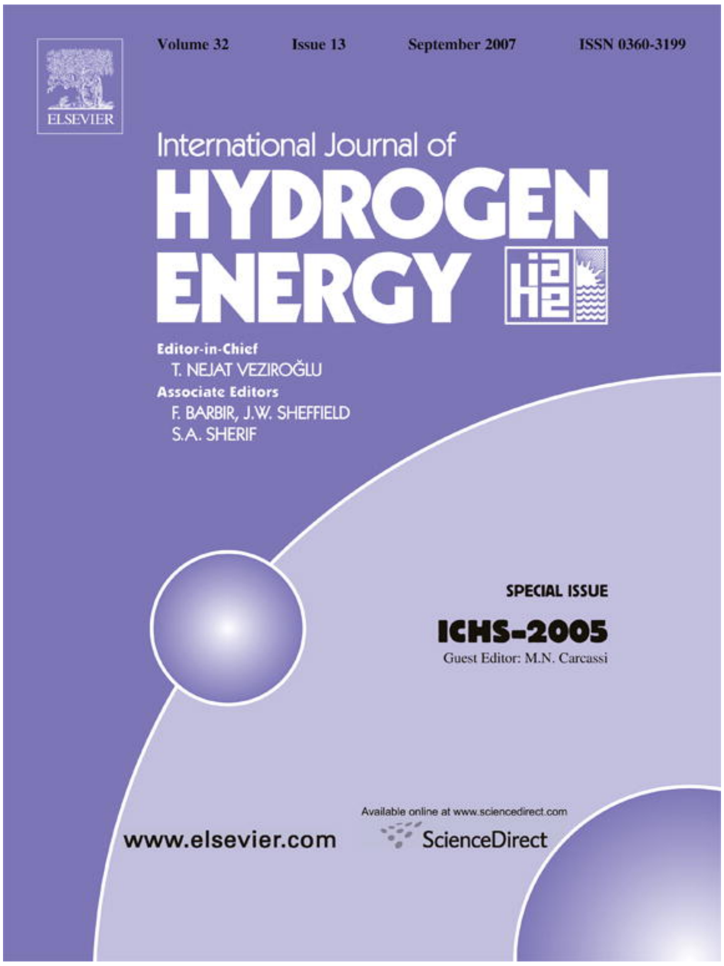
Volume 32
Issue 13
September 2007
ISSN 0360-3199
ELSEVIER
International Journal of
HYDROGEN ENERGY
Editor-in-Chief
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Available online at www.sciencedirect.com
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ELSEVIER
International Journal of Hydrogen Energy 32 (2007) 2134 – 2143
International Journal of HYDROGEN ENERGY
www.elsevier.com/locate/ijhydene

Canadian hydrogen safety program

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Available online 29 May 2007

Abstract

The Canadian hydrogen safety program (CHSP) is a project initiative of the Codes & Standards Working Group of the Canadian transportation fuel cell alliance (CTFCA) that represents industry, academia, government, and regulators. The Program rationale, structure and contents contribute to acceptance of the products, services and systems of the Canadian Hydrogen Industry into the Canadian hydrogen stakeholder community. It facilitates trade through fair insurance policies and rates, effective and efficient regulatory approval procedures and accommodation of the interests of the general public. The Program integrates a consistent quantitative risk assessment methodology with experimental (destructive and non-destructive) failure rates and consequence-of-release data for key hydrogen components and systems into risk assessment of commercial application scenarios. Its current and past six projects include Intelligent Virtual Hydrogen Filling Station (IVHFS), Hydrogen clearance distances, comparative quantitative risk comparison of hydrogen and compressed natural gas (CNG) refuelling options; 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 International Energy Agency (IEA) Task 19 Hydrogen Safety.

Keywords: Canadian; Hydrogen; Safety; Risk comparison; Refuelling options; Computational fluid dynamics; Hydrogen sensors

1. Rationale

For over 30 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. 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 options, 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 (CHSP). 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.

