CANADIAN HYDROGEN SAFETY PROGRAM

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ABSTRACT

This paper discusses the rationale, structure and contents of the Canadian Hydrogen Safety Program developed by the Codes & Standards Working Group of the Canadian Transportation Fuel Cell Alliance consisting of representatives from industry, academia, government, and regulators. The overall program objective is to facilitate acceptance of the products, services and systems of the Canadian Hydrogen Industry by the Canadian Hydrogen Stakeholder Community to facilitate trade, ensure fair insurance policies and rates, ensure effective and efficient regulatory approval procedures and to ensure that the interests of the general public are accommodated. The Program consists of four projects including Comparative Quantitative Risk Assessment of Hydrogen and Compressed Natural Gas (CNG) Refuelling Stations; Computational Fluid Dynamics (CFD) Modeling Validation, Calibration and Enhancement; Enhancement of Frequency and Probability Analysis, and Consequence Analysis of Key Component Failures of Hydrogen Systems; and Fuel Cell Oxidant Outlet Hydrogen Sensor Project. The Program projects are tightly linked with the content of the IEA Task 19 Hydrogen Safety. The Program also includes extensive (destructive and non-destructive) testing of hydrogen components.

1.0 RATIONALE

For the past 30 plus years Canada has played a leading role in bringing hydrogen technologies to their current viable role in changing the energy infrastructure. From an industrial innovation initiative in essential technologies such as production by electrolysis and end-use in fuel cells to government leadership initiatives in supporting codes and standards writing, Canada maintains a strong position in the hydrogen and new energies communities. Canada is a signatory to the Kyoto Protocol. In June of 2001 the Canadian Transportation Fuel Cell Alliance (CTFCA) one of the initiatives under Action Plan 2000 for Greenhouse Gas emission reductions was created by the Government of Canada. Its prime focus is to demonstrate and evaluate different processes for the production and delivery of hydrogen to fuel cell vehicles at fuelling stations. It also conducts studies and assessments of various fuelling routes, provides related communications activities and facilitates the development of appropriate codes and standards. ***Regardless of the merits of hydrogen technologies in meeting environmental goals, safety issues require quantitative assessment to facilitate acceptance of hydrogen by the stakeholder community.***

To address this need, Codes & Standards Working Group (C&S WG) of the CTFCA has developed the Canadian Hydrogen Safety Program. The C&S WG consists of representatives from industry, academia, government, and regulators, thus ensuring that the Program is vetted by a wide spectrum of Canadian stakeholders and gets their support.

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Although the C&S WG was originally created to offer codes and standards support to the fuelling station and vehicle demonstrations of the other CTFCA working groups it has become the lead federal forum to address Canadian codes and standards issues with regard to hydrogen. This group spearheads Canada's input into safety issues internationally, including the IEA and the IPHE.

2.0 OVERALL PROGRAM OBJECTIVE

The overall program objective is to facilitate acceptance of the products, services and systems of the Canadian Hydrogen Industry by the Canadian Hydrogen Stakeholder Community while ensuring the high level of safety expected by the public:

- Industrial – to facilitate trade;
- Insurers – to ensure fair insurance rates;
- Regulators – to ensure effective and efficient approval procedures
- General Public – to ensure diverse interests are accommodated

3.0 SAFETY CONTEXT

In addition to the technologies of production, storage and handling and end use, safety has long been recognized as an essential consideration for the deployment of hydrogen technologies in consumer-centered applications such as personal and public transportation systems and appliance fuelling. Until now, this safety concern has been accommodated in the development of codes and standards that establish minimum safety levels. Such standards have evolved from an accumulated operating experience in professionally managed systems such as industrial plants and aerospace systems. The lack of operating experience with hydrogen energy systems in consumer environments, and dependence on professionally managed system guidelines may lead to a tendency for such codes and standards to be unnecessarily restrictive to ensure that an acceptable level of safety is maintained and may be a barrier to widespread adoption of these systems and the development of the required infrastructure.

It is therefore more appropriate that the reference for new hydrogen systems, like refuelling stations or power generation systems, be similar to facilities for related fuels like natural gas, which have an established safety record. This is a familiar reference point for the public, regulators and insurers who have a vested interest in safety. Acceptance of hydrogen systems will be more likely if the safety of hydrogen installations can be compared favorably or at par with an already familiar fuel technology. ***Thus, there is a requirement to establish a quantitative reference for hydrogen systems with respect to directly analogous fuel systems.***

One of the known methods of reducing potential consequence, and thus risk of a hazard, is early detection. Anticipated commercialization of hydrogen fuel cell vehicles requires that issues related to potential faulty conditions of fuel cells on-board vehicles resulting in the exhaust of hydrogen fuel be addressed from the point of early detection of potential hydrogen emissions.

