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Ensuring Adequate Safety When Using Hydrogen as a Fuel

D. Allan Coutts
Washington Group International

Abstract

Demonstration projects using hydrogen as a fuel are becoming very common. Often these projects rely on project-specific risk evaluations to support project safety decisions. This is necessary because regulations, codes, and standards (hereafter referred to as standards) are just being developed. This paper will review some of the approaches being used in these evolving standards, and techniques which demonstration projects can implement to bridge the gap between current requirements and stakeholder desires.

Many of the evolving standards for hydrogen-fuel use performance-based language, which establishes minimum performance and safety objectives, as compared with prescriptive-based language that prescribes specific design solutions. This is being done for several reasons including: (1) concern that establishing specific design solutions too early will stifle invention, (2) sparse performance data necessary to support selection of design approaches, and (3) a risk-adverse public which is unwilling to accept losses that were incurred in developing previous prescriptive design standards.

The evolving standards often contain words such as: "The manufacturer shall implement the measures and provide the information necessary to minimize the risk of endangering a person's safety or health." This typically implies that the manufacturer or project manager must produce and document an acceptable level of risk. If accomplished using comprehensive and systematic process the demonstration project risk assessment can ease the transition to widespread commercialization. An approach to adequately evaluate and document the safety risk will be presented.

Evolving Requirements

Current efforts to establish appropriate safety levels for the use of hydrogen as a fuel involve many technical organizations. A partial list is presented in Table 1. More comprehensive lists may be found at http://www.fuelcellstandards.com/Matrix.htm and http://hcsp.ansi.org/default.asp. The standards that are being prepared to address hydrogen safety contain a mix of prescriptive and performance-based requirements. Examples prescriptive requirements are:

- For fuel tank connections above 2 inch (5.1 cm) nominal diameter, only welded connections shall be acceptable.

- One or more finished fuel tanks shall be drop tested at ambient temperature without developing a leakage rate above a defined value.

Table 1.--Partial list of organizations involved in the preparation of hydrogen safety standards

American Society of Mechanical Engineers (ASME)
American National Standards Institute
ASTM International
Compressed Gas Association
CSA America
Institute of Electrical and Electronic Engineers
International Code Council
International Electrotechnical Commission (IEC)
International Organization for Standardization (ISO)
National Fire Protection Association
National Hydrogen Association
Society of Automotive Engineers
Underwriters Laboratories

Achieving some of the requirements might be considered a technical challenge, but compliance is readily apparent. Performance-based requirements can take the form of:

- "A Failure Modes and Effects Analysis (FMEA) or equivalent reliability analysis intended to identify failures which have significant consequences affecting the fuel cell power system safety, shall be submitted to the testing agency for evaluation." (FC 1-2004)

- The device shall be designed and constructed to avoid any reasonably foreseeable risk of fire or explosion posed by the hydrogen generator itself or by the gases, liquids, dust, vapours or the other substances produced or used by the device.

Safety Management

Compliance with performance-based requirements must be done using a well-founded technical approach. For many demonstration projects the standards are not fully evolved. As such it is necessary to supplement the existing requirements with risk-based decisions. There are several techniques that may be used to support such decisions, and support performance-based designs. The US Department of Energy (DOE) is addressing the gaps though the development of Safety Plans (DOE 2005), which include:

- Identification Safety Vulnerabilities (ISV). A formal means to identify potential safety issues

- Risk Mitigation Plan. A description of the safety performance metrics, safety basis management (change control), standard operating procedures, employee training, procedures that ensure equipment integrity, and an emergency response plan.

- Communication Plan. The proposed techniques that will be used to conduct safety reviews during design, and incident reporting after operations commence.

Demonstration project risks include: safety risk, project risk and fiscal risk. The three are co-dependent. If safety risk is not successfully managed the project might not fulfil the project objectives (project risk) or might exceed budget constraints (fiscal risk). In managing the safely risk a five function process that is derived from Integrated Safety Management (ISM) is recommended (DiNunno, 1997). The five functions are illustrated in Figure 1. The objective of ISM is to systematically integrate safety considerations into management and work practices at all levels. This is accomplished by ensuring work is planned, analyzed, revised, approved and executed in a safe manner. There are five basic Core Functions that define how ISM is put into practice.

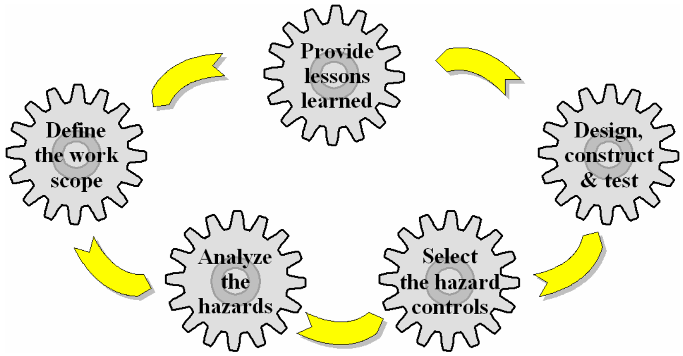

Figure 1, Functions of Integrated Safety Management

Define the Scope of Work. Translate the facility mission into work. Set expectations. Tasks are prioritized, and resources are allocated.

