrogen station within the risk aversion perspective of the general public, these analyses were carried out in parallel with corresponding analyses for CNG (methane) stations. The latter represent consumer facilities where a public risk aversion level has been established and provides a reference with which risk analysis can be conveyed on a cooperative basis.
The risks analyses in the project are those associated with unintentional releases of hydrogen. Twelve such release scenarios were considered through the hydrogen life cycle from sourcing at the station to the dispenser. Sourcing options included delivery by tube trailer and on-site generation by electrolysis and hydrocarbon reforming.

The release scenarios selected were based on a composite of the literature-based and in-house hazard identification analyses. They are a series of safety-critical issues that represent those concerns that provide key input to design and public acceptance decision making.

A two-fold risk analysis approach comprised determining the probability of the releases in each scenario developing and consequence modeling, the latter including analysis of the dispersion of hydrogen under the scenario release conditions and the consequences of ignition of the hydrogen. The probability component was computed using failure-rate data from the CTFCA database as input to fault and event tree analysis. The thermal consequence models provided a set of radiant heat fluxes expressed in kW/m² at a set of distances at which the following heat flux thresholds occurred:

- 4.7 kW/m²  A pain threshold
- 12.5 kW/m²  First-degree burn threshold
- 37.5 kW/m²  Mortality threshold

Each scenario is addressed via a table that contains a diagram with distances to selected thermal threshold levels. The diagrams show maximum values for each threshold level in radial direction, i.e. outside the jet flame. Because of different intensity of releases in selected scenarios, the maximum values are achieved at different axial distances from the point of release. In order to compare thermal effects at equal distances from the points of release and resulting jet fires, the tables also contain the numbers for locations 1 m and 5 m away from the point of release in axial direction and 1 m in radial direction. They are marked (x, R) = (1 m, 1 m) and (x, R) = (5 m, 1 m) respectively. The values of thermal effects at these locations are used for risk calculations in Risk Estimation section of this report. For cases when selected locations are within the flame (i.e. thermal flux is much greater than 37.5 kW/m²), the fatality probability is considered to be equal to 1.

Each of these distinct pairs of radiant heat flux and distances from the origin of the hazard was transformed into a probability of fatality at that specific distance, a consequence metric to be used for computation of risk. This transformation was performed using the Probit Equation (dose-response relationship).

Metrics were adopted to quantify the individual and societal risks associated with the scenarios analyzed in this project to effect comparisons between selected hydrogen sourcing, storage and hydrogen production components in hydrogen refuelling options. These were computed using HyQuantras™, a computerized toolkit for quantifying the risk associated with the jet-fire and flare scenarios used for these comparisons. Location-Specific Individual Risk (LSIR) and Potential Loss of Life (PLL) were used for the project comparisons.

The project data were used to compare various sourcing for hydrogen:

- Tube trailer delivery
and to compare the risk associated with storage modes of the two fuels. Also, the delivery of hydrogen by tube trailer and of natural gas through pipeline was compared.

2.1.5.1 TIAX FMEA Study

In 2005 TIAX released an FMEA study of the hydrogen refuelling option compared to a CNG refuelling option [10]. This TIAX study provides good qualitative guidance regarding the comparative risk of various hydrogen technologies vs CNG technology as well as regarding potential “stand-out” scenarios for more detailed modeling. The current study extends beyond the comparison at the qualitative FMEA level detailed quantitative comparison of “stand-out” elements that are either technology or fuel related. With the permission of TIAX, their FMEA approach and risk factors for various hydrogen technologies-based refuelling options in comparison with a CNG refuelling option are summarized below. The latter was chosen based on operation of CNG refuelling at UC Davis.

TIAX used a three-point scale of low (L), medium (M), and high (H) to rank both the frequency of occurrence (F) of the failure mode and the consequence of the failure mode (C) frequency and consequence for determining the relative risk of potential failures. This Frequency and Consequence rating scheme is presented below.

<table>
<thead>
<tr>
<th>Frequency Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (H)</td>
<td>Almost certain to occur repeatedly</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>Likely to occur to rarely likely to occur</td>
</tr>
<tr>
<td>Low (L)</td>
<td>Unlikely that failure would occur</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (H)</td>
<td>Potential for great harm or death if someone is present within the impact area.</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>Harm would require some medical treatment to some pain or discomfort if someone is present within the impact area</td>
</tr>
<tr>
<td>Low (L)</td>
<td>End user, if present, would not notice</td>
</tr>
</tbody>
</table>

The consequence and frequency ratings for each FMEA are combined in the risk-binning matrix to estimate risk. Each hazard is plotted on a frequency vs. consequence matrix that yields an estimate of risk as high, moderate, low, or negligible. High risks are considered combinations of M x H, H x M, and H x H ratings. Moderate risks are combinations of L x H, H x L, and M x M. Finally low risks are combinations of L x M, M x L, L x L, and no safety hazard or negligible risk scenarios.
Using this approach, TIAX developed binning matrices for the three hydrogen options and a CNG option.

This qualitative risk analysis by TIAX highlighted the following important conclusions:

- None of the hydrogen refuelling options considered presented high risk and generally all the hydrogen refuelling options considered were at par with a CNG refuelling option;
- In terms of medium risk, CNG refuelling presents less risk due to the simplicity of the system and generally lower pressure;
- In terms of medium risk, reformer technology is marginally riskier due to higher complexity arising from the need to deal with two fuels, methane and hydrogen, a higher process temperature and a higher internal inventory of gases;
- Electrolyser-based and tube trailer options are approximately at par in terms of medium risk.