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

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0360-3199/$ - see front matter © 2007 Published by Elsevier Ltd on behalf of the International Association for Hydrogen Energy.
doi:10.1016/j.ijhydene.2007.04.017

technical issues with regard to hydrogen. This group spearheads Canada's input into safety issues internationally, including the IEA and the IPHE.

2. 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. Safety context

In addition to production, storage and handling and end-use technologies, safety is 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 and a complete suite of codes and standards that have been extensively used for hydrogen applications in lieu of non-existent hydrogen codes and standards. 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 onboard vehicles resulting in the exhaust of hydrogen fuel be addressed from the point of early detection of potential hydrogen emissions.

4. 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 (QRA), 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. Project partners

While the CTFCA link provides broad, representative input from the Canadian hydrogen community, the Program projects are carried out by five lead partners.

TISEC Inc. is a non-destructive testing and reliability engineering firm. TISEC provides engineering consulting on code compliance for hydrogen systems and is active in codes and standards development. The company engineers apply QRA in both their engineering design and code compliance projects and collaborate with the other partners on developing and using CFD dispersion models, consequence analyses and the results of experimental studies to optimize designs of hydrogen safety with respect to performance, cost and safety.

A.V. Tchouvelev and Associates (AVT) is a research and consulting company in the field of hydrogen safety and codes & standards. Its core competencies are CFD modeling of gas release and dispersion (GRAD) of hydrogen and other flammable gases that is used for risk analysis, engineering design and ventilation optimization and codes and standards development, and assisting clients in obtaining regulatory approvals for their hydrogen containing equipment. AVT is active in hydrogen and fuel cells codes and standards development and in risk assessment field.

Powertech Labs has been involved in the evaluation, development, certification testing and retesting of compressed gas fuel systems for vehicles since 1983. Powertech provides compressed hydrogen and CNG system design verification for the automotiveand associated refueling industries. The laboratory has the equipment and expertise to perform all tests required in any national and international standards covering pressure vessels, hydride storage systems and fuel system components. Facilities are available to perform safety related tests such as vehicle fires, cylinder impact, vent ignition, pneumatic bursts of flawed cylinders and materials performance tests.

Safety of hydrogen energy system is one of the core R&D activities of the Hydrogen Research Institute (HRI) of the Université du Québec à Trois-Rivières (UQTR). The Institute is actively involved in hydrogen storage and in the study of fundamental aspects of hydrogen safety studies, namely CFD simulation of choked and subsonic releases, physical effects analysis and the effect of the storage technology on the safety analysis of a hydrogen system. HRI is also active in various codes and standards committees. It heads the Auto 21 Network of Centres of Excellence project "Safety and infrastructure study of hydrogen powered vehicles", which involves 4 Canadian universities (Université du Québec à Trois-Rivières, the University of Victoria, Concordia University and the University of Calgary) in partnership with AVT and Tisec.

Ballard Power Systems is recognized as the world leader in the design, development and manufacture of zero emission proton exchange membrane (PEM) fuel cells. Ballard's proprietary technology enables automobile, bus, electrical equipment, portable power and stationary product manufacturers to develop environmentally clean products. Ballard is commercializing fuel cells for the transportation market and electric drives for both fuel cell and battery-powered electric vehicles, power electronics and fuel cells for both portable and stationary power generation markets. Ballard is also a Tier 1 supplier of friction materials to the automotive industry for automatic transmissions as well as a supplier of carbon fiber paper gas diffusion layers (GDL) to the fuel cell industry.

Each of these has other contributing partners.

6. Program projects

6.1. Approach to projects

The CHSP was initiated in mid 2003. The Program addresses various aspects of hydrogen safety ranging from QRA 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. It is a living program whose individual projects contribute four components as shown in Fig. 1. Past projects and ongoing projects identify further knowledge gaps that are critical for the stakeholders. These knowledge gaps are used to develop the scope of future projects thus ensuring smooth and logical continuation of the Program. For example, project results have been used as input to the development of Canadian hydrogen installation code and new issues have been identified as critical for further code development. They provide a basis for new Program projects.