Analyze the Hazards. Safety hazards and environmental aspects and impacts associated with the work activity and work output are identified, analyzed, and categorized.

Develop and Implement Controls. Applicable standards and requirements are identified. Controls to prevent/mitigate hazards are identified. Safety controls are established, communicated, and implemented. This process defines the safety envelope.

Perform Work. The establishment of the controls is confirmed. Work is started, performed and completed safely.

Encourage Feedback and Continuous Improvement. Feedback information is collected and opportunities for improvement are identified. Action Items to effect improvement are tracked and implemented. Oversight is provided to help identify improvement opportunities and enforce requirements.

Analytical Process

The DOE Guidance for Hydrogen Projects cites a comprehensive approach to hazard analysis as one method to conduct the ISV. This methodology was developed by WSMS in establishing and documenting the operational safety of its nuclear and chemical processing facilities. It has been successfully adapted to hydrogen demonstration projects (Coutts, et.al.) This methodology employs a systematic, graded approach and ensures that the greatest attention is applied to the most significant concerns. The steps below summarize the method.

1. Hazard identification. The process began by identifying any hazardous material or energy source associated with the equipment. A checklist can be used as a guide to aid in developing a comprehensive list of hazards that are characterized in terms of form, quantity, and location. Table 2 provides an excerpt from a project that evaluated the safety of hydrogen-fuel use in a coal mining environment.(Coutts and Thomas, 1998) This is the project that provides the example presented in the DOE Safety Guidance Report (DOE 2005).

2. Scenario development. The second step in the overview hazard analysis is development of detailed, reasonable-worst-case, credible scenarios describing process upsets, human errors, system failures, etc. that result in unwanted or unacceptable consequences. These scenarios are postulated without regard for existing design safety features. (See Figure 2 for an example of how the results from this step can be documented.)

3. Risk assessment. The scenarios developed in step 2 are individually assessed to determine (a) likelihood of occurrence (expressed as frequency of occurrence per year and defined per Table 3), and (b) severity of consequence as defined in Table 4. This assessment is made by considering both the cause(s) of the scenario (or initiating event(s)) and the hazardous material or energy released as a result of the scenario. A sample result from this step is presented in Figure 2. During this phase of the analysis, no credit is taken for preventive or mitigative features in reducing frequency or consequence, thereby focusing analysis on the hazards that are of the greatest concern.

4. Risk binning. Each hazard is plotted on the frequency/consequence matrix shown in Figure 3.

5. Graded approach. Hazards falling in the High and Moderate risk bins are carried forward for further analysis. Low- and negligible-risk hazards are addressed further as management/operational issues, but are excluded from further attention in the formal hazard/safety analysis work.

Table 2.--Example of a hazard iIdentification checklist (partial)

	Hazard Energy Sources and Materials																																
	Electrical																		Thermal								Friction						
Location (identifier for system, sub-system, or operational feature in this facility section)	Battery Banks (BB)	Cable Runs (CB)	Diesel Units (DU)	Electrical Equipment (EE)	Hot Plates (HP)	Heaters (HT)	High Voltage (HV, >220 v)	Locomotive, electrical (LE)	Motors (MT)	Pumps (PM)	Power Tools (PT)	Switchgear (SG)	Service Outlets, fittings (SO)	Transformers (TF)	Transmission Lines (TL)	Underground Wiring (UW)	Wiring (WR)	Other	Bunsen Burner, Hot Plate (BR)	Electrical Equipment (EE)	Furnaces (FR)	Heaters (HT)	Steam Lines (SL)	Welding Torch (WT)	Exothermic Reactions (ER)	Other	Belts (BL)	Bearings (BR)	Fans (FN)	Gears (GE)	Motors (MT)	Power Tools (PT)	Other
Working vehicle	X	-	-	X	X	-	1	X	X	X	X	-	X	X	2	-	X	3	-	X	-	-	-	X	4	5	X	X	X	X	X	X	X
Underground refueling operation	X	-	-	X	X	-	1	X	X	X	X	-	X	X	2	-	X	3	-	X	-	-	-	X	X	5	X	X	X	X	X	X	X
Refueling transport vehicle	X	-	-	X	X	-	1	X	X	X	X	-	X	X	2	-	X	3	-	X	-	-	-	X	4	5	X	X	X	X	X	X	X
Fuel transfer (not covered)																																	
Hydrogen mfg. (not covered)																																	

1. High Voltage (HV). Voltages above 1000 volts are typically not permitted in the underground environment. (There are exceptions for transmission lines. See the discussion in Coutts, 1998.) Thus, when the vehicles are underground, there is not exposure to these voltages. If the vehicles exit the mine, there is potential for overhead transmission lines that carry these voltages.
2. Transmission Lines (TL). There are instances where 4160 or 7200 volt transmission lines have been installed in mines. These insulated conductors have very limited protection from vehicle impact.
3. Other. Within the mine there is the potential for exposed conductors, which would be used to support trolley lines. Typically, these systems range from 300 to 600 volts DC.
4. Exothermic Reactions (ER). The hydrogen-oxygen reaction in the fuel cell is an exothermic reaction
5. Other. Brake disks on mining equipment can get hot and have been known to cause fires.