4.0 SOCIAL CONTEXT

Acceptability of new systems is traditionally measured against regulations, industry and company practices and the judgment of design and maintenance engineers. Contemporary practice also includes risk-based decision-making based on systematic methods of risk measurement and risk criteria balanced with costs. Risk assessment (RA), particularly quantitative risk assessment, is the foundation of these management decisions. It goes beyond the baseline safety levels imposed by compliance with mandatory regulatory requirements to provide a rational basis for making the decisions required to meet safety, reliability and environmental protection goals at the lowest possible cost.

RA assists operators in making system integrity and safety design decisions that ensure regulatory compliance, reduce failure frequency, minimize risk exposure, and extend service life. Firstly, it provides a more complete awareness of all hazards. It can be used to develop risk profiles, evaluate and rank parts of a system with respect to risk, identify high-consequence areas, compare integrity management options and develop optimal maintenance plans. In these areas where risks are either not known or not well understood, it provides an assessment of acceptability and alternatives. Its quantitative approach consistently estimates financial, environmental and safety risks using state-of-the-art, verified engineering models to calculate failure probabilities, failure consequences and risk levels for all major threats to system reliability and safety. The approach provides accurate and objective risk estimates for each system component taking into account on-going and future integrity maintenance activities.

As a result, RA assists designers, management, and the general public and their regulators in risk decisions by providing a basis to assess if risks are acceptable and defines the most effective strategy to reduce or eliminate the risks. It provides a means to compare risks of different designs or operations and to identify problems, which require further safety measures. The ultimate outcome includes assisting in regulatory compliance, minimizing business interruption, improved safety performance resulting in less risk to the public, employees, property and the environment and improved relations with the public and employees.

5.0 PROGRAM PROJECTS

The Canadian Hydrogen Safety Program was initiated in mid 2004. It is a living program whose individual projects contribute to the overall Program objectives. The Program addresses various aspects of hydrogen safety ranging from quantitative risk assessment to development of sensor-based detection systems to extensive testing for database development and model validation. The program has a very strong scientific foundation that allows applying a scientifically-based approach to definition of tasks and scenarios, phenomena classification, selection of models and modeling tools, measuring instruments and experiment set ups, interpretation of results and drafting of recommendations.

The Program currently consists of four projects:

1. Comparative quantitative risk assessment of hydrogen and natural gas fuelling stations

2. Validation, calibration and enhancement of CFD modeling capabilities for simulation of hydrogen releases and dispersion using available experimental databases

3. Enhancement of frequency and probability analysis, and consequence analysis of key component failures of hydrogen systems

4. Fuel Cell Oxidant Outlet Hydrogen Sensor Project

The Program and each project follow the methodology of risk analysis of technological systems based on IEC 300-3-9: 1995 standard. This standard has been adopted as a National Standard of Canada as CAN/ISO-CEI/IEC 300-3-9-97 thus providing a legitimate and credible foundation for this analysis. To complement the scope of the standard in the area of risk evaluation (risk criteria and risk measurement) the project uses recent recommendations and practices developed by world-leading organizations in this area like DNV, TNO, UK Health and Safety Executive and others. Also, ISO/IEC Guide 73: 2002 Risk Management – Vocabulary – Guidelines for Use in Standards has been used to stay consistent with international terminology on risk management. Figure 1 shows the linear QRA process outlined in the standard referenced above to which this project adds a feedback loop to clearly show the role of QRA analysis in a dynamic communications exercise in meeting the project objectives for the industrial, insurance, regulatory and public stakeholders. This approach provides a unifying framework for each project and facilitates their incorporation into the project objectives and into the IEA Task 19 work.