Effort is applied to developing a consistent and rigorous QRA methodology for each of the applications to which it is applied. This provides a common basis for comparison of the output of analyses across the Canadian context, for incorporation into IEA Task 19 work and a common frame of reference for dialog with respect to risk among hydrogen stakeholders including the public and their regulators.

The Program and each project build upon the methodology of risk analysis of technological systems based on IEC 300-3-9: 1995 standard [1]. This standard has been adopted as a National Standard of Canada as CAN/ISO-CEI/IEC 300-3-9-97 [2] 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 draws on recent recommendations and practices developed by organizations active in this area such as DNV, TNO, and the UK Health and Safety Executive. Also, ISO/IEC Guide 73: 2002 Risk Management—Vocabulary—Guidelines for Use in Standards [3] has been used to be consistent with international terminology on risk management. Fig. 2 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.

The experimental program fills in the requirements for failure rate data, CFD model validation and consequence model validation. The consumer and industrial applications are drawn from the needs of the hydrogen system suppliers, the regulators and the end users as a basis for consensual decision making related to safety issues. Each project in the Program contributes to these three components.

6.2. Projects undertaken

Since its inception, the program has undertaken six projects of which the first five are complete:

- Intelligent virtual hydrogen filling station (IVHFS)—completed in August 2004.

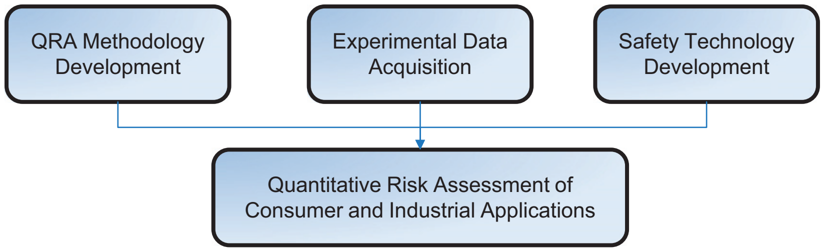

Fig. 1. Canadian hydrogen safety program elements.

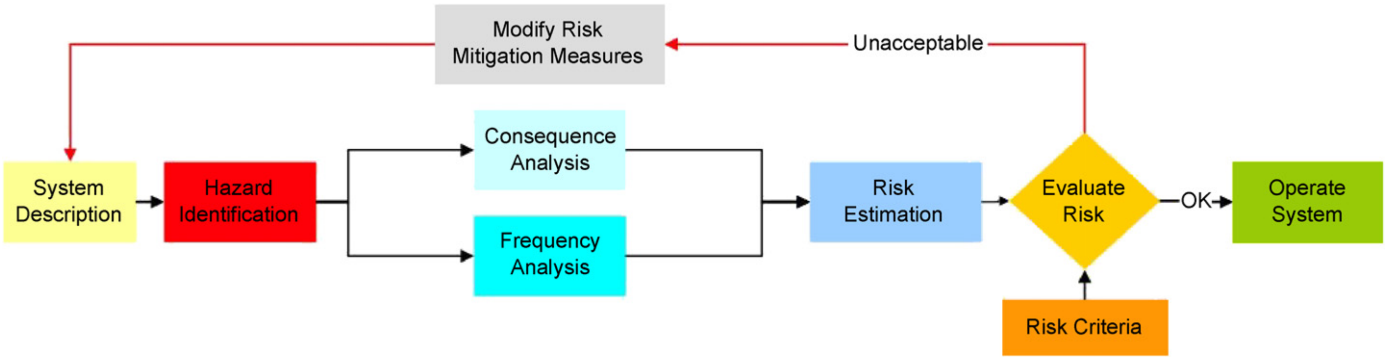

Fig. 2. The QRA process.

- Hydrogen clearance distances—completed in September 2004.
- Quantitative risk comparison of hydrogen and natural gas refuelling options—completed in April 2006.
- Validation, calibration and enhancement of CFD modeling capabilities for simulation of hydrogen releases and dispersion using available experimental databases—completed in June 2005.
- Fuel cell oxidant outlet hydrogen sensor project—completed in June 2006.
- Enhancement of frequency and probability analysis, and consequence analysis of key component failures of hydrogen systems—ongoing; completion August 2007.