Some of the scenarios considered by TIAX in the FMEA analysis were identified as “stand-outs” and were used for this project. They are identified below.

2.1.5.2 Refuelling Station Design Basis
An existing CNG refuelling station was taken as a basis for design comparison of all 4 refuelling options. Table 2 below presents the design basis selected for the QRA.

The refuelling capacity is based on filling ten (10) hydrogen or CNG vehicles per day. Table below shows how the fuel fill rates reflect vehicle fuel economy and driving assumptions.

<table>
<thead>
<tr>
<th>Refueling Station Common Design Bases</th>
<th>Hydrogen</th>
<th>CNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vehicles refueled</td>
<td>10 per day</td>
<td></td>
</tr>
<tr>
<td>Amount of fuel per fill</td>
<td>3 kg (1270 scf)</td>
<td>15.4 kg (743 scf)</td>
</tr>
<tr>
<td>Driving per fill</td>
<td>185 km (115 miles)</td>
<td></td>
</tr>
<tr>
<td>Vehicle refueling time</td>
<td>10 min/fill</td>
<td></td>
</tr>
<tr>
<td>Station average consumption</td>
<td>30 kg/day</td>
<td>7430 scf/day</td>
</tr>
<tr>
<td>Nominal dispensing capacity</td>
<td>5 vehicles in 2 hours</td>
<td></td>
</tr>
<tr>
<td>Typical fuel consumption (gasoline equivalent)</td>
<td>4 L/100 km (60 mpg)</td>
<td>7.9 L/100 km (30 mpg)</td>
</tr>
</tbody>
</table>

The assumed energy consumption (in Btu/mile) of the CNG vehicles is roughly twice that of an identical hydrogen fuel cell vehicle. The relationship between CNG and hydrogen vehicle energy consumption would be different for dissimilar vehicles or power plant configurations.

2.1.5.3 Scenario Definition
The following scenarios were selected after detailed review of available HazOPs and FMEA analysis, including TIAx report:
<table>
<thead>
<tr>
<th>Technology</th>
<th>Scenario Description / Details</th>
</tr>
</thead>
</table>
| Tube Trailers | 1. Small size leak (1 mm) on a ½” pipe line during unloading. Pressure – 2,640 psig, leak direction – horizontal; type of release – sonic jet. Mode of release – steady state, constant flow.  
4. Venting of released hydrogen from scenario 3 through the exhaust fan from the generator to atmosphere. Mode of release – transient.  
5. Hydrogen line leak downstream of compressor towards storage outdoors. Pressure – 6,000 psig; effective leak orifice – 1 mm on a 3/8” tubing. Line flow rate – 1.25 kg/h. Type – sonic; mode – steady state. (This scenario will apply to reformer technology as well). |
| Reformer | 6. Natural gas supply line leak outdoors. Line pressure – 5 psig; leak size ¼” effective diameter on a ¾” pipe. Side leak at the ground level; steady state.  
7. Natural gas line leak downstream of compressor towards reformer. Line pressure 150 psig (10 bars); effective leak orifice – 1 mm on a 3/8” tubing. Full flow in the line – 5.04 kg/h.  
8. Catastrophic failure hydrogen release inside enclosure due to failure of the line between PSA unit and compressor. Line pressure – 10 bars; leak orifice – ½”. Mode – transient to release hydrogen contained in six PSA units and a surge tank. Type of release – sonic. |
| CNG Station | 9. Natural gas supply line leak outdoors. Line pressure – 5 psig; leak size ¼” effective diameter on a ¾” pipe. Side leak at the ground level; steady state.  
10. Natural gas line leak downstream of compressor towards storage. Pressure – 4,000 psig; effective leak orifice – 1 mm on a 3/8” tubing. Line full flow rate – 18 kg/h; leak direction – horizontal, towards storage; Type – sonic; mode – steady state. Leak location: 4 ft from storage and 2 ft above ground level. See diagram Fig. 4-17 of TIAF FMEA report. |
| Gas Storage | 11. Hydrogen and CNG similar catastrophic type leaks through a ½” orifices from a 3-cylinder bank at 4,100 psig. Type – sonic; mode – transient; leak direction – horizontal.  
12. Venting of hydrogen and CNG through the same vent stack at 2,000 CFM flow rate. Type – sonic and subsonic; mode – steady state. |
2.1.5.4 Source Modeling
Due to limited size of the paper only most significant results in terms of sizes of resulting hydrogen clouds are being discussed here, namely tube trailer scenarios (small and large leaks for comparison) and both hydrogen and CNG ground storage.

Tube Trailer Failure Scenarios
Tube trailers are generally used to economically transport large quantities of compressed hydrogen. A typical hydrogen steel tube trailer contains several high-pressure cylinders for hydrogen storage, as shown below.

As per adopted modeling scenarios, the task was to simulate an effect of potential hydrogen releases by evaluating the LFL hydrogen cloud caused by leaks from the high-pressure cylinders. It is assumed that the initial release pressure is 2640 psig (182 bars). The CFD modeling of hydrogen releases and dispersion is used for the failure scenarios that consider the following conditions:

1) Small size leak (1 mm leak orifice) on a ½” pipe line during unloading. The stagnation pressure inside the cylinders is 2640 psi. Leak direction is horizontal and is perpendicular to the central line of the cylinders. Due to the high leak pressure, the leak is choked (sonic jet release).