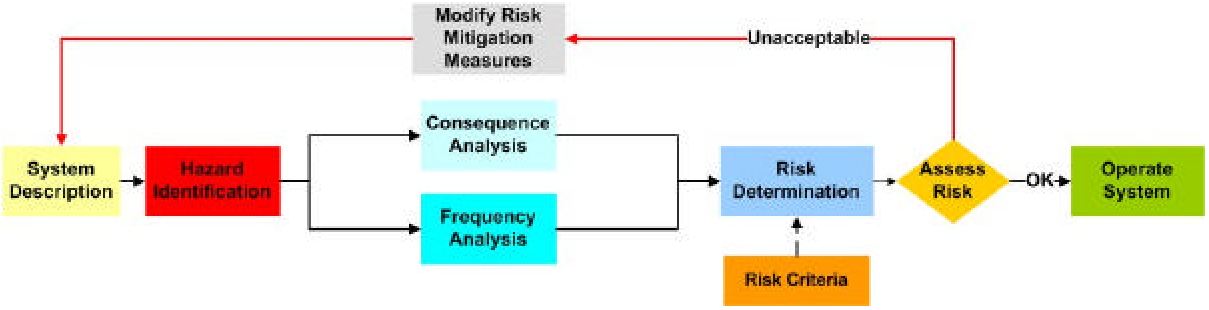


Figure 1. The QRA Process

The projects, particularly the first three, have direct relevance to IEA Task 19 Hydrogen Safety. A brief description of each project follows.

In addition, with strong industry support from CTFCA members, 5 university teams from across the country (Université du Québec à Trois-Rivières, Concordia University, the University of Victoria, the University of Calgary and the University of Toronto) joined forces through the Auto 21 Network of Centres of Excellence to investigate certain fundamental properties of hydrogen pertaining to safety issues, such as the use of real gas law in CFD leak simulations, deflagration-to-detonation transition, combustion, etc. This academia led project (Auto 21 project D201-DHS *Safety and Infrastructure Study of Hydrogen Fuelled Vehicles*) is in line and driven by the industry needs to support codes and standards development and improve understanding of hydrogen properties from risk management prospective.

5.1. Comparative quantitative risk assessment of hydrogen and natural gas fuelling stations

The project follows the methodology of risk analysis of technological systems based on IEC 300-3-9: 1995 standard. It is important that this standard has been adopted as a National Standard of Canada thus providing a legitimate and credible foundation for this analysis. To complement the scope of the standard in the area of risk evaluation (risk criteria and risk measurement) the project uses recent recommendations and practices developed by world leading organizations in this area like DNV, TNO, UK Health and Safety Executive and others.

The project addresses the refuelling station scenarios outlined in Figure 2 for hydrogen and natural gas. It considers both delivery and on-site generation. Delivery includes compressed gas for hydrogen and pipeline delivery for natural gas. The on-site generation applies to hydrogen and includes both reformer and electrolysis options. The pipeline delivery of natural gas and the on-site reforming option for hydrogen provide the basis for the closest comparison of two gaseous fuels and the other hydrogen scenarios provide a comparison of the hydrogen sourcing options.

Only risks associated with differences in technologies or refuelling options are being addressed by this project. All other possible risks associated with a refuelling station in general are presumed to be equal.

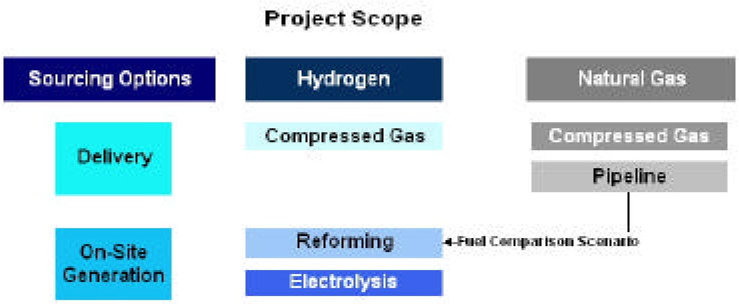


Figure 2. Scope of the fueling station comparison project

To summarize, the following four fuelling station configurations based on selected technologies have been identified for comparison:

- CNG – base line for comparison,
- CH2: tube trailer delivery, on-site electrolysis and reforming.

To ensure consistency of Hazard Identification (HazID) process for all four considered technologies, the HazID will be performed on a generic station that consists (regardless of technology) of the following major components: Fuel delivery / on-site production (will also include purification for reformer technology); Compression; Storage; Dispensing / vehicle interface (vehicles themselves are excluded).