The projects have direct relevance to IEA Task 19 Hydrogen Safety. A brief description of each project follows. Additional projects are expected to come on line later in 2007 pending government approval.

In addition to the CTFCA projects described herein, the Auto 21 Network of Centres of Excellence is investigating certain fundamental properties of hydrogen pertaining to safety issues such as the use of the real gas law in CFD leak simulations, deflagration-to-detonation transition, and combustion. With strong industry support from CTFCA members, five 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 in an academia-led project (Auto 21 project D201-DHS *Safety and Infrastructure Study of Hydrogen Fuelled Vehicles*). Driven by the industry needs, this project supports codes and standards development and improves understanding of hydrogen properties from a risk management prospective.

6.3. Intelligent virtual hydrogen filling station

The IVHFS is designed to enable users who plan design and construct fuelling stations or are involved in regulation or other safety issues to, using a graphical interface, select station components and their layout and to create a comprehensive description of applicable codes and standards for the jurisdiction in which the station is located. This graphical user interface is shown in Fig. 3.

The graphical user interface is accompanied by a comprehensive listing of codes and standards in a matrix where the axes are the hydrogen life-cycle components on a filling station from hydrogen supply to dispensing and the applicable jurisdictions. This matrix is complemented by a description of the regulatory structure and process in the target jurisdictions. These are shown in Fig. 4.

Initial implementation by the CTFCA CHSP was followed by an APEC project funded through Partnership Advancing Transition to Hydrogen (PATH), to include the APEC economies. At present the IVHFS covers Canada, Mexico, the United States and Japan in detail with additional information on the other nineteen APEC countries. Thus, input into this project has been from a group of Canadian experts as well as a broad international community.

The IVHFS is being used in the CHSP as a graphical reference for input into the modeling and risk analysis work in the project comparing natural gas and hydrogen filling

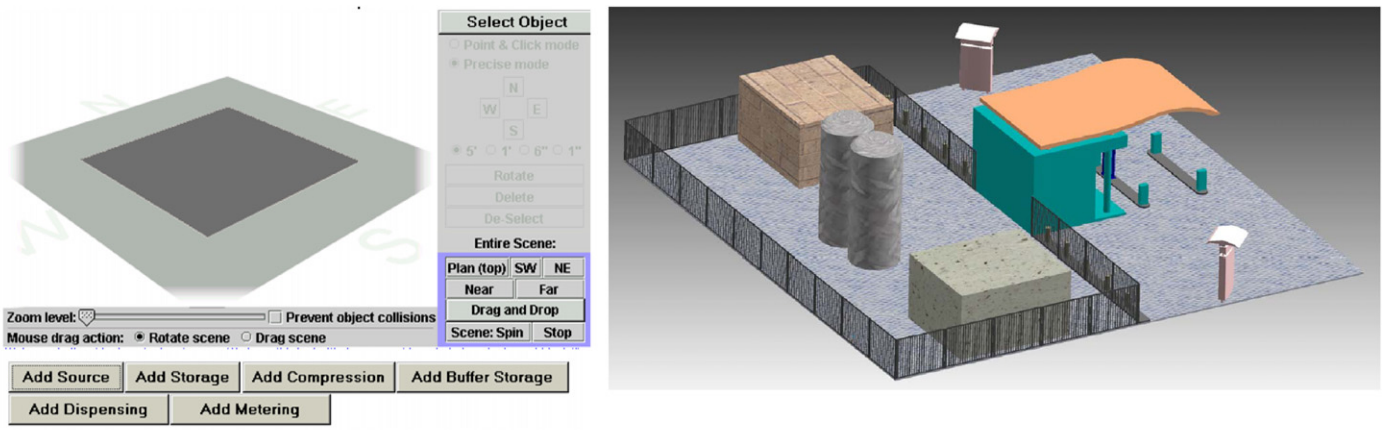

Fig. 3. Virtual filling station with the 3-D modeling workstation on the left and a station set up on the right.