2) Catastrophic failure hydrogen release from ½” pipe line during unloading. It is estimated that the internal diameter for the leak orifice is 8.48 mm. The pressure inside the cylinders is 2640 psi. The leak direction is horizontal and parallel to the central line of the cylinders. It is a sonic jet release.

Figure below shows the two modeling scenarios for the current task. We assume that the total cylinder water volumes are large enough, and therefore, the mode of release can be simplified as a steady state and a constant flow.
Numerical Results

**Scenario 1:**
Horizontal hydrogen release from the 1 mm orifice was simulated using a domain size of 12.5 m long by 9 m wide by 5 m high with a grid size of 34×23×29. The compressible CFD models exploited the real gas law implemented by the Abel—Noble Equation of State and the LVEL turbulent models for the steady state simulation. Figure below shows the numerical results for the hydrogen concentration distribution along the leak direction. The LFL hydrogen cloud extent is about 4.26 m long from the leak orifice in the horizontal direction.

**Scenario 2:**
Horizontal hydrogen release from 8.48 mm ID orifice was simulated using a domain size of 70 m long by 12 m wide by 15 m high with a grid size of 29×26×27. The real gas law represented by the Abel—Noble Equation of State was implemented into the compressible CFD models. Figure below shows the numerical results for the LFL hydrogen cloud along the leak direction. The maximal horizontal cloud extent is about 40.5 m from the leak orifice.
High Pressure Gas Storage Failure Scenarios
This section focuses on applying validated CFD models to simulate compressed hydrogen and methane release and dispersion from high-pressure gas storage tanks shown below.

Compressed hydrogen (H₂) or methane (CH₄) is released from a set of storage tanks. The release orifice is 8.48 mm (1/2” OD).
3 big tanks (brown): OD 20”, length 23½”, volume 33.1 ft³, pressure 4100 psi. The storage set is composed of three connected tanks, each of which has a diameter of 20” and a volume of 33.1 ft³. The total liquid volume for the storage is 99.3 ft³. The whole storage set has a length of 23½” (7.023 m) and a height of 53¾” (1.365 m). The working pressure is 4100 psi (284.4 bars) in each tank. The centerline of the storage tanks is in the middle of the domain and the wind in the domain is 0.5 m/s. The ambient temperature is 20 °C.

Numerical Results

‘Phoenics’ Simulations:
Table below shows the comparison of LFL clouds caused by the hydrogen and methane releases with time using the real-gas law, (the hydrogen release model was implemented by using the Abel-Noble real gas law and methane release was implemented using NIST real-gas properties. Note that Abel-Noble real gas law does not show consistency with methane under high pressure.) The LFL hydrogen cloud volume is larger than that of methane at each time and that the buoyancy force affects the hydrogen clouds much more than the methane clouds. The convection force prolongs the methane cloud in the leak direction more effectively than it does the hydrogen cloud.

<table>
<thead>
<tr>
<th>Time</th>
<th>Hydrogen</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 s</td>
<td><img src="image1" alt="Hydrogen 5s" /></td>
<td><img src="image2" alt="Methane 5s" /></td>
</tr>
<tr>
<td>15 s</td>
<td><img src="image3" alt="Hydrogen 15s" /></td>
<td><img src="image4" alt="Methane 15s" /></td>
</tr>
<tr>
<td>30 s</td>
<td><img src="image5" alt="Hydrogen 30s" /></td>
<td><img src="image6" alt="Methane 30s" /></td>
</tr>
</tbody>
</table>
Figures below show the transient hydrogen and methane cloud extents from the leak orifice for 60 seconds. The buoyancy forces substantially reduce the LFL cloud extent for hydrogen along the center line in comparison with the maximal cloud extent. This phenomenon was not observed for methane.

Hydrogen maximum and centerline cloud extents with time.

Methane maximum and centerline cloud extents with time.
‘Fluent’ Simulations:
Figures below show the results from ‘Fluent’ simulations conducted for the same scenario for verification purposes. They show good qualitative agreement with ‘Phoenics’ simulation results.

Methane horizontal cloud extent along the wind direction

Hydrogen horizontal cloud extent along the wind direction

2.1.5.5 Probability Analysis
Probabilistic fault tree (FTA) and event tree (ETA) analyses provide a systematic and logical procedure to identify how system failures and sequences of failures can lead to the release scenarios and the likelihood of the end hazard or accident occurring. In this project the FaultTree+ program from Isograph Inc. was adopted for computation and display of the fault and event trees. The fault tree technique provides a method for evaluating the integrity of a system, particularly with regard to the ability of the system to survive the effects of minor failures of components without causing a hazardous condition. The fault tree analysis is a top-down method that has been used in almost all the fields to determine the frequency of the accident scenario. Potential accident outcomes and the general accident progression such as jet fire, flash fire, explosion or fireball for certain scenarios are then determined using the event tree analysis.

For the scenarios outlined in this report, probabilistic analysis first computed the likelihood of the Loss Of the Containment (LOC) scenarios occurring using a fault tree analysis (FTA). Pre-incident event trees then were used to further assess the effect of automatic system response and emergency
operator actions, which are the overall mitigating systems in place, on the probability of post-release duration/or severity effects.

- Failure of the hydrogen detection and automatic shutdown leading to Automation-Limited Release
- Failure of the hydrogen detection and manual shutdown leading to Manual-Limited Release
- Failure of both automated and human intervention systems leading to No Intervention-Unlimited Release

**Ignition Probabilities**

This section is described in greater detail in the Knowledge Gaps White Paper.