Each component may represent hazards and there are hazards associated with connections between the components. This approach is visually illustrated by the diagram below:

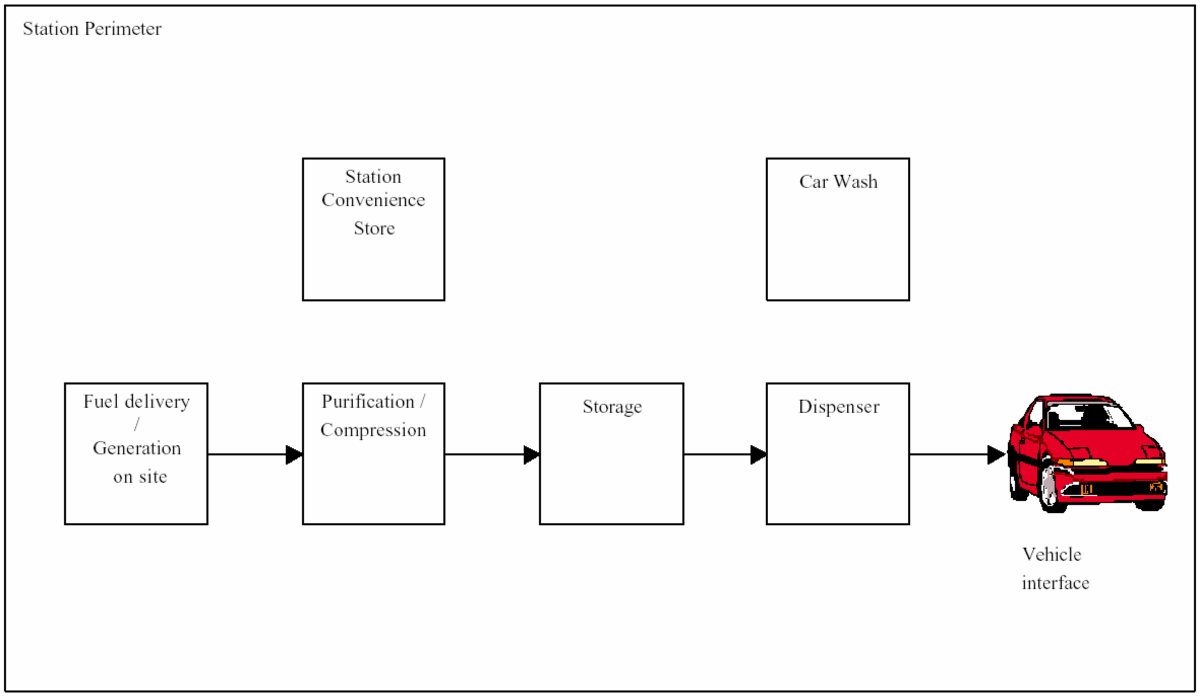


Figure 3. Generic station configuration for QRA

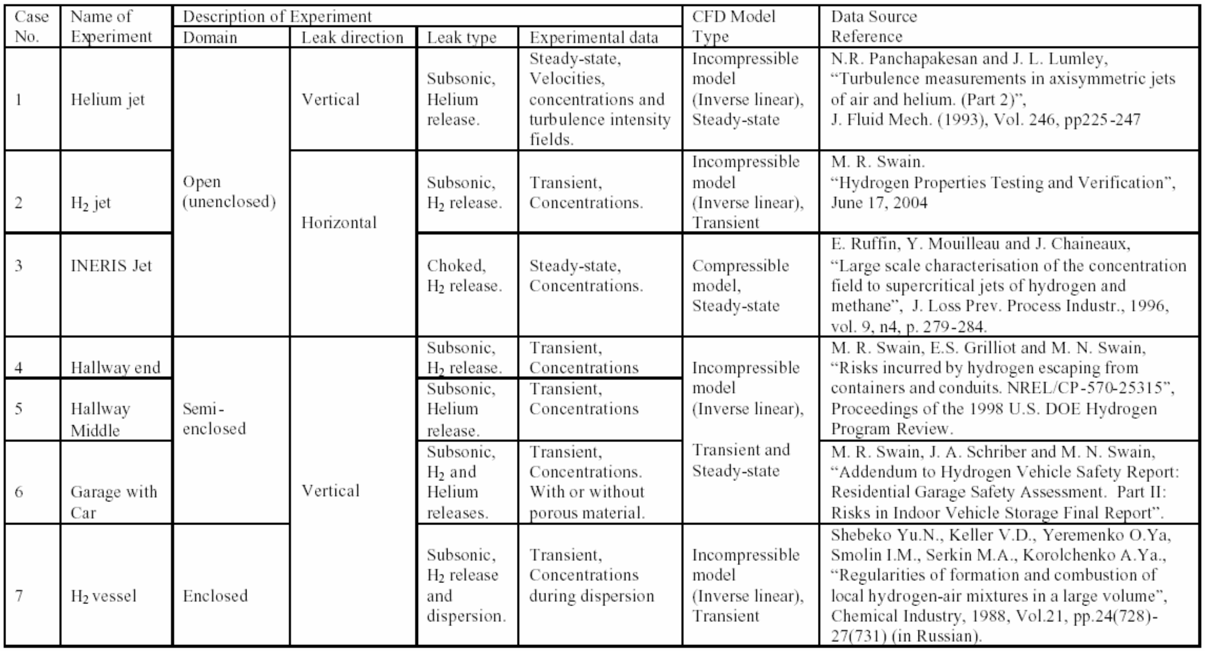
5.2. Validation, calibration and enhancement of CFD modeling capabilities for simulation of hydrogen releases and dispersion using available experimental databases

