HYDROGEN SAFETY, TRAINING AND RISK ASSESSMENT SYSTEM

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Abstract

The rapid evolution of information related to hydrogen safety is multidimensional ranging from developing codes and standards to CFD simulations and experimental studies of hydrogen releases to a variety of risk assessment approaches. This information needs to be transformed into system design, risk decision-making and first responder tools for use by hydrogen community stakeholders. The Canadian Transportation Fuel Cell Alliance (CTFCA) has developed HySTAR^{tm}, an interactive Hydrogen Safety, Training And Risk System. The HySTAR^{tm} user interacts with a Web-based 3-D graphical user interface to input hydrogen system configurations. The system includes a Codes and Standards Expert System that identifies the applicable codes and standards in a number of national jurisdictions that apply to the facility and its components. A Siting Compliance and Planning Expert System assesses compliance with clearance distance requirements in these jurisdictions. Incorporating the results of other CTFCA projects, HySTAR^{tm} identifies stand-out hydrogen release scenarios and their corresponding release condition that serves as input to built-in consequence and risk assessment programs that output a variety of risk assessment metrics. The latter include on- and off-site individual risk, probability of loss of life and expected number of fatalities. These results are displayed on the graphical user interface used to set up the facility. These content and graphical tools are also used to educate regulatory approval and permitting officials and build a first-responder training guide.

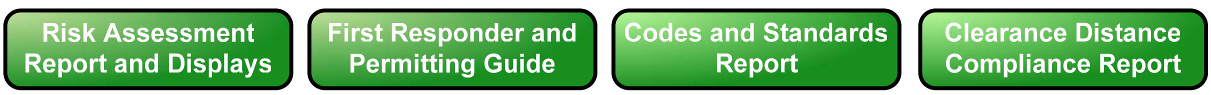
1. A HYDROGEN SAFETY KNOWLEDGE SYSTEM

1.1 Organizing CTFCA Program Knowledge

The Canadian Transportation Fuel Cell Alliance is a Canadian federal government initiative to demonstrate and evaluate fuelling options for light, medium and heavy-duty fuel-cell vehicles. Its Codes and Standards Working Group focuses effort on facilitating the development of appropriate codes and standards and testing procedures to facilitate acceptance and installation of related fuel-cell and hydrogen technologies including storage, fuelling station configurations and locations, and fuelling interfaces with fuel-cell vehicles. The Codes and Standards Working Group has also undertaken CFD analyses of stand-out hydrogen release scenarios and detailed quantitative risk assessments of fuelling station options and developed training and information guides for the stakeholder community including:

- ✓ *Regulatory and Permitting officials*
- ✓ *Designers, owners and operators of hydrogen systems*
- ✓ *Insurers and investors*

This extensive body of data and the context of its application and analysis require an effort to distill and organize the knowledge and present it effectively to the stakeholders for a variety of purposes of which the CTFCA has identified:



Risk assessment is used as a tool for quantitative exchange among the stakeholders regarding issues of the probability and consequences of harmful events. The same considerations are conveyed to first responders and designers, owners and operators of hydrogen systems to assist in decision making throughout the system life cycle from design through operation and maintenance and for mitigation of consequences in the event of unintended releases. Codes and standards are part of this knowledge base and play an important role throughout the life cycle. This knowledge base has been compiled into HySTAR^{tm}, the *Hydrogen Safety, Training And Risk* system to capture knowledge generated in the CTFCA programs mainly for education and training purposes.

1.2 Contents of the Hydrogen Safety Knowledge System

The purpose of HySTAR^{tm} is to provide guidelines for siting and safety measures in hydrogen applications. The siting issues may occur during design of the system or during assessments for code compliance assessment and for procurement of facility insurance.

HySTAR^{tm} is a comprehensive system that incorporates a multifunctional capability in four expert system modules that cover a range of information and target audiences involved in assessing and ensuring the safe design and operation of hydrogen systems. It comprises an ensemble of third-party commercial off-the-shelf software components and proprietary project software for analysis, assessment and training for a broad audience of users involved in the safety of hydrogen systems. Through an interface called HyVIEW^{tm} Web-based Hydrogen Virtual Interactive Expert Workplace, HySTAR^{tm} provides four expert tools:

HyQuantras™	the Hydrogen Quantitative Risk Assessment program
HyCASE™	the Hydrogen Codes and Standards Expert to identify the Codes and Standards requirements for hydrogen facilities and components
HyPOST™	Hydrogen Public Officials Safety Training for first responders and permitting authorities.
HySCAPE™	Hydrogen Siting Compliance and Planning Expert