Immediate ignition of hydrogen releases leads to different consequences than delayed ignition. Immediate ignition will lead to jet fires for continuous leaks and fireballs for rupture, whereas delayed ignition of a continuous or instantaneous leak leads to a flash fire and / or deflagration. Hence it is essential in the risk study to separately control both the immediate and the delayed ignition probability, which should be in line with historical ignition probability data.

The DNV database provides extensive historical ignition probability data. It also shows the reported ratio of immediate to delayed ignition probability historically is 2 to 1.

The data for hydrocarbons shows that probability of ignition for gas leaks lower than 1 kg/s is 0.01. The hydrogen leak rates in this study are also within this range. Following the DNV guideline would imply that all hydrogen leaks would have to be modeled with an overall ignition probability of 1 percent.

However, for a given mass leak rate, hydrogen would form an 8 x larger flammable cloud than methane, as the cloud size this is determined by the flow in mole per second, rather than flow in kg/s. (8 x, as both hydrogen and methane have a similar lower flammable limit). It is obvious that for delayed ignition the ignition probability increases with increased flammable cloud size. Hence an argument may be made to change the critical release rate for hydrogen by a factor 8; i.e. 1 kg/s for methane is equivalent to 0.125 kg/s for hydrogen, etc.

The flammable range of hydrogen is 4 to 75 volume percent, which is a factor 7.3 higher than for methane (5 to 15 volume percent). One may be inclined to think that this would significantly increase the likelihood of delayed ignition of hydrogen when compared to methane. However, this is contradicted by consequence modeling dispersion results for equal size clouds (i.e. for similar mole/s leak flow rates). For both methane and hydrogen, the size of a cloud above 15 mole percent is approximately 16% of the total size of cloud above LFL. Hence the larger flammable range of hydrogen does not materially affect the delayed ignition probability.

Given the very low minimum ignition energy for hydrogen (0.02 mJ, when close to stoicheometric mixture) as compared to methane (0.29 mJ), a 1 percent overall ignition probability for hydrogen leaks < 0.125 kg/s would seem to be too low, as hydrogen may be easily ignited by very weak ignition sources including static, which may be caused by line friction, build-up static on operator clothing, rotating machinery, or accidental uncoupling of a re-fuelling hose. This would justify increasing the hydrogen release ignition probability to be higher than the 1 percent suggested by DNV data.
An opposing argument is that the hydrogen ignition probability should be regarded as similar to methane, as at concentrations up to 10% vol. hydrogen would require similar ignition energy as methane.

Despite significant research, DNV has not been able to locate definitive data on historical hydrogen release ignition probabilities. Hence, based on the above discussion it was proposed to reasonably conservative approach:

- Reduce the leak flow ranges by a factor 8 for hydrogen, allowing for differential molecular weight as compared to methane, which directly affects the size of flammable cloud.
- Increase the gas ignition probabilities by 16 percent, allowing for the ratio of the flammable range of hydrogen compared to methane, and allowing that the 15 vol. % to 75 vol. % portion of any hydrogen cloud (due to pressurized releases) constitutes only 16 percent of the total cloud size above LFL.
- Treat the ignition probability of hydrogen as similar to methane, allowing that for most of the flammable cloud size is near the lower flammable range, where the minimum ignition energy required is similar to methane.
- Consider overall hydrogen ignition probability as 0.012 and immediate ignition probability as 0.008.

### 2.1.5.6 Consequence Analysis – Thermal Effects

In this study only immediate ignition thermal effects are analyzed.

Potential thermal effects resulting from the horizontal releases of hydrogen and methane (Scenarios 1 to 11) were simulated by using the correlations and model developed by Y. R. Sivathanu [11] and W. Houf [12]. This model assumes that a high-pressure leak of hydrogen or methane is ignited at the source can best be described as a classic turbulent-jet flame. For turbulent-jet flames, the radiative heat flux at an axial position and radial position can be expressed in terms of the non-dimensional radiant power and total emitted radiative power. The approach is validated by the reported experimental measurements of large-scale hydrogen jet flames. The experiments verified that measurements of flame length, flame width, radiative heat flux, and radiant fraction are in agreement with non-dimensional flame correlations reported in the literature. The current work exploits such correlations to predict the radiative heat flux from a wide variety of hydrogen and methane flames (Scenarios 1 to 11).

The thermal fluxes emitted by methane or hydrogen vertical flares (Scenario 12) were calculated based on fixed volumetric flow rate by assuming a 9 m/sec crosswind towards a vertical target surface area. The differences between hydrogen and methane flares mainly stem from their different densities and heat of combustions. The net heat release is proportional to the gravimetric heat of combustion multiplied by the density. At fixed volumetric flow rate, the heat release of methane is 2.8 times larger than hydrogen. The model also predicts somewhat longer and broader flames for methane. The Shell-Research at Thornton model (Chamberlain, 1987) was used to calculate the properties of the flame and the thermal flux from the venting of hydrogen and natural gas at 2,000 SCFM (Scenario 12). The model has been validated for natural gas and is considered reliable for hydrocarbon gases. We should note that this model is usually applied to large scale flares (the TNO [13] example is for a 30 kg/second outflow). It predicts shorter flame lengths for flares in the presence of a crosswind.
Below, as a representative example, is the description of thermal effects that could potentially be produced by modeled failure scenarios for tube trailer and storage. Each scenario is addressed via a table that contains a diagram with distances to selected thermal threshold levels. The diagrams show maximum values for each threshold level in radial direction, i.e. outside the jet flame. Because of different intensity of releases in selected scenarios, the maximum values are achieved at different axial distances from the point of release. In order to compare thermal effects at equal distances from the points of release and resulting jet fires, the tables also contain the numbers for locations 1 m and 5 m away from the point of release in axial direction and 1 m in radial direction. They are marked (x, R) = (1 m, 1 m) and (x, R) = (5 m, 1 m) respectively. The values of thermal effects at these locations are used for risk calculations in Risk Estimation section below. For cases when selected locations are within the flame (and thermal effects thus exceed 37.5 kW/m²), the fatality probability is considered to be equal to 1.

