Hydrogen Infrastructure Safety Technical Assessment and Research Results Gap Analysis

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13. ABSTRACT (Maximum 200 words)

Public acceptance of hydrogen as an energy carrier for transportation and power generation technologies will depend on confidence in the safety of vehicles and power systems, and supporting delivery and storage infrastructure. Ensuring safety of the infrastructure for transporting, storing, and delivering hydrogen will be critical to the successful implementation of a hydrogen economy.

Industry is developing new packaging technologies and delivery systems to increase the efficiency and reduce the cost of deploying hydrogen to consumer applications. Many technologies use new materials or operate at increased pressure over existing industrial applications of hydrogen.

To enable successful introduction of hydrogen into the marketplace, the development of appropriate technical codes, standards, and regulations providing high levels of safety and environmental protection should proceed in parallel with the substantial pace of new technology development. If appropriate codes and standards are not developed in pace with new technology, the risks are twofold:

1. The lack of appropriate safety requirements could result in delayed technology introduction, lowered technology adoption rates, or unnecessary additional costs to deploy new technologies.
2. Technologies could be introduced and adopted which, to some degree, pose unnecessary safety and/or property risks.

This report identifies gaps in the current hydrogen technology base, and recommends solutions to U.S. DOT for closing these gaps.

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NOTICE

NOTICE

Metric/English Conversion Factors

English to Metric

LENGTH (Approximate)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (Approximate)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS-WEIGHT (Approximate)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilograms (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (Approximate)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (Exact)

[(x - 32) (5 / 9)] °F = y °C
(x + 460) / 1.8 = y °K

PRESSURE (Exact)

1 psi = 6.8948 k Pa

ENERGY & ENERGY DENSITY (Exact)

1 Btu = 1.05506 kJ
1 Btu/lb = 2.326 kJ/kg

Metric to English

LENGTH (Approximate)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (Approximate)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (he) = 2.5 acres

MASS-WEIGHT (Approximate)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (Approximate)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)

1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 13 cubic yards (cu yd, yd^3)

TEMPERATURE (Exact)

[(9 / 5) y + 32] °C = x °F
(y x 1.8 B 460) = x °F

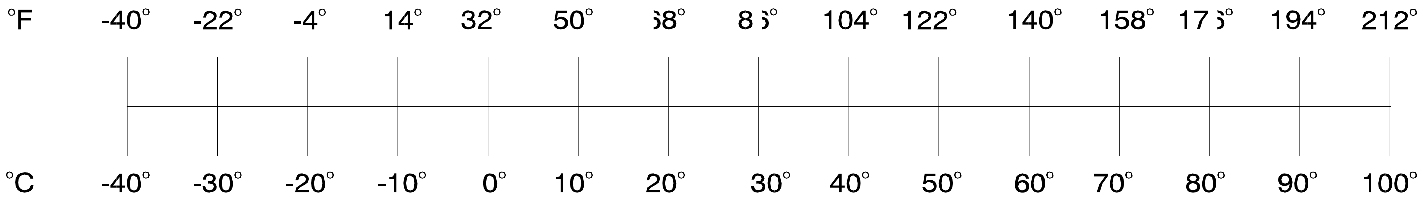
PRESSURE (Exact)

1 M Pa = 145.04 psi

ENERGY & ENERGY DENSITY (Exact)

1 MJ = 947.81 Btu
1 MJ/kg = 430 Btu/lb

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



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Executive Summary

Public acceptance of hydrogen as an energy carrier for transportation and power generation technologies will depend on the public's confidence in the safety of those vehicles and power systems as well as the supporting energy delivery and storage infrastructure. Ensuring the safety of the infrastructure for transporting, storing, and delivering hydrogen will be critical to the successful implementation of a hydrogen economy.

Industry has begun developing new packaging technologies and delivery systems—such as mobile refueling stations—to increase the efficiency and reduce the cost of deploying hydrogen to end use consumer applications. Many of these technologies involve packaging that uses new materials or operates at increased pressure over existing industrial applications.