These tools are deployed on the Internet and are available at www.hydrogensociety.net. They are applicable to the following applications of interest to the Canadian hydrogen community:

- *Filling stations configurations*
- *Vehicle releases during refueling operations and in parking garages*
- *Stationary power*
- *Warehouse serviced by FC-powered fork lift*
- *Transit maintenance facilities*

2. THE GRAPHICAL USER WORKPLACE

HyVIEW^{TM} provides user interactivity and control over the functions of the program in terms of the logical characteristics of each interface between the software product and its users. This includes those configuration characteristics such as required screen formats, page or window layouts, content of any reports or menus, or availability of programmable function keys necessary to accomplish the software requirements. It defines the fundamental actions that must take place in the software in accepting and processing the inputs and in processing and generating the outputs. It establishes overall functional hierarchy of functions organized by either common inputs, common outputs, or common internal data access. Data flow diagrams and data dictionaries show the relationships between and among the functions and data.

A common virtual interactive expert workplace, the HyVIEW^{tm} interface, has been developed for HySTAR^{tm}. This interface and the associated tools are programmed in Java and operate on the Internet without the need to download plug-in graphics tools. With this graphical interface, the user designs the target facility to be the subject of analysis by one or all of the four expert modules by:

- ✓ *Defining a site configuration*
- ✓ *Recalling a site configuration*
- ✓ *Saving and storing a site configuration*
- ✓ *Specifying the types of reports and recommendations required from the system.*

The system component inventory entry interface is a custom tool developed for HySTAR^{tm} and the graphical layout entry is a capability to import third-party CAD 3-D graphical descriptions of the component and their layout on the site. Entries into this module are stored in a database for the project to facilitate assessments of various parametric scenarios. The component library will consist of stock drawings of components for various storage options, including liquid, gaseous and hydride; on-site generation methods; dispensing and metering configurations and piping and fluid control components. It will cover various types of hydrogen fuelling stations being considered as well as complementary components found in current fuelling stations used for gasoline, diesel, natural gas and propane where dual or multiple fuels will be used.

The graphics-enhanced, text-based interface in Figure 1 guides the user to ensure that major categories of components are selected and provide recommendations for compatibility among components. With this interface the user can:

- ➢ *Select a hydrogen scene such as a filling station or stationary power supply facility from pre-set configurations.*
- ➢ *Design a hydrogen scene such as a filling station or stationary power supply facility from a set of basic components.*
- ➢ *Generate the* HyCASE ^{tm} *and* HySCAPE ^{tm} *reports from the Workplace interface.*