An ability to accurately model potential releases of hydrogen under a large range of geometrical and environmental conditions is critical in accurate consequence and, hence, risk analysis. It is also important for deriving recommendations for codes and standard development as well as for engineering designs of hydrogen systems.

A total of seven scenarios were selected for the validation and calibration project. They are

- Vertical turbulent buoyant helium jet;
- Horizontal helium and hydrogen jet release;
- INERIS hydrogen jet;
- Hydrogen release at the end of a hallway;
- Helium release in a hallway;
- Hydrogen/helium release in a garage with a vehicle;
- Hydrogen release in an enclosed vessel.

The experimental validation matrix for the project and its data sources are shown below. The modeling scenarios were selected to cover a variety of release phenomena ranging from open to enclosed environment and from relatively slow to sonic releases.



Case No.	Name of Experiment	Description of Experiment				CFD Model Type	Data Source Reference
		Domain	Leak direction	Leak type	Experimental data		
1	Helium jet	Open (unenclosed)	Vertical	Subsonic, Helium release.	Steady-state, Velocities, concentrations and turbulence intensity fields.	Incompressible model (Inverse linear), Steady-state	N.R. Panchapakesan and J. L. Lumley, "Turbulence measurements in axisymmetric jets of air and helium. (Part 2)", J. Fluid Mech. (1993), Vol. 246, pp225-247
2	H_2 jet		Horizontal	Subsonic, H_2 release.	Transient, Concentrations.	Incompressible model (Inverse linear), Transient	M. R. Swain. "Hydrogen Properties Testing and Verification", June 17, 2004
3	INERIS Jet			Choked, H_2 release.	Steady-state, Concentrations.	Compressible model, Steady-state	E. Ruffin, Y. Mouilleau and J. Chaineaux, "Large scale characterisation of the concentration field to supercritical jets of hydrogen and methane", J. Loss Prev. Process Industr., 1996, vol. 9, n4, p. 279-284.
4	Hallway end	Semi-enclosed	Vertical	Subsonic, H_2 release.	Transient, Concentrations	Incompressible model (Inverse linear), Transient and Steady-state	M. R. Swain, E.S. Grilliot and M. N. Swain, "Risks incurred by hydrogen escaping from containers and conduits. NREL/CP-570-25315", Proceedings of the 1998 U.S. DOE Hydrogen Program Review.
5	Hallway Middle			Subsonic, Helium release.	Transient, Concentrations		
6	Garage with Car			Subsonic, H_2 and Helium releases.	Transient, Concentrations. With or without porous material.		M. R. Swain, J. A. Schriber and M. N. Swain, "Addendum to Hydrogen Vehicle Safety Report: Residential Garage Safety Assessment. Part II: Risks in Indoor Vehicle Storage Final Report".
7	H_2 vessel	Enclosed		Subsonic, H_2 release and dispersion.	Transient, Concentrations during dispersion	Incompressible model (Inverse linear), Transient	Shebeko Yu.N., Keller V.D., Yeremenko O.Ya, Smolin I.M., Serkin M.A., Korolchenko A.Ya., "Regularities of formation and combustion of local hydrogen-air mixtures in a large volume", Chemical Industry, 1988, Vol.21, pp.24(728)-27(731) (in Russian).