To enable successful introduction of hydrogen and fuel cells into the marketplace, the development of appropriate technical codes, standards, and regulations providing high levels of safety and environmental protection should proceed in parallel with the substantial pace of new technology development that is underway. If appropriate technical codes, standards, and regulations are not developed in pace with new technology development, the risks are twofold:

1. The lack of appropriate safety requirements could result in delayed technology introduction, lowered technology adoption rates, or unnecessary additional costs to deploy new technologies.
2. Technologies could be introduced and adopted which, to some degree, pose unnecessary safety and/or property risks.

The purpose of this project is to identify gaps in the current hydrogen technology base and to recommend solutions for closing these gaps.

The study used a hazard assessment-like procedure that incorporated the following steps:

1. Identifying the Key Areas required for a safe hydrogen economy and their criticality.
2. Assessing the state of these Key Areas:
    - Identifying that the important factors have been or are being addressed.

    - Determining if prior work is still applicable or if recent breakthroughs or observations render the prior work obsolete.
3. Identifying and prioritizing priority “gaps” and highlight areas that warrant further study
4. Developing recommendations for Key Areas, including research, studies, or trials that could close gaps and resolve shortcomings in understanding all aspects of safe hydrogen gas operations in consumer end-use environment.

Each Key Area was assigned a criticality and progress categorization. Criticality was categorized as high, medium, or low while the state of progress used the following categories:

- Fully Addressed: technology is mature and safety procedures (not necessarily regulations) are established.
- Addressed, Monitoring: technical work is well underway and safety procedures are reasonably well developed.
- Addressed, Not Adequately: technical work has started and safety procedures are under development.
- Not Addressed: no progress, or efforts are only identified or getting organized.

Criticality and progress were assigned weights and the score for each Key Area is then calculated as the product of criticality and progress weights. The Key Areas were also divided into three groups—Pipeline (continuous transport), Transport (discrete transport), and Crosscut (areas which affect both pipeline and transport). The Crosscut group largely dealt with material and environmental issues, such as embrittlement, strength and fatigue, pressure and temperature, etc. The timeframe for initiation of efforts to address issues was also assessed. This is not necessarily the same as the timeframe at which it is anticipated that the technology will be widely deployed.

A total of 86 Key Area items were assessed: 8 Crosscut, 47 Pipeline, and 31 Transport. In terms of criticality, 64 items were assessed High, 21 Medium, and 1 Low. All of the Crosscut items were assessed at High criticality, largely because material and environmental issues potentially impact a number of transportation technologies.

In terms of progress, 37 Key Areas have progress assessments of Not Addressed, 47 Addressed, Not Adequately, and 2 Addressed, Monitoring. Most of the Crosscut items have progress assessments of Addressed, Not Adequately as there are a number of material and environmental efforts underway, but most are in their early stages or are just getting underway. The Pipeline group is more evenly divided between Not Addressed and Addressed, Not Adequately while Transport has fewer Not Addressed compared to Addressed, Not Adequately.

The distribution of scores—the product of the weights of criticality and progress—is 29 scores of 40, 8 scores of 24, 33 scores of 20, with the rest at 12 or below. A score of 40 represents a combination of High criticality and progress of Not Addressed. A score of 24 represents a combination of Medium criticality and progress of Not Addressed. A score of 20 represents a combination of High criticality and progress of Addressed, Not Adequately. The Pipeline group has the highest number of 40 scores, also representing the largest Key Area count for the scores both within the Pipeline and overall. The Crosscut group is mostly 20 scores, reflecting the progress assessment distribution for those items. For Transport, nearly half the items have 20 scores (High criticality and progress of Addressed, Not Adequately) as these items tend to be areas where applicable safety practices could be adapted to new transport technologies.

In terms of timeframe, 62 Key Areas have assessments of 0 to 5 years and 24 of 5 to 15 years. All the Crosscut items are short term while 60% to 80% of the Pipeline and Transport items, respectively, are short term. Most needs are short term, either because the technologies are currently or shortly being deployed or because there is a long lead-time anticipated for development of safety practices for the item.

Examining the combination of score and timeframe, there are 20 items in the short term with scores of 40, 3 items with scores of 24, and 29 items with scores of 20.

Specific recommendations are found in each Key Area Item Assessment.