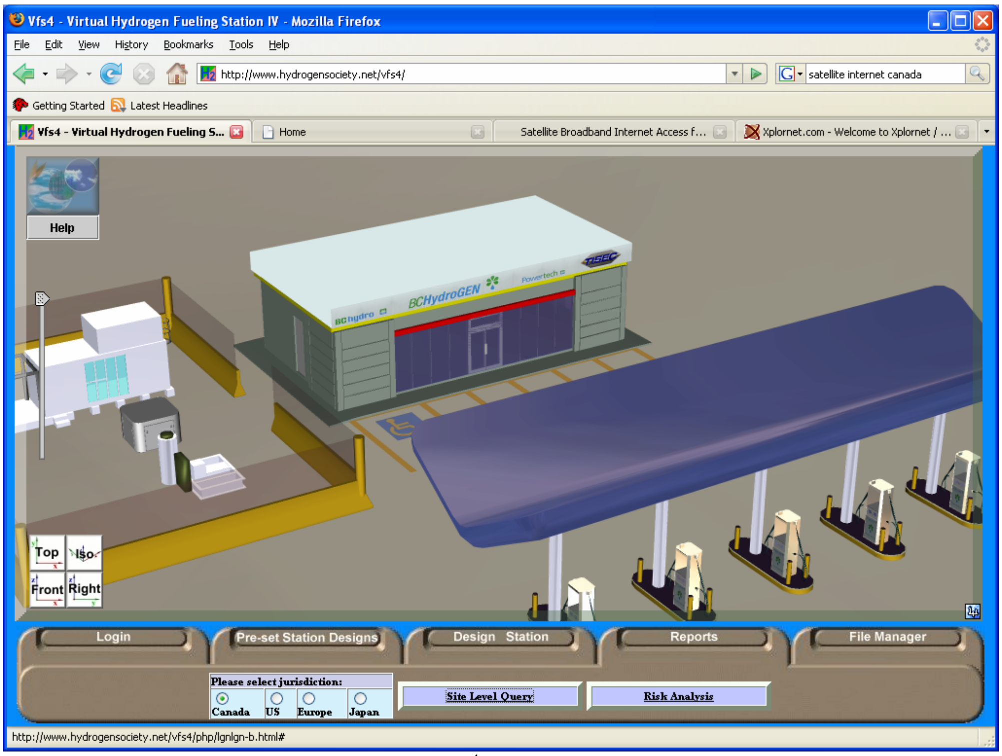


Figure 1 HyVIEW^{tm} interactive workplace

Once the components are selected and sized, they can be set on the plan view of a proposed site by dragging them from a component library and dropping them on the site. Data display and reporting include display of output text, tabulations and quantitative metrics in Web-deployable formats and as overlays on the 3-D site scene. This module also provides an effective means to distribute site set up information as well as HySTAR^{tm} interpretations and decisions to parties involved in follow up actions.

3. LINKS TO EXPERT SYSTEM MODULES

HyVIEW^{tm} outputs a list of the facility components that includes descriptors that permit operation on these objects by the expert system modules. It also provides a matrix of distances between components that enable clearance distance code compliance assessments. These data are available for processing by the four expert system modules.

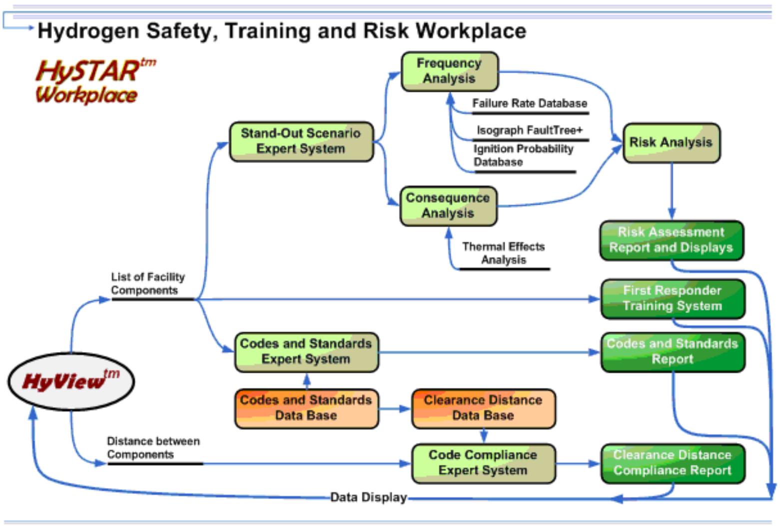


Figure 2: Information content and flow in HySTAR

4. HYCASE^{tm}

For a site with its components as defined in the HyVIEW^{tm} workspace, a comprehensive set of applicable codes and standards is generated for the jurisdiction in which the facility is located by the HyCASE^{tm} expert system. The system is implemented for Canada at present and is being extended to other jurisdictions. One such output report is shown in Figure 3