**Tube Trailer – Scenario 1**
Small size leak (1 mm) on a ½” pipe line during unloading. Pressure – 2640 psig. leak direction – horizontal; type of release – sonic jet. Mode of release – steady state, constant flow.

<table>
<thead>
<tr>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiative heat fluxes for hydrogen jet flame</strong></td>
</tr>
<tr>
<td>Inside high-pressure tank:</td>
</tr>
<tr>
<td>Stagnation pressure: 182 bars Stagnation temperature: 293.15 K</td>
</tr>
<tr>
<td>Leak orifice diameter: 1 mm</td>
</tr>
<tr>
<td>Visible flame length: 2.172 m Visible flame width 0.369 m</td>
</tr>
</tbody>
</table>

- **Thermal flux at** (x, R) = (1.0 m, 1.0 m) (kW/m²) **(3.0)**
- **Thermal flux at** (x, R) = (5.0 m, 1.0 m) (kW/m²) **(0.0)**

**Tube Trailer – Scenario 2**
Catastrophic failure hydrogen release from ½” pipe line during unloading. Mode of release – steady state, constant flow.
### Hydrogen and Methane Gas Storage – Scenario 11

Hydrogen and CNG similar type leaks through a 8.48 mm orifices from a 3 cylinder bank at 4,100 psig. Leaks are sonic and horizontal.

#### Thermal effects for methane gas storage

<table>
<thead>
<tr>
<th>Thermal flux at (x, R) = (1.0 m, 1.0 m) (kW/m²)</th>
<th>Location within the flame. Thermal effects are much greater than 37.5 kW/m². Fatality.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal flux at (x, R) = (5.0 m, 1.0 m) (kW/m²)</td>
<td>Location within the flame. Thermal effects are much greater than 37.5 kW/m². Fatality.</td>
</tr>
</tbody>
</table>
Thermal effects for hydrogen gas storage

**Diagram**

<table>
<thead>
<tr>
<th>Thermal flux at (x, R) = (1.0 m, 1.0 m) (kW/m²)</th>
<th>Location within the flame. Thermal effects are much greater than 37.5 kW/m². Fatality.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal flux at (x, R) = (5.0 m, 1.0 m) (kW/m²)</td>
<td>Location within the flame. Thermal effects are much greater than 37.5 kW/m². Fatality.</td>
</tr>
</tbody>
</table>

Hydrogen and Methane Gas Storage Venting – Scenario 12

Venting of hydrogen and CNG through the same vent stack at 2,000 CFM flow rate. Type – sonic and subsonic; mode – steady state.

<table>
<thead>
<tr>
<th>Model</th>
<th>TNO Yellow Book, Shell Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Storage</td>
<td>Scenario 12</td>
</tr>
<tr>
<td>Gas Type</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>Nature of the outflow</td>
<td>Sonic</td>
</tr>
<tr>
<td>Flow rate, m³/sec</td>
<td>0.94</td>
</tr>
<tr>
<td>Mass flow rate kg/s</td>
<td>0.63</td>
</tr>
<tr>
<td>Stack height (m)</td>
<td>3.66</td>
</tr>
<tr>
<td>Stack diameter (cm)</td>
<td>2.5</td>
</tr>
<tr>
<td>Net flame length (m)</td>
<td>4.50</td>
</tr>
<tr>
<td>Min flame diameter (m)</td>
<td>0.35</td>
</tr>
<tr>
<td>Max flame diameter (m)</td>
<td>1.68</td>
</tr>
<tr>
<td>Lift-off height (m)</td>
<td>0.88</td>
</tr>
<tr>
<td>Tilt angle (degrees)</td>
<td>31.43</td>
</tr>
<tr>
<td>Max rad. flux at Human Height (kW/m²)</td>
<td>10.64</td>
</tr>
<tr>
<td>Distance to maximum flux (m)</td>
<td>2.71</td>
</tr>
<tr>
<td>Distance to 1.6 kW/m² (m)</td>
<td>14.92</td>
</tr>
<tr>
<td>Distance to 4.7 kW/m² (m)</td>
<td>8.23</td>
</tr>
<tr>
<td>Distance to 12.5 kW/m² (m)</td>
<td>N/A</td>
</tr>
<tr>
<td>Distance to 37.5 kW/m² (m)</td>
<td>N/A</td>
</tr>
</tbody>
</table>
2.1.5.7 Risk Metrics and Risk Estimation

Metrics were adopted to quantify the individual and societal risks associated with the scenarios analyzed in this project to effect comparisons between selected hydrogen sourcing, storage and hydrogen production components in hydrogen refuelling options. These were computed using HyQuantras™, a computerized toolkit for quantifying the risk associated with the jet-fire scenarios used for these comparisons.