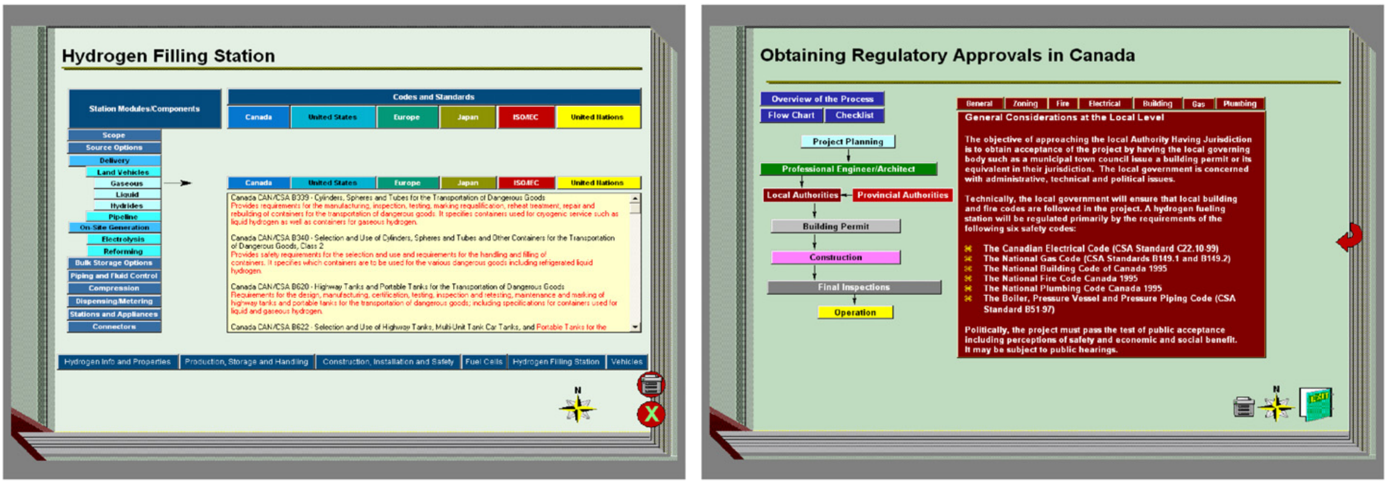

Fig. 4. Hydrogen codes and standards matrix (left) and the regulatory approval process flow chart for Canada (right).

station risks and the project on enhancement of frequency and probability analysis, and consequence analysis of key component failures of hydrogen systems. It is being extended to cover applications beyond the filling station. The modeling workplace and the codes and standards matrix are available at www.hydrogensociety.net and the descriptions of the regulatory structures and processes are available on the Sourcebook for Hydrogen Applications CD-ROM from TISEC Inc.

6.4. Hydrogen clearance distances project

The project was part of the CTFCA Codes and Standards Working Group work plan to Develop Quantitative Clearance Distance Criteria. It is a benchmark reference of quantitative hydrogen safety guidelines for updating Canadian model safety codes and for writing a Canadian Hydrogen Installation Code and related standards. Its objective is to ensure that clearance distances and related safety factors, such as the ventilation rates used to declassify hazardous zones in current standards and recommended practices and model codes are based on sound hydrogen-specific scientific and engineering principles and data.

These requirements reduce to three primary objectives:

- To develop sound scientific and engineering specifications that can be used to specify quantitative values for:
  - Clearance, offset, or separation distances for hydrogen storage, production and handling components in hydrogen energy systems.
  - Hazardous zone classifications.
  - Declassifying hazardous zones with ventilation.
- To provide clear guidelines for the use of these new specifications in commercial applications.
- To use the project data to develop scientifically based guidelines to create updates to the Canadian model codes and especially the Canadian Electrical Code.

In addition, the project included tasks to validate the simulation approaches and evaluate the consequences of releases. These objectives provide the basic tools required for economic design and construction as well as regulatory acceptance of hydrogen energy systems.