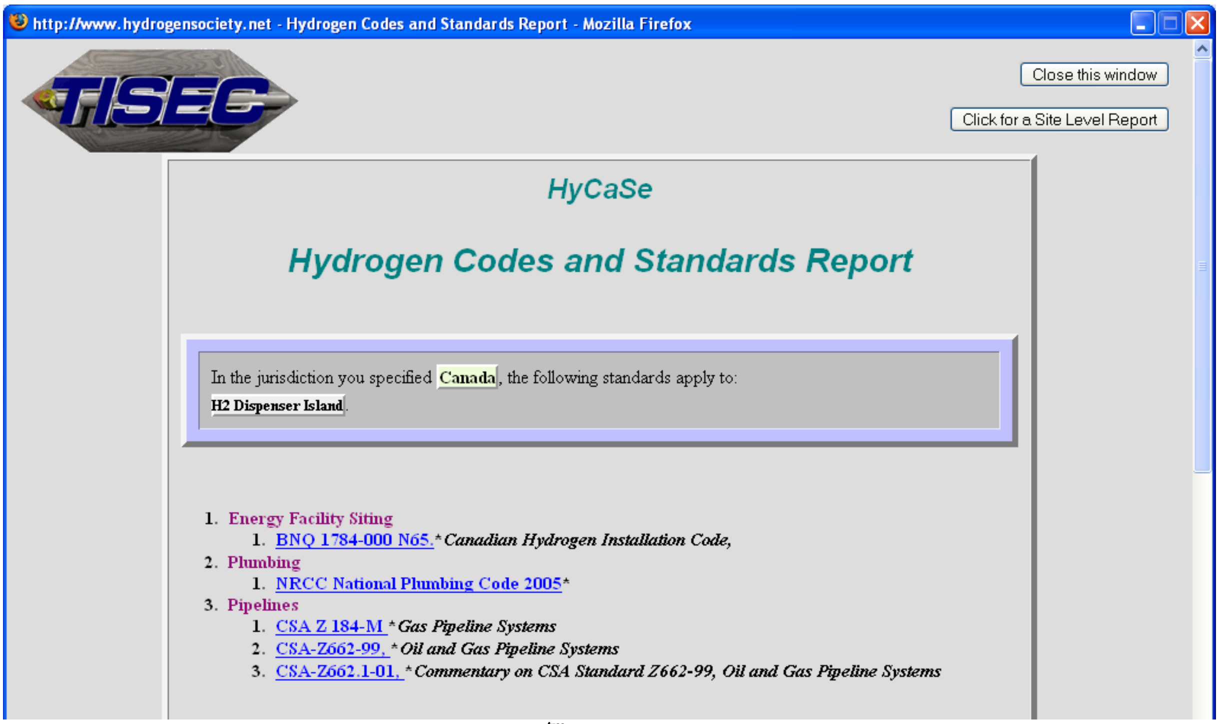


Figure 3 HyCASE^{tm} codes and standards report.

5. HYSCAPE^{tm}

For the applicable codes in the jurisdiction of interest, HySCAPE^{tm} assesses compliance of the system for clearance or separation distances. HySCAPE^{tm} uses the capability of the HyVIEW^{tm} to measure distances on the scene and generate a matrix of distances between the site components as shown in Figure 2. Those offsets that are acceptable to the codes are shown clearly and differentiated, and those combinations of objects to which the analysis does not apply or for which data are not available are also indicated. The user can interactively adjust the location of components on the site to assess compliance and determine an acceptable layout.

6. HYPOST^{tm}

HyPOST is an information and training aid for regulatory officials and the stakeholders they serve. The scope of the information content is shown in Figure 5. It establishes the context of the regulatory process for the stakeholder community, the structure of the regulatory system and the pathway and requirements for regulatory approval. At present it covers, Canada, the United States, Mexico, Japan and the APEC countries. Of these, North American jurisdictions are covered in the most detail. As an example, for Canada, it provides an explanation of how the Canadian standards development organizations and safety authorities operate including:

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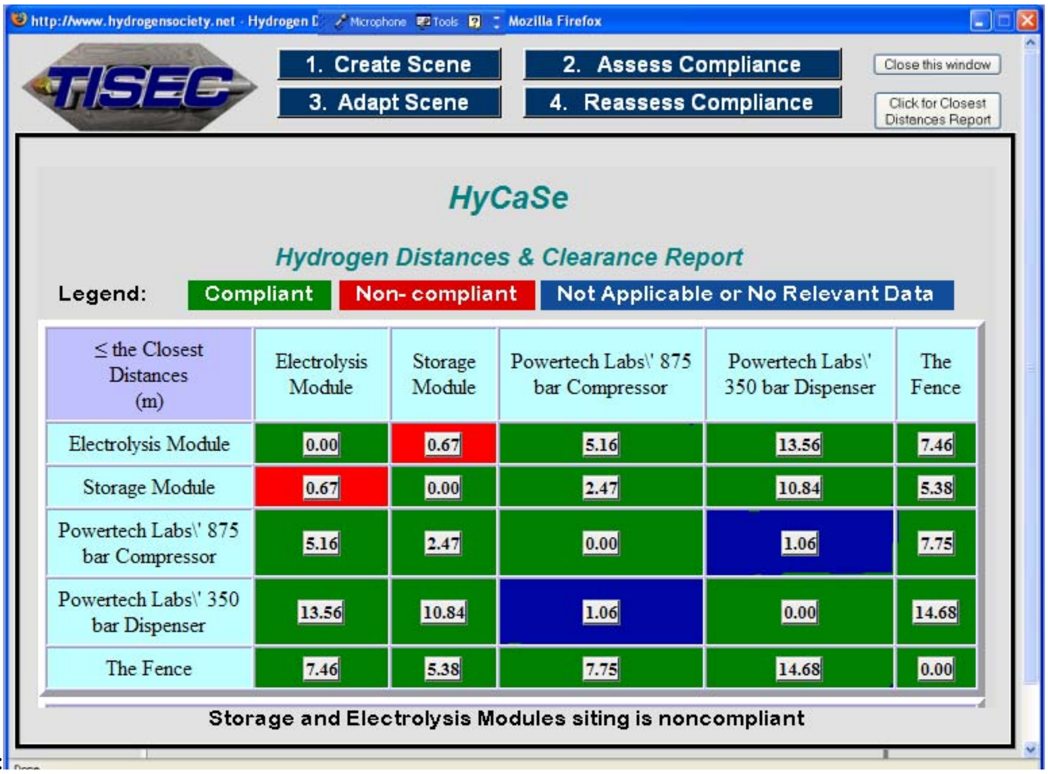
- ✓ Present existing and developing codes and standards that apply to hydrogen technologies operating in Canada including information on codes and standards developmental activities and status updates.
- ✓ Instructions on how to apply for approval permits for novel hydrogen systems.
- ✓ Identification of the authorities active in each target Canadian jurisdiction and the supporting documents they require and the order in which they should be submitted.