Examples of modeling cases are shown in Figure 4:

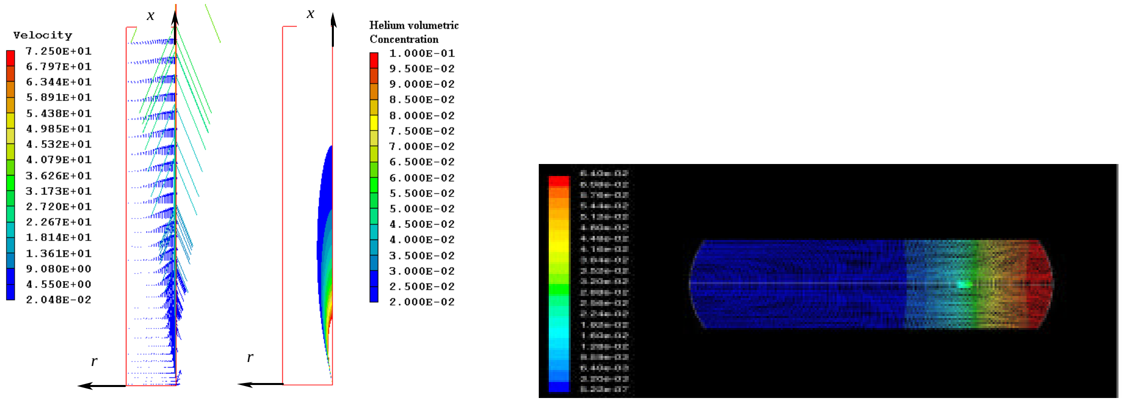


Figure 4. Examples of modelling cases

5.3. Enhancement of frequency and probability analysis, and consequence analysis of key component failures of hydrogen systems

5.3.1. The Need for Hydrogen-Specific Release and Consequence Analysis Enhancement

Risk associated with unwanted hazardous events is a combination of two factors, the likelihood of the event and the seriousness of the event. There is a large accumulated body of knowledge on both the likelihood and severity of unwanted (accidental) events in conventional fuels such as gasoline, propane and natural gas (methane). The corresponding analyses for hydrogen have been highly dependent on the information and procedures for the latter conventional fuels. However, it is becoming increasingly apparent that dependency on data and models and modeling techniques derived from the conventional fuels can generate highly divergent evaluations of the behavior of hydrogen upon release and the consequences.

5.3.2. The Need for Hydrogen Applications Failure Rate Data

In addition to modeling of failure modes and their effects, component and system failure rate data are key data for assessing the likelihood of component and system failure. In view of lack of experience with hydrogen systems in consumer environments, there is a corresponding lack of credible failure rate data for quantitative risk assessment. Both likelihood and consequence analyses as well as failure rate data for these systems are currently conducted using a “big refinery” approach, which often leads to very conservative risk estimates. They also show a very strong sensitivity to modeling parameters and boundary conditions when based on well-established conventional approaches. To date a substantial failure rate database has been developed for hydrogen applications.

5.3.3. Overall Project Requirement

There is therefore a requirement that quantitative risk analysis for plug-and-play hydrogen systems and retail facilities that operate in a consumer environment be based on hydrogen-specific data and modeling approaches. This includes the real failure rate of key components installed in such systems with respect to their size and operating conditions and, on the other hand, on scientifically and experimentally based data and methodologies for predicting consequences of failures of such key components. This requirement extends to a broad cross section of the Canadian hydrogen community that manufactures and uses hydrogen systems. The project also meets the requirements of International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety. One of its requirements is to cooperatively conduct a testing program to validate the results of numerous models that have been developed and to use the data for further refinement of those tools for use in real-life scenarios. A second requirement is to undertake a program of destructive testing to assess the impacts of various hydrogen systems under real-life accident scenarios. A third requirement is to develop targeted information packages to communicate the project results to key hydrogen community stakeholders. In addition to meeting Canadian requirements, this project provides a major Canadian contribution to the IEA Annex.

5.3.4. Experimental Studies

This subtask will generate information on the effects of component or system failures of hydrogen systems. The results of these tests will be compared with those predicted by various models and differences of actual versus predicted will be evaluated and refinements will be made.

Experimental studies to be carried out in this subtask have the two objectives to provide:

- Validation data for the CFD models for selected project applications
- Validation of accident progression analysis as obtained via fault and event trees
- Quantitative consequence data for risk analysis

Some issues identified by industry as recorded in the report on the IEA proposed Annex 19 on Hydrogen Safety include such factors as turbulence in hydrogen releases into air and its effect on the size of the flammable cloud compared to simple dispersion models and ventilation. As an example, industrial interests include a need to test the capabilities and adequacy of a coaxial piping design to protect personnel and property from all hazards associated with leakage from high pressure hydrogen compression and storage systems near occupied structures with respect to required clearance distances is requirements.