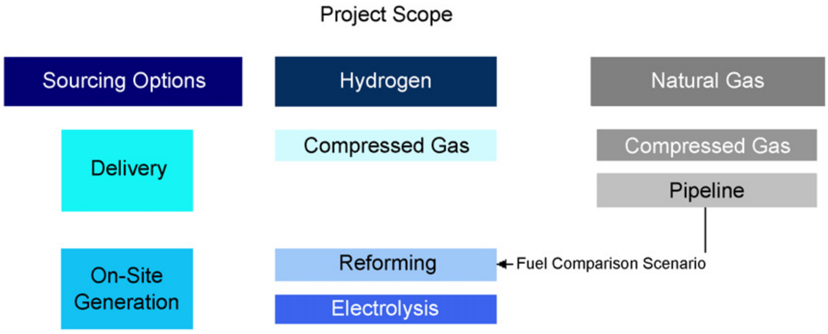

Fig. 5. Scope of the fuelling station comparison project.

6.5. Quantitative risk comparison of hydrogen and natural gas refuelling options

The project addresses the refuelling station scenarios outlined in Fig. 5 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 addressed by this project. All other possible risks associated with a refuelling station in general are presumed to be equal.

To ensure consistency of the Hazard Identification (HazID) process for all four considered technologies, the HazID is 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 in Fig. 6.

6.6. 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 in Table 1. 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. Examples of modeling cases are shown in Fig. 7. These validation experiments provide the quantitative basis for sound application of the modeling results obtained in other projects.

6.7. Fuel cell oxidant outlet hydrogen sensor project

This project was initiated as a result of an industry-recognized need to improve the state of the technology for hydrogen sensors used in automotive applications. The project evaluated and improved the state of technology for hydrogen sensors used in the oxidant outlet of an automotive fuel cell system 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 project addresses the area shown in red and marked 5A on Fig. 8.

Following development of a requirements document it was submitted to the CTFCA Codes & Standards Committee for review and discussion. This requirements document is a living document and will change with new or modified requirements for use by relevant standards developing organizations such as ISO or SAE for consideration.

A testing capability comprising the test plan, test station specification, test station, and testing capability was developed as a standard against which to evaluate hydrogen sensor technologies for this, and possibly other, fuel-cell-related applications. These testing capabilities will reside with the NRC Institute for Fuel Cell Innovation and will be made available for sensor suppliers, OEMs, and other related companies and organizations.

Confidential reports were provided to each sensor supplier. These reports are intended to provide the supplier with a gauge to measure their sensor performance against the requirements of the Canadian manufacturers such as Ballard and Hydrogenics

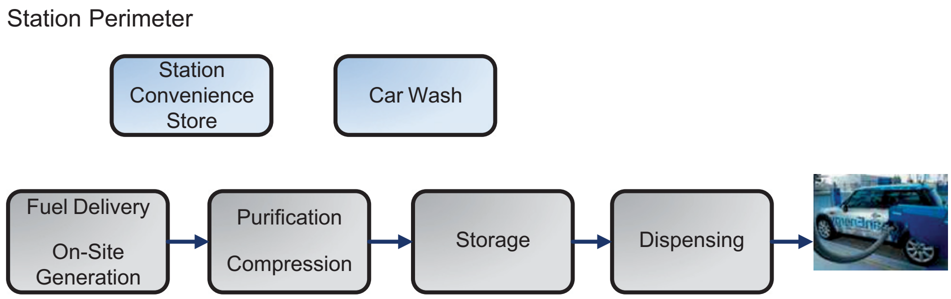

Fig. 6. Generic station configuration for QRA.