List of Acronyms

Organizations and Facilities

ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
CaFCP	California Fuel Cell Partnership
CGA	Compressed Gas Association
CSA	CSA America
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
GTI	Gas Technology Institute
ICAO	International Civil Aviation Organization
ICC	International Code Council
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JARI	Japanese Auto Research Institute
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
NACE	NACE International
NASFM	National Association of State Fire Marshals
NFPA	National Fire Protection Association
NHA	National Hydrogen Association
NREL	National Renewable Energy Laboratory
OHMS	Office of Hazardous Materials Safety
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RITA	Research and Innovative Technologies Administration
SAE	Society of Automotive Engineers
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
UIUC	University of Illinois at Urbana-Champaign
UL	Underwriters Laboratories Inc.
UN SCETDG	UN Sub-Committee of Experts for the Transport of Dangerous Goods

Technical Terminology

HAZ	Heat affected zone
MAOP	Maximum allowable operating pressure
ORM	Other regulated materials
ORM-D	Other regulated materials, domestic
PRD	Pressure relief device
RTP	Reinforced thermoplastic pipe
SMYS	Specified minimum yield strength

Other Acronyms

AHJ	Authority having jurisdiction (local inspector or marshal)
CDO	Codes developing organization
CFR	Code of Federal Regulations
HMR	Hazardous Materials Regulations
ORM	Other regulated materials
ORM-D	Other regulated materials, domestic
SDO	Standards developing organization

Commonly Referenced Documents

ASME B31.1: Standards of Pressure Piping - Power Piping

This code prescribes minimum requirements for the design, materials, fabrication, erection, test, and inspection of power and auxiliary service piping systems for electric generation stations, industrial institutional plants, central and district heating plants.

ASME B31.3: Standards of Pressure Piping - Process Piping

Rules for this section have been developed considering piping typically found in petroleum refineries; chemical, pharmaceutical, textile, paper, semiconductor and cryogenic plants; and related processing plants and terminals.

ASME B31.8: Standards of Pressure Piping - Gas Transmissions and Distribution Piping Systems

This code covers the design, fabrication, installation, inspection, testing, and safety aspects of operation and maintenance of gas transmission and distribution systems, including gas pipelines, gas compressor stations, gas metering and regulation stations, gas mains, and service lines up to the outlet of the customers meter set assembly.

ASME B31.8S: Standards of Pressure Piping - Managing System Integrity of Gas Pipelines

This standard applies to on-shore pipeline systems constructed with ferrous materials and that transport gas. The principals and processes embodies in integrity management are applicable to all pipeline systems.

ASME B31.12 : Standards of Pressure Piping - Hydrogen Piping and Pipelines

This standard activity has been formed to develop a new code for hydrogen piping and pipelines that contains requirements specific to hydrogen service in power, process, transportation, distribution, commercial, and residential applications. It will include equivalent information found in B31.3, B31.8, and NFPA 54 for natural gas.

ASME B31Q: Standard on Pipeline Personnel Qualification

This standard is anticipated to address issues such as methods for determining applicable tasks, initial qualification and reevaluation methods and intervals, required personnel qualification program elements, applicable definitions, abnormal operating conditions, record keeping, and management of change.

Introduction

The success of the President's vision for a hydrogen economy will rely largely on the capability of a multi-modal hydrogen delivery infrastructure to supply needed quantities of hydrogen at competitive costs. Concurrently, there needs to be sufficient demand for fuel cell and other hydrogen-powered vehicles and power generation devices. Public acceptance of this new transportation and power technology will depend on the public's confidence in the safety of those vehicles and power systems, as well as their supporting energy delivery and storage infrastructure.

The infrastructure to support hydrogen fuels production, distribution, storage, and delivery to hydrogen-powered vehicles and power generation devices will likely evolve in stages. In the near term, a transition to a hydrogen economy can be expected to rely on an infrastructure that supports on-site production of hydrogen, limited use of regional hydrogen pipelines for large industrial users, and some shipments of hydrogen by highway and other selected transportation modes. Future distribution and delivery systems will be determined by market forces and the technologies to support them, but could be expected (at sufficient levels of demand) to evolve towards an efficient and extensive pipeline delivery network similar to natural gas.