The route to regulatory approval in Canada is shown in Figure 6 and a checklist of required approvals in one of the Canadian provinces in Figure 7.



≤ the Closest Distances (m)	Electrolysis Module	Storage Module	Powertech Labs\' 875 bar Compressor	Powertech Labs\' 350 bar Dispenser	The Fence
Electrolysis Module	0.00	0.67	5.16	13.56	7.46
Storage Module	0.67	0.00	2.47	10.84	5.38
Powertech Labs\' 875 bar Compressor	5.16	2.47	0.00	1.06	7.75
Powertech Labs\' 350 bar Dispenser	13.56	10.84	1.06	0.00	14.68
The Fence	7.46	5.38	7.75	14.68	0.00

Figure 4 Matrix of distances between objects on the HyVIEW^{tm} workplace assessing compliance with applicable codes

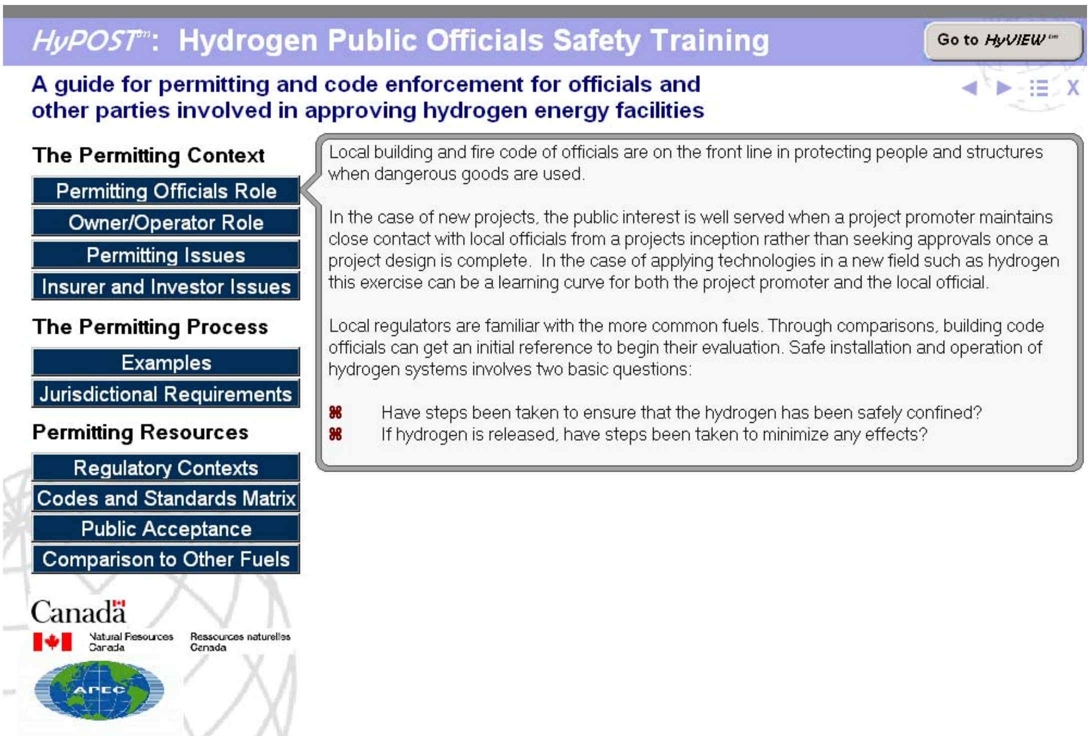


Figure 5 HyPOST^{tm} information content

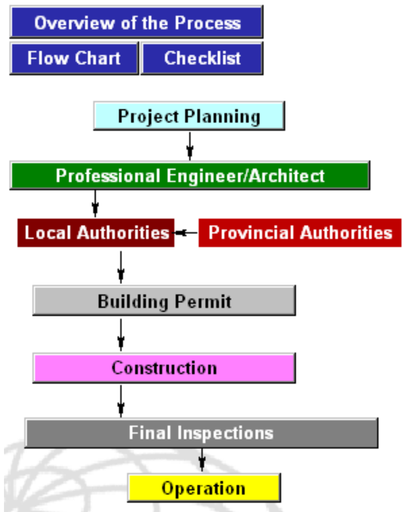


Figure 6 The regulatory approval process in Canada

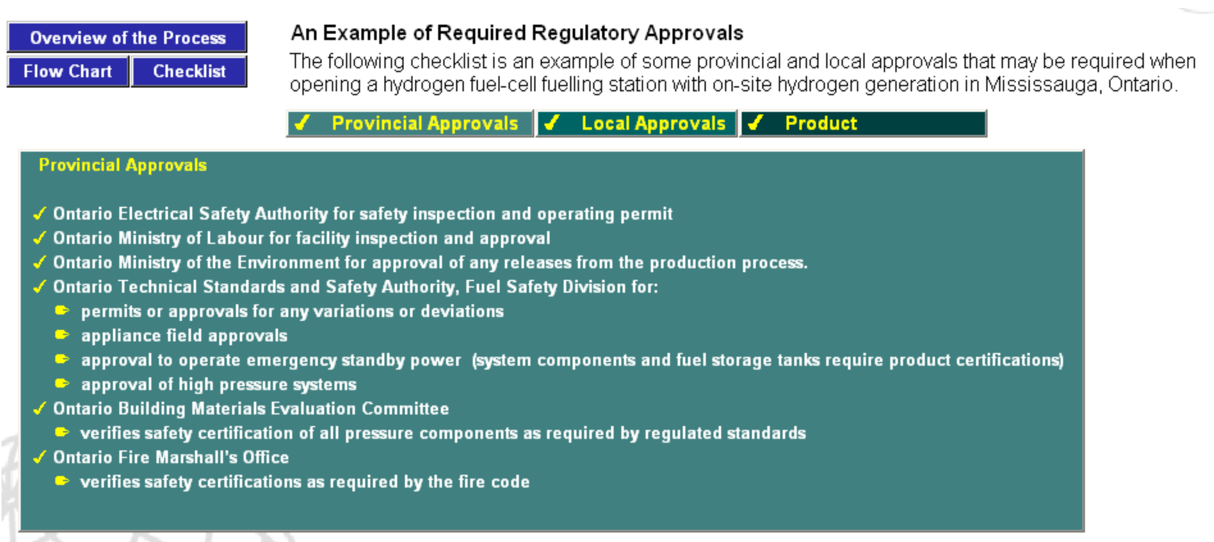


Figure 7 A checklist of the approvals required in the province of Ontario.

7. RISK ASSESSMENT IN HYSTAR^{tm}

The approach HySTAR^{tm} was developed within the "QRA Project" [1] under the Canadian Hydrogen Safety Program [2] and is based on the identification of so-called "stand-out release scenarios", i.e. those failure scenarios that are representative of considered refueling options, include both more realistic higher probability but lower consequence scenarios as well as credible catastrophic component failures and, thus, can be used for risk comparison with other similar refueling options. HySTAR^{tm} follows conventional risk assessment methodology to estimate risk. In its current version, however, it does not benchmark results against risk criteria. This will be part of the future development.