HyQuantras™ computes the risk as individual and societal risk measures

- Location-Specific Individual Risk (LSIR)
- Individual-Specific Individual Risk (ISIR)
- Potential Loss of Life (PLL)
- Expected Number ofFatalities (ENF)

Of these, the LSIR and PLL were used for the project comparisons.

While individual risk is based upon the risk at a specific location, the societal risk (SR) indicates how many people can be involved in an accident simultaneously and is related to defined population that could be affected, usually in terms of injury or fatality. Societal risk gives an indication of the risk of an industrial activity in a specific populated environment; hence societal risk depends upon both the type and magnitude of the release activity and the distribution of the surrounding population. It is often expressed as the likelihood of specified number of fatalities or the expected number of fatalities per unit of time, for example, the potential loss of life (PLL) associated with a facility that is given by:

\[ PLL = LSIR \times n_{\text{present}} \]

where \( n_{\text{present}} \) is the number of persons present and exposed to the event.

Exposure times of 20 seconds and one-minute (60 seconds) were selected for the analysis with exceptions of shorter times for release scenarios in electrolyser and reformer enclosures. The Probit equation used in this analysis is that given for outdoors (or for unprotected people) in the TNO “Purple Book” Guidelines for Quantitative Risk Assessment [14]. The number of people exposed to the hazard was considered as 4.

Examples of Risk Estimation

Below are examples of risk estimation for tube trailer failure scenarios.

Tube trailer data are available from Scenarios 1 and 2 analyses that describe small and large releases, respectively, during unloading. In Table below for Scenario 1, there is no significant risk due to an insufficient dose-response because, being a small leak through a 1 mm\(^2\) effective orifice, the quantity of hydrogen does not produce significant heat radiation and, secondly, because at the selected exposure times of 20 and 60 seconds there is no significant harm to an individual located at the points \((x, R) = 1,1\) and \((x, R) = 5.1\).
Scenario 1: Small leak from a tube trailer

However, the Onset Threshold column shows that, at the heat radiation level of 3 kW/m² for the closest location (x, R)=1.1 an average exposure of 100 seconds would account for 1% lethality among the people exposed to it at the LSIR and PLL values shown in the table.

Scenario 2: Large leak from a tube trailer

In Table above for Scenario 2 representing a large hydrogen leak, due to the large amount of hydrogen released the thermal load received by an individual at the two considered locations, that in this case are inside the flame, is very large and exceeds 37.5 kW/m² producing to 100 % lethality for the selected exposure times of 20 and 60 seconds. At further distances from these reference locations, 12.5 and 4.7 kW/m² heat load impacts yield 92 % lethality at (x,R) = 10.5,6.4 and 2 % lethality (x,R) = 10.5, 10.4 for people exposed to those values. The LSIR values corresponding to 100 % lethality for the first and second locations equal the frequency of the end outcome. The LSIR for 12.5 kW/m² for the third location indicating a value of 92 % lethality is very close to that of the reference distances. At the threshold level of 4.7 kW/m² there is a 2 % lethality for the people happen to be there.

2.1.5.8 Conclusions

Producing hydrogen on-site by electrolysis presents a lower individual and societal risk than producing hydrogen on-site by steam methane reforming (SMR), presumably because the complexity of the installation in the SMR case and also because in the SMR there are the both gases present. Sourcing hydrogen on-site and off-site present almost the same risk. From the individual risk, the electrolysis process presents the lower risk, followed by tube trailer and the third with highest risk for the reformer.

A comparison of the relative risk associated with hydrogen and natural gas storage shows that hydrogen storage facility presents a marginally lower (within 20%) risk compared to an identical CNG storage in regards to accidental horizontal-jet release from storage connecting piping. In terms of storage venting, a CNG storage facility may require either a larger clearance than an identical
hydrogen storage facility or a higher vent stack to achieve the same level of thermal radiation from a vertical flare.

In summary, an electrolysis refuelling option that includes compressed hydrogen storage presents the lowest risk among the refuelling options that were considered including a CNG station of equal refuelling capacity to provide equivalent travel mileage.

2.2 Discussion

2.2.1 Selection of Representative Leak Sizes

Selection of representative leak size is always a challenge while performing a risk assessment. Traditional classification of “large” and “small” leak size developed in the oil and gas industry is hardly applicable to plug-and-play hydrogen systems operating at much higher pressures. It is interesting in this sense to compare the assumptions made in reported case study with the assumptions of the risk-informed approach to safety distances presented by Sandia National Labs (SNL) by Jeff LaChance at the experts’ meeting in Vancouver on September 6, 2006 [15].

For example, HyTrec study used the following assumptions regarding the leak (hole) sizes and their representative dimensions:

**Assumptions and Study Basis**

- **Hole sizes**: All piping valves and fittings are assumed to be of 10 mm size. Experience indicates that a leak from a storage tank itself is unlikely, but is more likely to occur from the connections of piping and equipment into the tank.
  - **Small**: 0-5 mm. Representative hole size: 1 mm
  - **Large**: 5-10 mm. Representative hole size: 10 mm

<table>
<thead>
<tr>
<th>Hole Size Class</th>
<th>Representative Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>-</td>
<td>Rupture of a storage vessel. Stored hydrogen is released instantly and it explodes, if ignited.</td>
</tr>
<tr>
<td>Medium</td>
<td>10mmΦ</td>
<td>Rupture of pipe or filling hose. Massive discharge of hydrogen leads to explosion or jet fire, depending on ignition timing, if ignited.</td>
</tr>
<tr>
<td>Small</td>
<td>1mmΦ</td>
<td>Relatively small opening such as crack and pinhole on piping and filling hose. Leakage is continuous and it leads to explosion or jet fire, depending on ignition timing, if ignited.</td>
</tr>
<tr>
<td>Very Small</td>
<td>-</td>
<td>Very small opening such as leakage from gland packing of valves.</td>
</tr>
</tbody>
</table>
It is interesting here that HyTrec study classifies a pipe rupture as a “large” leak, while Japanese study classifies the same size rupture as a “medium” leak reserving the “large” leak size for a vessel rupture. Italian study did not identify leak hole sizes, however, we may suggest them being similar to the above.