Ensuring the safety of the infrastructure for transporting, storing, and delivering hydrogen will be critical to the success of a hydrogen economy, as demand increases during the transition from industrial hydrogen (used mainly for hydrogen's chemical attributes) to more widespread consumer applications based on hydrogen as an energy carrier.

For example, the current U.S. Department of Transportation (DOT) packaging system which addresses small-scale use of hydrogen may require substantial modifications to accommodate increased hydrogen demand. There is already evidence that even a small variance in demand due to evolving changes in technologies will have significant implications for the existing hydrogen transportation infrastructure.

In support of demonstration activities, industry has begun developing new packaging technologies and delivery systems—such as mobile refueling stations—to increase the efficiency and reduce the cost of deploying hydrogen to consumer end use applications. Many of these technologies involve packaging that uses new materials or operates at increased pressure over traditional industrial uses. DOT has regulatory responsibility for the validation, testing, and certification of many such new uses under the Hazardous Materials Regulations, as a prerequisite for deploying them in transportation. DOT is already experiencing an increased need for R&D in order to keep pace with and respond to industry requirements and innovation. This demand on regulatory resources is expected to grow in advance of the commercialization of hydrogen-powered vehicles, the growing use of novel portable fuel cell power devices, and the expansion of the hydrogen delivery and storage infrastructure.

To enable successful introduction of hydrogen and fuel cells into the marketplace, the development of appropriate technical codes, standards, and regulations providing high levels of safety and environmental protection should proceed in parallel with the substantial pace of new technology development that is underway. This development process requires a sound technology base. If appropriate technical codes, standards, and regulations are not developed in pace with new technology development, the risks are twofold:

1. The lack of appropriate safety requirements could result in delayed technology introduction, lowered technology adoption rates, or unnecessary additional costs to deploy new technologies.
2. Technologies could be introduced and adopted which, to some degree, pose unnecessary safety and/or property risks.

The purpose of this project is to identify gaps in the current hydrogen technology base and to recommend solutions for closing these gaps.

Work Plan

Any analysis of gaps or future technology needs for hydrogen distribution, transportation, and storage must encompass both centralized manufacture at sites remote from the user points (these could include large central station plants or midsize plants for regional markets) and distributed manufacture at the vehicle fueling facilities.

The study used a hazard assessment-like procedure that incorporated the following steps:

1. Identifying the Key Areas required for a safe hydrogen economy, and their criticality.
2. Assessing the state of these Key Areas:
    - Identify that the important factors have been or are being addressed.
    - Determine if prior work is still applicable or if recent breakthroughs or observations render the prior work obsolete.
3. Identifying and prioritizing “gaps” and highlight areas that warrant further study.
4. Developing recommendations for Key Areas, including research, studies, or trials that could close gaps and resolve shortcomings in understanding all aspects of safe hydrogen gas operations.

Although there may be considerable differences in “how” certain practices are performed, the general approach to design, construction, and operation of hydrogen pipelines is expected to be similar to standards and procedures for natural gas pipeline operations. Therefore, current DOT Safety Regulations were used as a reference for identifying a number of Key Areas.

Other resources, such as ASME Codes, the National Academy of Science (NAS) report *The Hydrogen Economy*, NASA’s *Safety Standard for Hydrogen and Hydrogen Systems*, the DOT Hydrogen Portal, DOE Hydrogen Program activities (particularly work underway at Sandia National Laboratories and the Hydrogen Pipeline Steering Group of which GTI is a member), and the comprehensive volume of related research performed by GTI was used to establish the comprehensive list of Key Areas.

The overall process for the analyses is depicted graphically in Figure 1. The bottom of this figure shows a matrix that was developed for facilitating the identification, filtering, and prioritization of Key Areas. Criticality was categorized as high, medium, or low while the state of progress used the following categories:

- Fully Addressed: technology is mature and safety procedures (not necessarily regulations) are established.
- Addressed, Monitoring: technical work is well underway and safety procedures are reasonably well developed.
- Addressed, Not Adequately: technical work has started and safety procedures are under development.
- Not Addressed: no progress, or efforts are only identified or getting organized.