Event		Postulated event	Causes	Preventive features		Freq.	Method of	Mitigative features		Consequence level		Risk
no.	type	description		design	admin.	level	detection	design	admin.	people	property	bin #
1	E-1	Fire starts remote from vehicle and propagates to involve the hydrogen system. Hydrogen is released.	General fire hazards		Fire protection program	U	Visual, smell	Mine arrangement	Emergency team	H	H	4
2	E-1	Fire starts on vehicle, but not in hydrogen system. Hydrogen is released.	Hot brakes, electrical short	Fuses	Brake maintenance	U	Visual, smell	Vehicle design, suppression system	Emergency team	H	H	4
3	E-1	Fire starts in hydrogen components. Hydrogen is released	Hydrogen leak		Fire protection program	U	Visual, smell	Hydrogen system integrity	Emergency team	H	H	4
4	E-1	Coal dust ignition by vehicle electrical system. Hydrogen is released	Electrical contacts close	Classified equipment	Inspections	EU	Visual, heat	Mine arrangement	Coal dusting	H	H	7
5	E-2	Battery explosion damages hydrogen system causing leak.	Battery short	Design		U	Visual, equipment fails to run	Design		H	H	4
6	E-2	Fire starts remote from vehicle and involves hydrogen system. Hydride tank bursts.	General fire hazards	Relief protection	Fire protection program	EU1	Visual, smell	Mine design	Emergency team	H	H	7
7	E-2	Fire starts on vehicle, but not in hydrogen system. Hydride tank bursts.	General fire hazards	Relief protection	Fire protection program	EU	Visual, smell	Vehicle design, suppression system	Emergency team	H	H	7
8	E-2	Fire starts in hydrogen components. Hydride tank bursts.	Hydrogen leak	Relief protection	Fire protection program	EU	Visual, smell	Hydrogen system integrity	Emergency team	H	H	7
9	E-2	Hydrogen explosion	Delayed ignition after leak	Design of vehicle, ventilation		U	Visual	Hydride metal	Emergency team	H	H	7

Figure 2, Example hazard evaluation result

Table 3.--Frequency criteria used for risk binning

Acronym	Description	Frequency level
A	Anticipated, Expected	≤ 1E-02 /yr
U	Unlikely	1E-4 ≤ f < 1E-02 /yr
EU	Extremely Unlikely	1E-6 ≤ f 1E-04 /yr
BEU	Beyond Extremely Unlikely	< 1E-06 /yr

Table 4.--Consequence criteria used for risk binning

Consequence Level	Impact on Populace	Impact on Property/Operations
High (H)	Prompt fatalities, Acute injuries - immediately life threatening or permanently disabling	Damage > $1 million Vehicle destroyed & surrounding property damaged
Moderate (M)	Serious injuries, Permanent disabilities, Hospitalization required	$10,000 < damage < $1 million Vehicle destroyed Minor impact on surroundings
Low (L)	Minor injuries, No permanent disabilities, No hospitalization	Damage < $10,000 Reparable damage to vehicle, Significant operational down-time, No impact on surroundings
Negligible (N)	Negligible injuries	Minor repairs to vehicle required, Minimal operational down-time

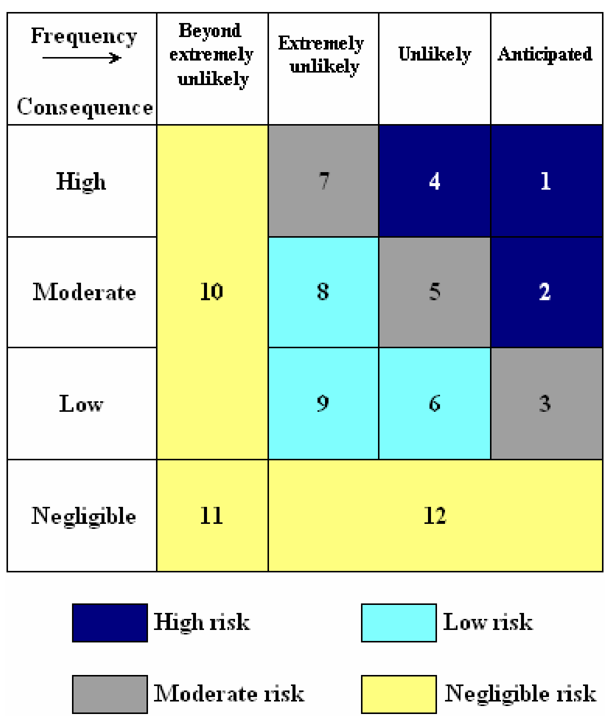

Figure 3, Functions of Integrated Safety Management

Conclusion

An overview of how the evolving codes and standards will define requirements has been presented. The paper then presents a method that a demonstration project can implement that will satisfactorily demonstrate compliance with new performance-based requirements, bridge gaps where existing standards don't provide coverage, and properly manage safety risk. The techniques, if properly implemented, can then reduce both project and fiscal risks.

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