Examples of potential experiments are shown in Figures 5, 6 and 7.

Figure 5. Examples of destructive and non-destructive experiments at Powertech Labs

In destructive valve tests (Fig. 5, picture on the left) forces were applied to the valves to simulate impact during vehicle collisions.

In hydrogen release simulation tests (Fig. 5, picture on the right) hydrogen flow rates were measured from a cylinder filled to 400 bar and released through various orifice sizes. These tests were used to validate the CFD modeling.

In order to assess the failure rates of components, experimental studies will be performed simulating the in-service operating conditions. For example, a fuelling nozzle used in a hydrogen filling station is expected to supply at least 100,000 fills before it is replaced with a new one. Figure 6 shows an experimental apparatus to test the nozzle by automatically connecting the nozzle to the receptacle from the vehicle. The nozzle is then pressurized to service pressure and then de-pressurized to simulate a filling of the vehicle. The nozzle is then disconnected and reconnected to complete one cycle. The apparatus automatically completes 100,000 pressure cycles. The nozzle is then checked to ensure there is no leakage and is still functional. Results from these types of tests will provide reliability data for performing quantitative risk assessments.

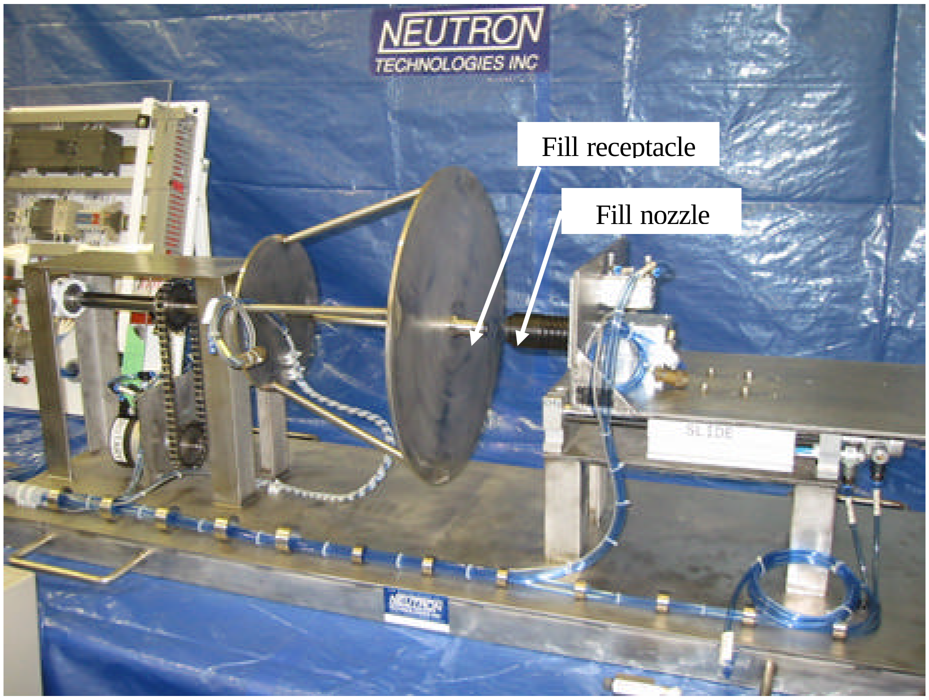


Figure 6. Testing apparatus for hydrogen filling nozzle and receptacle at Powertech Labs

A project on detonation of hydrogen releases has also been initiated at Valcartier Military Establishment. The objective of the project is to perform experimental detonations and deflagrations of open air hydrogen releases under various release and confinement conditions in order to determine their likelihood, their effect and the degree of relevance of such events under various release conditions. The test site for detonation trials is shown on Figure 7.

Figure 7. 16 Hydrogen Detonation Trials: Plateau test site (open space). Photo: courtesy of Defence R&D Canada - Valcartier

5.3.5. Project Approach

The project is initially addressing two types of applications:

- Transportation with an emphasis on hydrogen fuelling stations, and
- Stationary installations with an emphasis on auxiliary power supplies.

While the approach will be developed for configurations with generic application, the details of the sites are being obtained from representative commercial or demonstration facilities and components to provide realistic representations for modeling and experimental studies.

5.4. Fuel Cell Oxidant Outlet Hydrogen Sensor Project

Objective: Evaluate and Improve the State of Technology for Hydrogen Sensors used in the Oxidant Outlet of an Automotive Fuel Cell System.