Criticality and progress were assigned weights as indicated in the following table. The score for each Key Area was then calculated as the product of criticality and progress weights. Non-linear weighting was employed to emphasize the Not Adequately Addressed and Not Addressed progress categories.

	Description	Weight
Criticality	High	5
	Medium	3
	Low	1
Progress	Fully Addressed	1
	Addressed, Monitoring	2
	Addressed, Not Adequately	4
	Not Addressed	8

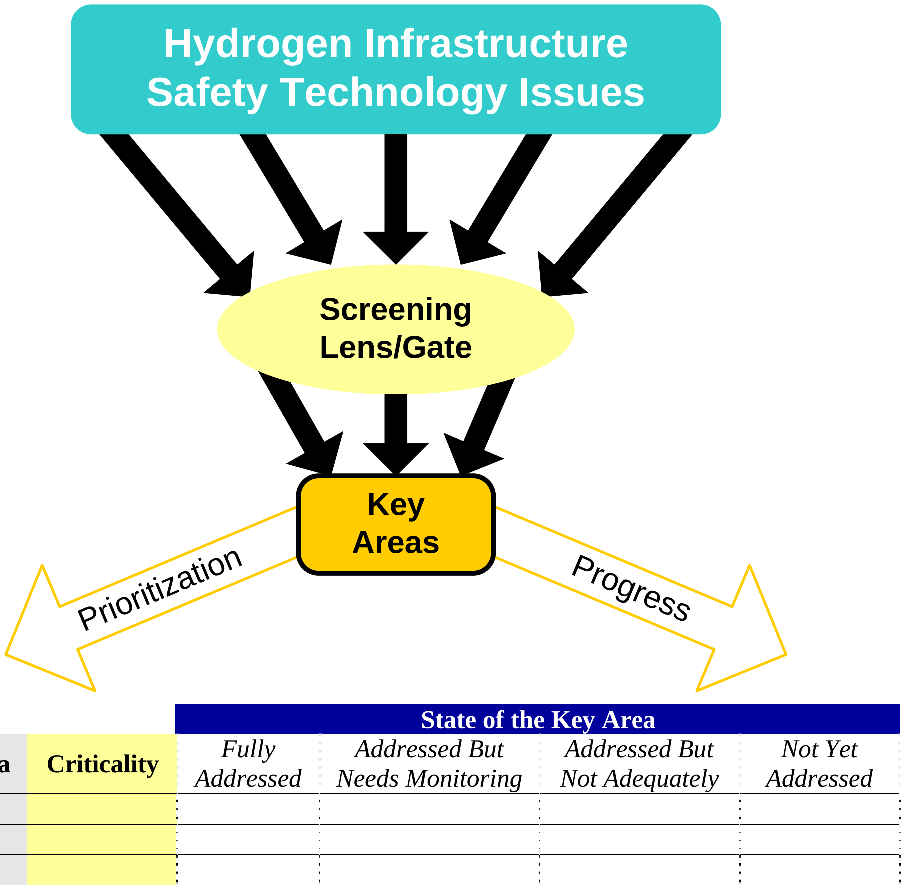


Figure 1. Analysis Process Schematic

The anticipated deployment scope for technology categories was considered in formulating recommendations. The assessment of deployment scope was represented in the Usage Matrix in Figure 2. The matrix identifies categories of hydrogen transport technologies from high pressure gas to developing technologies such as hydrides and physisorption materials. The columns of the matrix identify the scale of transport from pipeline at the large end to small-scale (man portable) systems at the small end. Bulk and non-bulk are defined regulatory terms. From 49 CFR 171.8:

> Bulk packaging means a packaging, other than a vessel or a barge, including a transport vehicle or freight container, in which hazardous materials are loaded with no intermediate form of containment and which has:
>
> (1) A maximum capacity greater than 450 L (119 gallons) as a receptacle for a liquid;

> (2) A maximum net mass greater than 400 kg (882 pounds) and a maximum capacity greater than 450 L (119 gallons) as a receptacle for a solid; or
> (3) A water capacity greater than 454 kg (1000 pounds) as a receptacle for a gas as defined in §173.115 of this subchapter.