Canadian study also compared leaks of 1 mm with “catastrophic” leaks caused by either valve, pipe or fitting failures of similar diameters as above.

(LPG case study from Netherlands is not discussed here as it deals with a different substance and, thus, uses very different approach.)

To the contrary to the above, SNL assumptions on leak size representative dimensions are quite different:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lower reported frequency range (/m-yr)</th>
<th>Upper reported frequency range (/m-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small leak:</td>
<td>3E-6 – 1E-5 Selected value: 3E-6</td>
<td>1E-5 – 9E-4 Selected value: 5E-5</td>
</tr>
<tr>
<td>Assumed diameter &gt; 0.1 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large leak:</td>
<td>3E-7 Selected value: 3E-7</td>
<td>2E-6 Selected value: 5E-6</td>
</tr>
<tr>
<td>Assumed diameter &gt; 1 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rupture:</td>
<td>3E-8 – 1E-7 Selected value: 3E-8</td>
<td>8E-8 – 1E-5 Selected value: 5E-7</td>
</tr>
<tr>
<td>Assumed diameter &gt; 10 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This comparison speaks loud and clear about uncertainties of the meaning of “small” and “large”, and cautions us to be careful using those adjectives without actually specifying the leak size. Needless to say that operating pressure plays critical role in setting the size of a leak, which is really defined by the mass flow rate rather than its orifice. Which hints that maybe representative leak sizes should be selected based on operating pressure and, thus, based on a certain leak rate rather than a specific orifice size. Obviously, a 700 bar system would be much less tolerant to leaks than a 70 bar system in general and 1 mm hole maybe treated as “large” or “small” depending on expected consequences, i.e. size of flammable cloud.

### 2.2.2 Selection of Representative Leak Frequencies

Selection of representative leak frequencies is another challenge. Needless to say that assumptions on leak frequencies make a critical contribution to estimation of risk. Due to substantial uncertainty in data for plug-and-play hydrogen system the difference in selected leak frequencies may vary by a few orders of magnitude.
Below is an illustration of this, which is demonstrated by comparing assumptions made during HyTrec case study and SNL study of risk-informed safety distances. Here are the leak frequencies used by the HyTrec study:

<table>
<thead>
<tr>
<th>Module</th>
<th>Estimated leak frequency (per year)</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small (&lt;5mm)</td>
<td>Large (5-10mm)</td>
</tr>
<tr>
<td>Marintek line</td>
<td>4 E-4</td>
<td>8 E-5</td>
</tr>
<tr>
<td>Reformer H₂</td>
<td>1 E-2</td>
<td>2 E-3</td>
</tr>
<tr>
<td>Reformer NG</td>
<td>7 E-3</td>
<td>1 E-3</td>
</tr>
<tr>
<td>SOFC</td>
<td>1 E-2</td>
<td>2 E-3</td>
</tr>
<tr>
<td>H₂ storage</td>
<td>3 E-2</td>
<td>5 E-3</td>
</tr>
<tr>
<td>Fuel station</td>
<td>2 E-4</td>
<td>4 E-5</td>
</tr>
<tr>
<td>Electrolyser</td>
<td>4 E-3</td>
<td>7 E-4</td>
</tr>
<tr>
<td>LNG storage</td>
<td>3 E-2</td>
<td>5 E-3</td>
</tr>
<tr>
<td>TOTAL</td>
<td><strong>0.092</strong></td>
<td><strong>0.017</strong></td>
</tr>
</tbody>
</table>

One can see that the above frequencies are quite high. Taking the assumptions of the study into account, in particular that the pipe size is 10 mm and the representative orifice of a large leak is also, 10 mm, the above data communicates that a large leak at hydrogen storage, which has to be the pipe rupture considering the representative diameter, may happen 5E-3/year.

Let’s compare these numbers with SNL selected leak frequencies:
As it can be seen, SNL leak frequencies are substantially lower. Third line from the bottom represents the frequency of a (appr.) 10 mm leak. The numbers are in m-yr, meaning that this frequency needs to be multiplied by actual pipe length to obtain a cumulative frequency. Let’s take the upper bound number, 5.3 E-7 and compare it with the number used in the HyTrec study - 5 E-3. The HyTrec number is likely a cumulative number of all piping at the hydrogen storage. As it is seen, SNL number is 4 orders of magnitude smaller than HyTrec number, meaning that 10,000 m of pipe need to be used at the hydrogen storage system for the numbers to be comparable. Normally the piping system would be using up to a 100 m of piping, which suggests that HyTrec numbers are approximately 2 orders of magnitude larger than the ones used by SNL.

### 2.2.3 Estimation of Consequences

Selection of appropriate tools for consequence analysis is a very important step. Both Norwegian and Italian studies used PHAST (quasi-CFD) software to determine thermal effects consequences. Canadian study used CFD modeling for dispersion and experimentally-confirmed engineering correlations to determine thermal effects. The latter was also applied by SNL in the study of risk-informed safety distances.