This project has been initiated as a result of an industry-recognized need to improve the state of the technology for hydrogen sensors used in automotive applications. The primary focus of this project is the hydrogen sensor used within the oxidant outlet for safety, emissions, and diagnostic functions. In support of the CTFCA mandate, this has been identified as an enabling technology that is directly linked to the safe demonstration of fuel cell vehicles.

The main project target is presented in the diagram below. The project addresses the area shown in red and marked 5A.

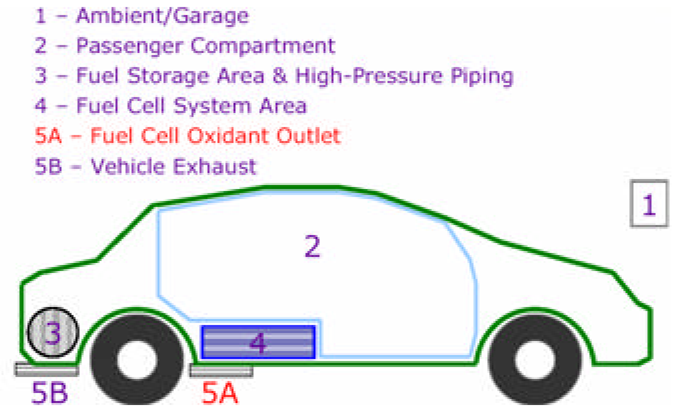


Figure 8. Areas of potential hydrogen detection

Deliverables:

The output from this activity is fourfold:

1. The requirements document itself will be submitted to the CTFCA Codes & Standards Committee for review and discussion. Later, it is anticipated that the requirements document be forwarded to the relevant standards developing organizations such as ISO or SAE for consideration. It should be noted that the requirements document is a living document and will change with new or modified requirements.

2. A specific testing capability (test plan, test station specification, test station, and testing capability) will be provided as a standard against which to evaluate hydrogen sensor technologies for this, and possibly other, fuel-cell-related applications. It is anticipated that, at the conclusion of this effort, testing capabilities will reside with the NRC Institute for Fuel Cell Innovation and will be made available for sensor suppliers, OEM's, and other related companies and organizations.

3. Confidential reports will be provided to each sensor supplier. These reports are intended to provide the supplier with a gauge for which to measure their sensor performance against the requirements of the Canadian manufacturers of fuel cell systems for automotive applications (e.g. Ballard and Hydrogenics). In essence, this will provide the sensor suppliers with feedback regarding the degree of suitability of their sensor technology, and will serve as a gap analysis (to identify areas for potential improvement).

4. Finally, a more generic report will be published by the project participants and made available first to the CTFCA membership and later to the public, outlining the state of the technology in terms of meeting the needs of industry. This report would describe, for example, the strengths and weaknesses of general hydrogen sensor technologies against a particular attribute requirement such as response time, or operation in a low temperature environment, etc. It is anticipated that supplier identifications and specific test results will not be provided in this report. However, some amount of classification, such as by sensor technology groupings, will be considered.

6.0 COOPERATION WITH US DOE SAFETY AND CODES & STANDARDS PROGRAM

In addition to collaboration on the IEA H2 safety annex representatives of CTFCA and US DOE programs met at Sandia National Laboratory and decided to closely cooperate in the development of recommendations for hydrogen clearance distances and hazardous locations. Since then both teams have shared project information and conducted project meetings. This close cooperation has now been extended to hydrogen safety initiatives. Recent examples of this cooperation are a joint paper on application of ideal and real gas law for high pressure releases of hydrogen, and CTFCA involvement in the US DOE initiative related to the introduction of risk analysis tools in the development of codes and standards (so-called risk-informed codes and standards).

7.0 CONCLUSIONS

The Canadian Hydrogen Safety Program has been developed by the C&S WG of the CTFCA to facilitate acceptance of hydrogen technologies and hydrogen as a fuel by Canadian stakeholders. Stakeholder input comes from the industrial, academic, government, and regulatory representation on the C&S WG as well as direct input into each project by these stakeholders.

REFERENCES

1. International Standard IEC 300-3-9 Dependability management, Part 3: Application guide, Section 9: Risk analysis of technological systems, First edition 1995-12.
2. Canadian Standard CAN/CSA-CEI/IEC 300-3-9-97, fully adopted IEC standard as shown above.
3. ISO/IEC Guide 73: 2002 Risk Management – Vocabulary – Guidelines for Use in Standards.