At each intersection of technology and scale is an indication of the likelihood of that technology being used at that scale.

The timeframe matrix in Figure 3 uses the same overall structure, but with each intersection indicating the recommended timeframe in which the issues associated with the technology at that scale need to begin being addressed. This is not necessarily the same as the timeframe at which it is anticipated that the technology will be widely deployed. The timeframe coding is also shown for each Key Area in the Master Item Table below.

The analysis of each Key Area is presented in a consistent format which encompasses a description of the Key Area, a discussion of criticality, a discussion of progress, and finally recommendations. A number of Key Areas have similarities and therefore similar discussion. While this can lead to some repetitiveness when reading multiple Key Area assessments, the benefit is that each assessment can largely be read and understood in isolation.

This work was conducted by a multi-faceted implementation team, with oversight provided by a highly experienced and diverse expert panel. The expert panel provided high-level input on the direction of this study while providing review of interim and draft final documents. The implementation team consisted of Gas Technology Institute, Lincoln Composites (Dr. Norm Newhouse), Proteus Services Group (Dr. Ned Stetson), and St. Croix Research (Mr. Charles Powars).

The following individuals served on the Expert Panel for this effort: Addison Bain (NASA, retired), Jim Campbell (Air Liquide), Don Cook (California Department of Industrial Relations), David Haberman (IF, LLC), John Koehr (ASME), George Parks (ConocoPhillips), and Ralph Tribolet (Linde, retired). The panel members represent the breadth of hydrogen economy participants—from technology developers, industrial gas and energy companies, standards developing organizations, and public safety officials. Additional commentary was provided by Mr. Louis Hayden, chairman of the ASME B31.12 Hydrogen Piping and Pipelines Project Team.

Increasing Public Interaction →

Usage Matrix

Existing/Likely Use ●
Possible/Unlikely Use ○

	Pipeline	Bulk	Non-bulk	Small Scale
HP Gas: Metallic	●	●	●	
HP Gas: Composite	●	●	●	
Cryogenic		●	○	
Metal Hydride			●	●
Cryogas		●	○	
Physisorption			●	●
Complex Hydrides			●	●
Reactives	●	●	●	●

Figure 2. Usage Matrix

Timeframe Matrix

Short Term (0-5 yrs) ●
Long Term (5-15 yrs) ○

	Pipeline	Bulk	Non-bulk	Small Scale
HP Gas: Metallic	●	●	●	
HP Gas: Composite	○	●	●	
Cryogenic		●	○	
Metal Hydride			●	●
Cryogas		○	○	
Physisorption			○	○
Complex Hydrides			○	○
Reactives	○	○	○	●

Figure 3. Timeframe Matrix

Summary of Findings

The Master Item Table which appears below lists each of the Key Areas assessed. A number of Key Areas were divided into sub areas. The Key Areas were also divided into three groups—Pipeline (continuous transport), Transport (discrete transport), and Crosscut (areas which affect both pipeline and transport). The Crosscut group largely dealt with material and environmental issues, such as embrittlement, strength and fatigue, pressure and temperature, etc.

A total of 86 Key and Sub Areas items were assessed. This number fluctuated somewhat as the effort progressed as new items were identified or eliminated and existing items were subdivided or consolidated. Of the 86 items, 8 are Crosscut, 47 Pipeline, and 31 Transport.

In terms of criticality, 64 items are assessed High, 21 Medium, and 1 Low. These are divided across the groups as shown in Figure 4. All of the Crosscut items are assessed as High, largely because material and environmental issues potentially impact a number of transportation technologies. Several Low items were dropped from the analysis at an early stage as their combination of Low criticality and level of progress yielded low scores which did not warrant further effort.

In terms of progress, 37 Key Areas have progress assessments of Not Addressed, 47 Addressed, Not Adequately, and 2 Addressed, Monitoring. These are divided across the groups as shown in Figure 5. Most of the Crosscut items have progress assessments of Addressed, Not Adequately as there are a number of material and environmental efforts underway but most are in their early stages or are just getting underway. The Pipeline group is more evenly divided between Not Addressed and Addressed, Not Adequately while Transport has fewer Not Addressed compared to Addressed, Not Adequately.