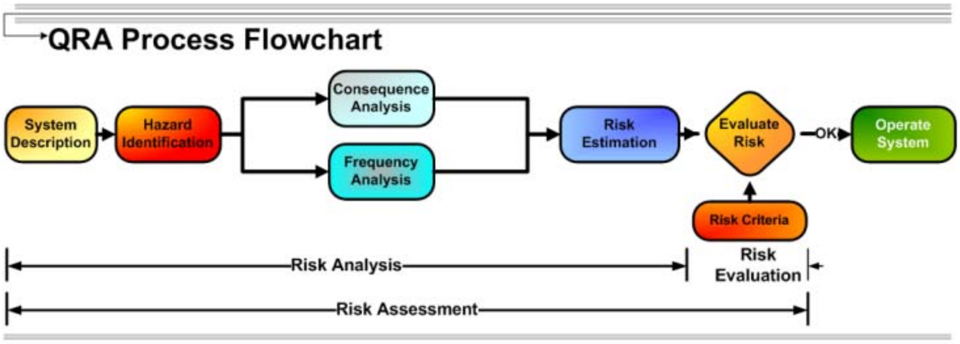


Figure 8 Quantitative risk assessment process

The HyQuantras[tm] interface is shown in Figure 9 and it can accept manual inputs from the user but also interfaces directly into HySTAR[tm] where it gets its input information from the scene set up on the HyVIEW[tm] workplace. The scene information identifies the above-mentioned stand-out applicable scenarios for which the frequency and consequence data are computed. These scenarios are described in Table 1. At present, the consequences of a release are modeled as jet flames upon ignition from which thermal intensity is computed. The latter data are fed into a probit equation and the risk is computed following guidelines of the TNO "Purple Book" [3]. The Interface also allows certain site-specific parameters to be entered into the analysis such as the number of people exposed to the hazard on-site and off-site, exposure time in the event of the release and its ignition, time of exposure to the hazard and the useful lifespan of the facility.

Thermal consequences that are currently limited to radiative heat flux effects are computed based on correlations and models developed by Y. R. Sivathanu [4], W. Houf [5] and Mogi [6] for free jets and by Shell Thornton (Chamberlain) for vertical flares explained in the TNO "Yellow Book" [7] . The interface of the thermal effects software is shown in Figure 11. It allows the user to select the flammable gas (hydrogen, methane or propane) as well its storage pressure and leak orifice. The software allows predicting a distance to any specified radiation level and vice versa – radiation level at any specified distance from the source of fire. Obtained results are fed directly into HyQuantras to obtain risk estimations.