Table 1
CFD modeling experimental validation matrix

Case no.	Case name	Description of experiment				CFD model	Data source reference
		Domain	Leak direction	Leak type	Experimental data		
1	Helium jet	Open	Vertical	Subsonic, helium release	Steady-state, velocities, concentrations and turbulence intensities	Incompressible, steady-state	[4]
2	H_2 jet		Horizontal	Subsonic, H_2 release	Transient, concentrations	Incompressible, transient	[5]
3	INERIS jet			Choked, H_2 release	Steady-state, concentrations	Compressible, steady-state	[6]
4	Hallway end	Semi-enclosed	Vertical	Subsonic, H_2 release	Transient, concentrations	Incompressible, transient and steady-state	[7]
5	Hallway middle			Subsonic, helium release	Transient, concentrations		
6	Garage with a car			Subsonic, H_2 and helium releases	Transient, concentrations		[8]
7	H_2 vessel	Enclosed		Subsonic, H_2 release and dispersion	Transient, concentrations during dispersion	Incompressible, transient	[9]

of fuel cell systems for automotive applications. In essence, this provides 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.

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.

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

6.8.1. Integration of project technologies

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.

While this project concentrates on frequency and consequence analyses, it serves an integrating role by bringing these into the complete risk analysis process for plug-and-play hydrogen systems and retail facilities that operate in a consumer environment across a broad cross section of the Canadian hydrogen community that manufactures and uses hydrogen systems. It incorporates hydrogen-specific data and the validated modeling approaches from other projects. This includes the 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. The project also contributes to the requirements of International Energy Agency Hydrogen Implementing Agreement Task 19—Hydrogen safety. One of its requirements

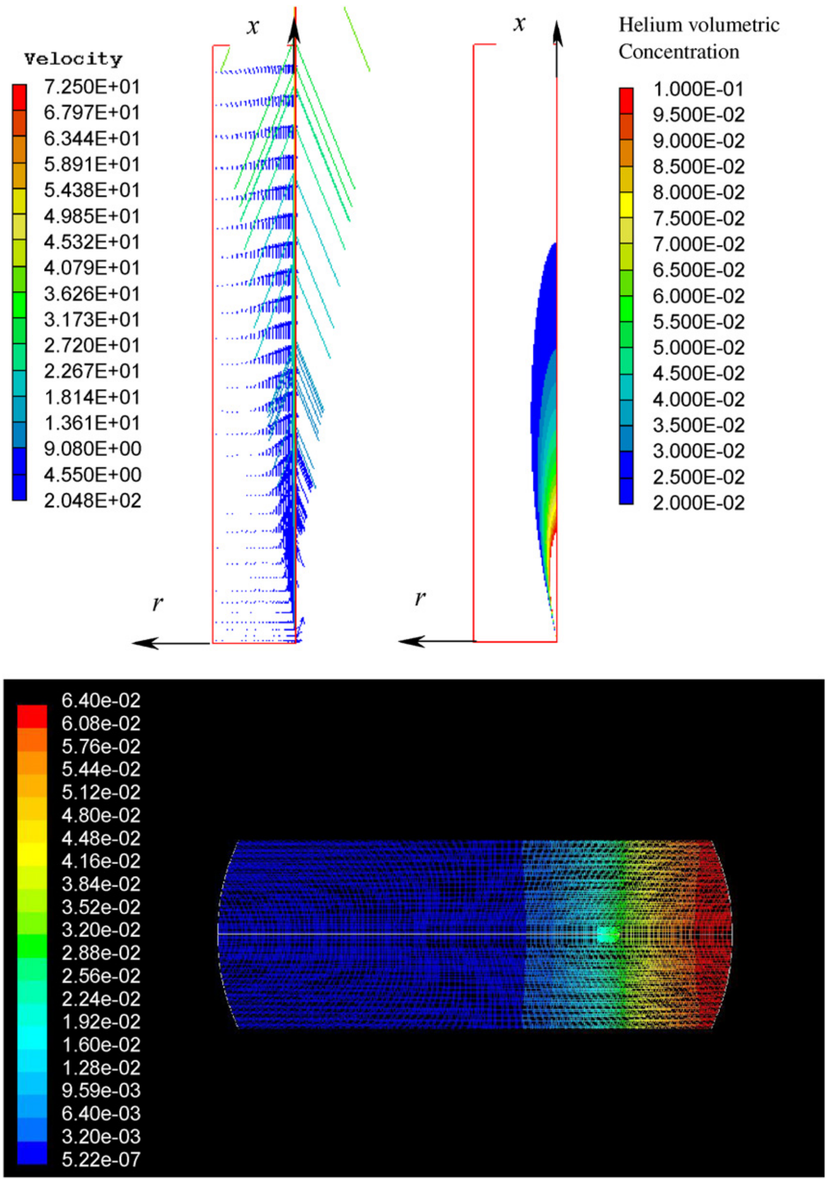

Fig. 7. Examples of modelling cases.