Below the difference in findings will be illustrated by comparing PHAST and engineering correlations for similar cases.

The HyTrec study estimated the following concentration envelopes and thermal effects from both “small” and “large” leaks using PHAST:

<table>
<thead>
<tr>
<th>Diameter of Leak (D) (mm)</th>
<th>F(D) Lower Bound Cumulative Pipe Leak Frequencies (/m-yr)</th>
<th>F(D) Upper Bound Cumulative Pipe Leak Frequencies (/m-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>3.0E-06</td>
<td>5.0E-05</td>
</tr>
<tr>
<td>0.18</td>
<td>1.7E-06</td>
<td>2.8E-05</td>
</tr>
<tr>
<td>0.40</td>
<td>7.5E-07</td>
<td>1.3E-05</td>
</tr>
<tr>
<td>1.00</td>
<td>3.0E-07</td>
<td>5.0E-06</td>
</tr>
<tr>
<td>2.38</td>
<td>1.3E-07</td>
<td>5.0E-06</td>
</tr>
<tr>
<td>4.23</td>
<td>7.1E-08</td>
<td>1.2E-06</td>
</tr>
<tr>
<td>6.35</td>
<td>4.7E-08</td>
<td>7.9E-07</td>
</tr>
<tr>
<td>9.52</td>
<td>3.2E-08</td>
<td>5.3E-07</td>
</tr>
<tr>
<td>11.50</td>
<td>2.6E-08</td>
<td>4.4E-07</td>
</tr>
<tr>
<td>13.50</td>
<td>2.2E-08</td>
<td>3.7E-07</td>
</tr>
</tbody>
</table>
Let’s just concentrate on hydrogen storage for simplicity. So, the table above communicates that a 1 mm (“small”) leak will generate 4.2 m 2% vol. hydrogen cloud extent and (in case of ignition) a 3.5 m extent to 12.5 kW/m² thermal radiation. The similar numbers for a 10 mm (“large”) leak will be 34.1 m and 25 m respectively. Though there is no clear indication of storage pressure, we presume that it is 400 bar, a reasonable assumption.

Let’s compare these numbers first with SNL results and then with the Canadian case study.

For a 1 mm orifice leak SNL has developed the following graph:
For simplicity let’s round numbers and have 6,000 psig equal to 400 bars. It can be seen from the above graph that 2% vol. extent then will be at around 11.6 m, while 12.5 kW/m$^2$ – around 2.2 m (in between 4.7 and 25 kW/m$^2$).

Unfortunately, SNL did not present numbers for a 10 mm leak, however, there are results for a 6.35 mm orifice:

![Pipe Leak Frequency Criteria = 8E-6/yr
(Limiting leak diameter = 6.35mm)](image)

As we can see from the above graph, 2% vol. extent is around 75 m, while 12.5 kW/m$^2$ extent is about 16 m. By analyzing the last two graphs we may conclude that a ratio between 2% vol. extent and 12.5 kW/m$^2$ extent is about 5:1 approximately. Other SNL results (not shown here) for other release orifices show similar ratio (+/- 0.5). Though an exact number for the ration may not necessarily be 5:1, the existence of a consistent number certainly makes sense because there is a non-random connection between concentration envelope and thermal radiation – they follow the same distribution pattern.

By looking at HyTrec data we can see a different pattern: for 1 mm leak the ratio is $(4.2 / 3.5) 1.2$ and for 10 mm it is $(34.1 / 25) 1.4$, which is much smaller than predicted by SNL engineering model

Canadian case study produced results similar to SNL for dispersion (based on tube trailer example discussed above in section 2.1.5):
Assuming that in this case we are considering a free jet that follows classic 1/x correlation in regards to concentrations decay, 2% vol. extent is twice as long as 4% vol. extent. This means that 2% vol. extent is about 8.5 m. In this case, however, the results are a bit skewed by a 0.5 m/s wind, otherwise the extent would be shorter. This correlates very well with SNL results for 1 mm leak orifice: numbers around 2,800 psig show about 4 m extent for 4% vol. and 8 m extent for 2% vol. envelopes.

For ½” OD (8.48 mm ID) the results are as follows:

Using the above logic, 2% vol. extent will be around 81 m. These numbers, though at a different size orifice, are in line with SNL predictions.

Italian case study also used PHAST for dispersion calculations for a line rupture scenario (see section 2.1.3 above). The results showed that maximum cloud extent was around 20 m:
Canadian findings for similar conditions of release and identical orifice (8.5 mm) for a free hydrogen horizontal jet using CFD resulted in maximum extent of 35 m with centerline extent of 22.5 m [16].
Similar vertical jet resulted in the flammable cloud extent of about 42.5 m (as shown in the picture below), which is well within predictions by proven engineering model by Birch, supported by numerous experiments.

![Cloud Extent Diagram](image)

Considering that Italian scenario analyzed the release upwards at 20 degree angle, centerline extent of the cloud should be longer than the one for a horizontal jet and can be predicted to be around 25-30 m.

Both considered examples raise a question of applicability and validity of PHAST hydrocarbon-based algorithms for hydrogen dispersion calculations.

### 3 NEXT STEPS

IEA Task 19 partners in the next 3-year term will strive to expand the number of studies for review and comparative analysis.

Partners will continue sharing information on their risk assessment activities, particularly on the topics identified herein within the discussion, namely approaches to leak sizes, leak frequencies and assessment of consequences.
4 REFERENCES