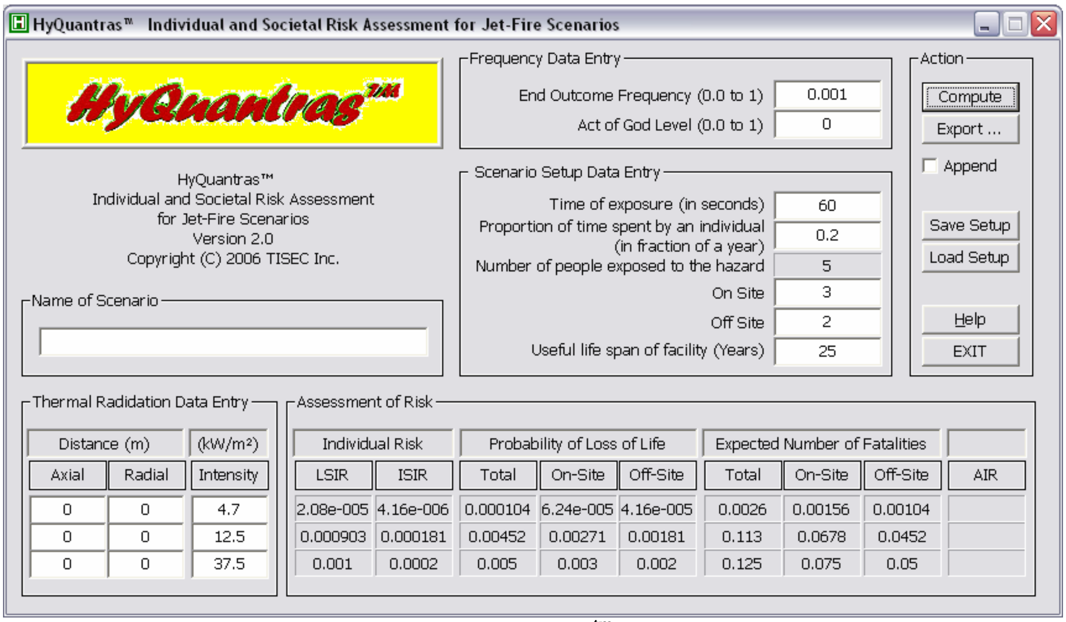


Figure 9 HyQuantras[tm] interface

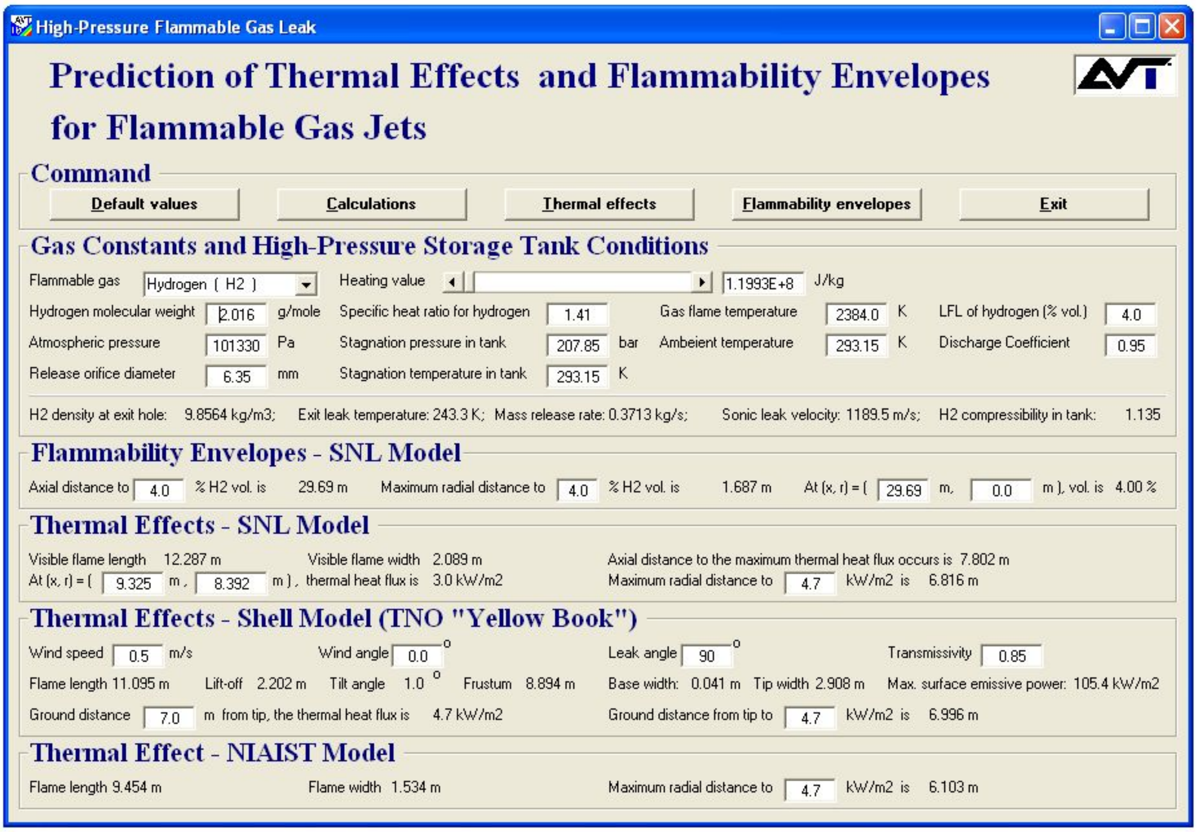


Figure 101. Thermal effects software interface

8. SUMMARY

A comprehensive web based tool, HySTAR^{tm}, has been developed for education and training purposes of various stakeholders involved in design, installation and approval of hydrogen applications.

Regulators can learn about potential consequences, frequencies / probabilities and risk of selected stand out failure scenarios related to various fixed station designs and technologies. Design engineers are informed about the risks of typical failures and are helped in developing adequate mitigation strategies. It also provides them with the list of relevant codes and standards and guides them in the placement of selected station components with respect to code requirements on clearance distances.

HySTAR^{tm} is not intended for risk assessment of specific facilities by the permitting officials because site-specific risk assessment can be quite different from generic component-based assessment and thus requires specialized knowledge in making appropriate judgment calls in regards to identification of credible failure scenarios and their consequences. Site specific risk assessment can be different for every real site even if components are the same due to differing environment and exposure levels. As HySTAR^{tm} evolves, it will incorporate the capability to be used for site-specific risk analysis by trained professionals who fully understand the methodology and have adequate knowledge of hydrogen behavior under various conditions.

Table 1 Fueling station release scenarios

Technology	Scenario Description / Details
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.
	2. Catastrophic failure hydrogen release from ½” pipe line during unloading. Details similar to above. Mode of release – transient, exponentially changing flow. Hydrogen quantity – 370 kg.
Electrolysis	3. Catastrophic failure hydrogen release from hydrogen rinser inside the electrolyser cabinet. Pressure – 10 bars; leak orifice – ¾” pipe; leak direction – horizontal; type of release – sonic jet. Hydrogen quantity – about 0.5 Nm3. Mode of release – transient.
	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 TIAX 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.

9. REFERENCES

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