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.

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.

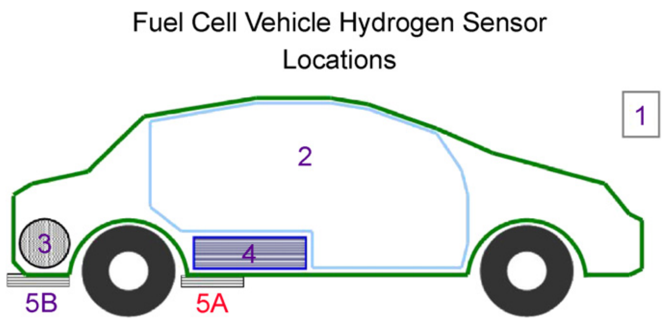

Fig. 8. Areas of potential hydrogen detection. 1 — Ambient/Garage; 2 — Passenger compartment; 3 — Fuel storage area & High-pressure piping; 4 — Fuel cell system area; 5A — Fuel cell oxidant outlet; 5B — Vehicle exhaust.

6.8.2. *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 QRA. 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. The project has documented the sources it uses for its analyses in a modest failure rate database and publishes it on the CHSP site at www.hydrogensociety.net to solicit feedback on the appropriateness of the values and complementary sources of data.

6.8.3. *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 will 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 by IEA 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 Figs. 9–11. In destructive valve tests (Fig. 9a) forces were applied to the valves to simulate impact during vehicle collisions. In hydrogen release simulation tests (Fig. 9b) 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. Fig. 10 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 depressurized 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 QRAs.

Fig. 9. Examples of destructive and non-destructive experiments 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 in Fig. 11.

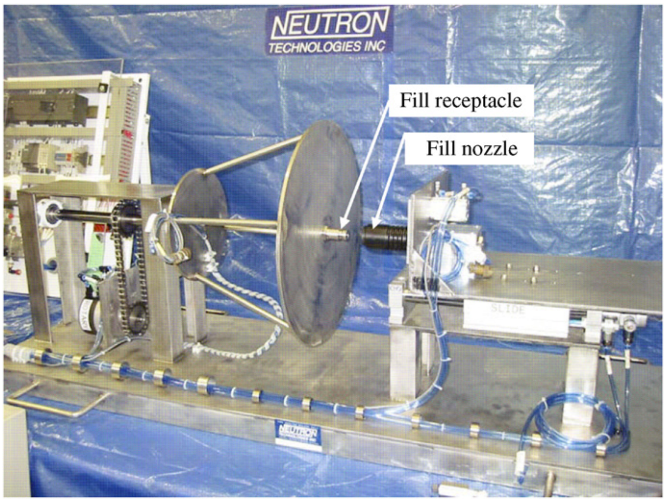

Fig. 10. Testing apparatus for hydrogen filling nozzle and receptacle at Powertech Labs.

Fig. 11. 16 Hydrogen detonation trials: Plateau test site (open space). Photo: courtesy of Defence R&D Canada—Valcartier.

7. 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 agreed 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 joint papers on application of ideal and real gas law for high pressure releases of hydrogen, and risk-informed process and tools for permitting hydrogen fueling stations.

8. Conclusions

Through the CTFCA Canadian Hydrogen Safety Program a sound quantitative risk assessment (QRA) methodology combined with experimental programs to develop failure rate data, validate dispersion and consequence models and develop sensor technology, and application-specific risk assessment studies are being applied to Canadian needs to facilitate acceptance of hydrogen technologies and hydrogen as a fuel by Canadian stakeholders. The Program is also a vehicle for Canada's contribution of stakeholder input from the industrial, academic, government, and regulatory sectors to international hydrogen safety programs.

References

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