The distribution of scores—the product of the weights of criticality and progress—is shown in Figure 6. There are 29 scores of 40, 8 scores of 24, and 33 scores of 20. A score of 40 represents a combination of High criticality and progress of Not Addressed. A score of 24 represents a combination of Medium criticality and progress of Not Addressed. A score of 20 represents a combination of High criticality and progress of Addressed, Not Adequately.

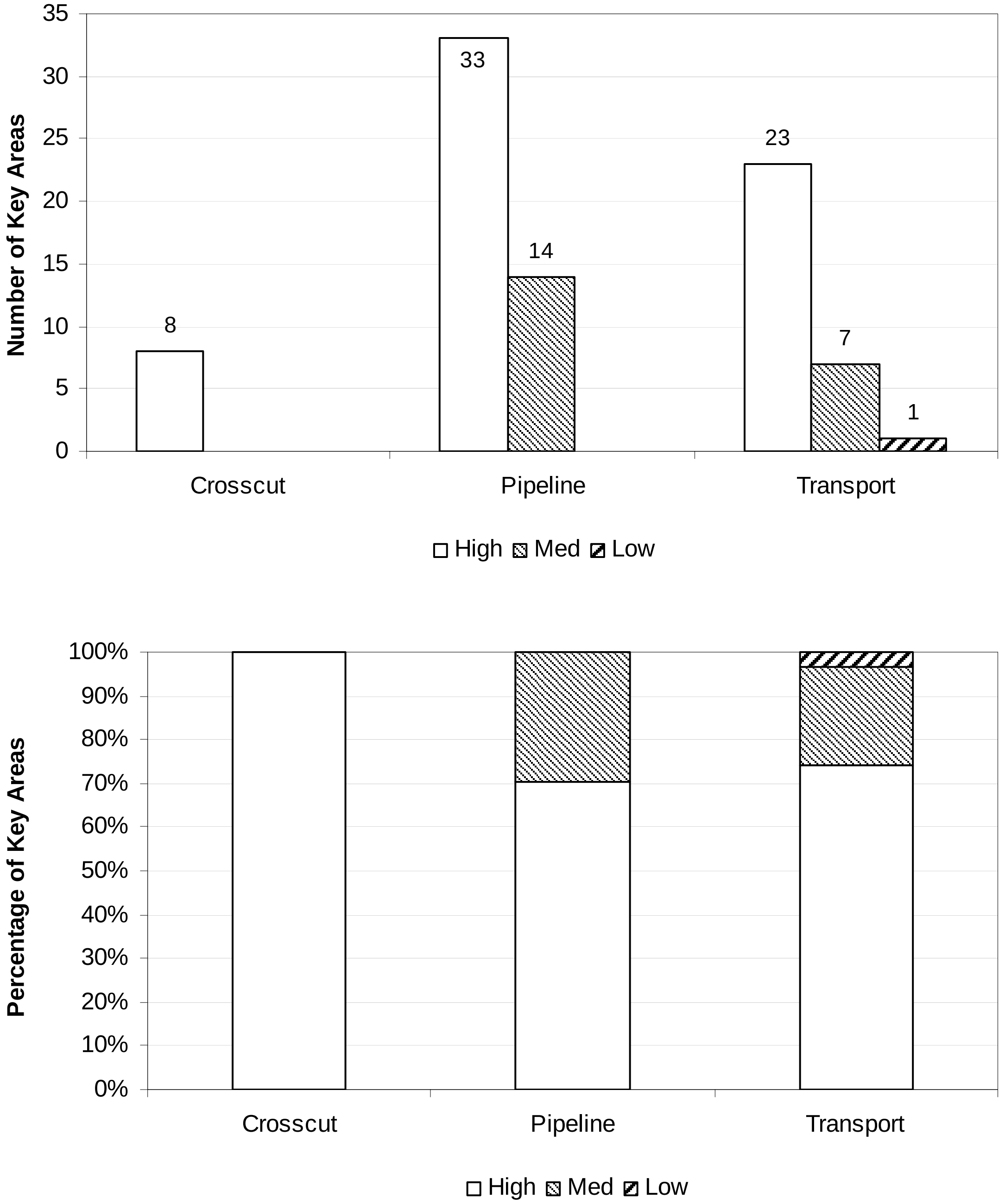


Figure 4. Distribution of Criticality

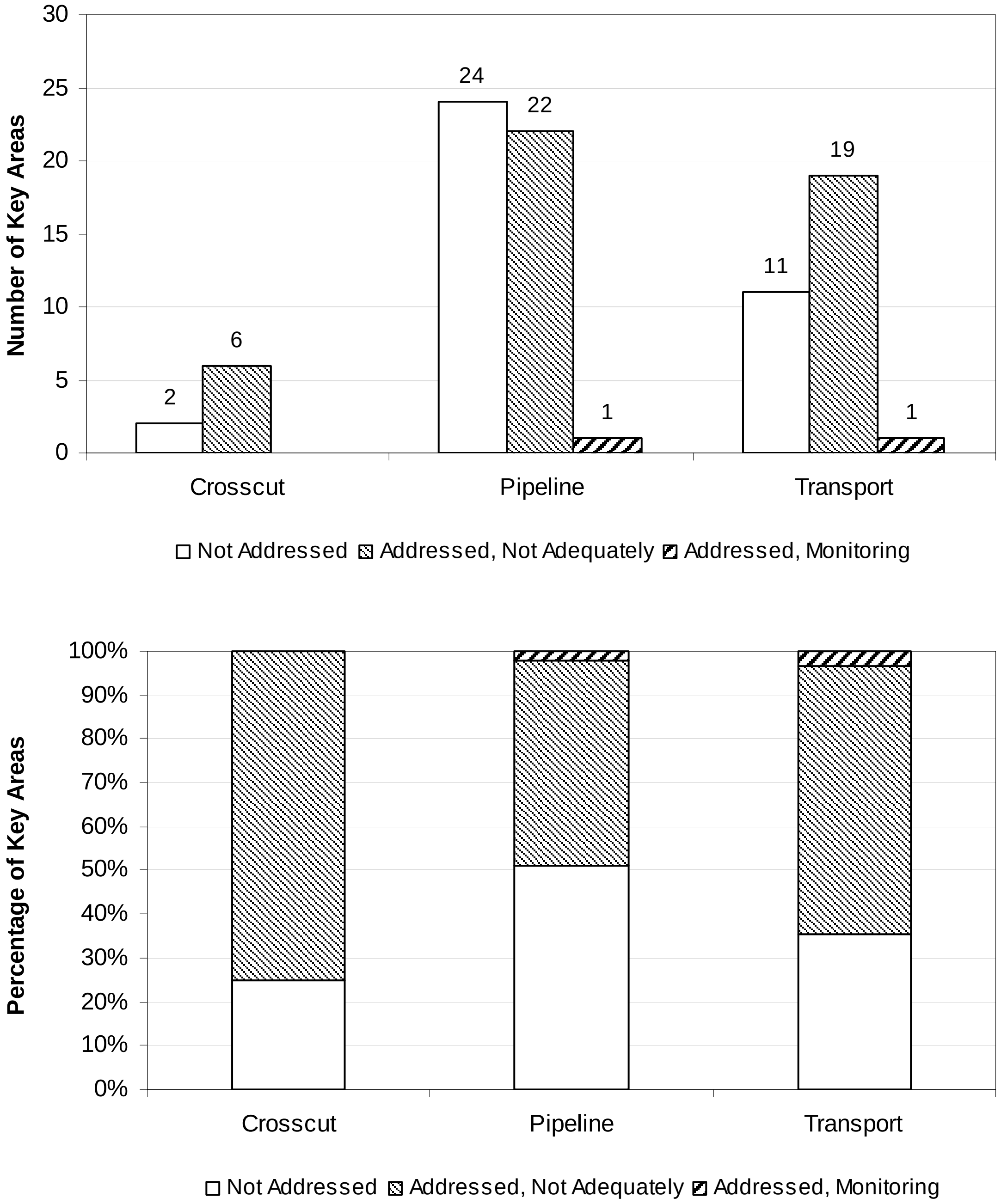
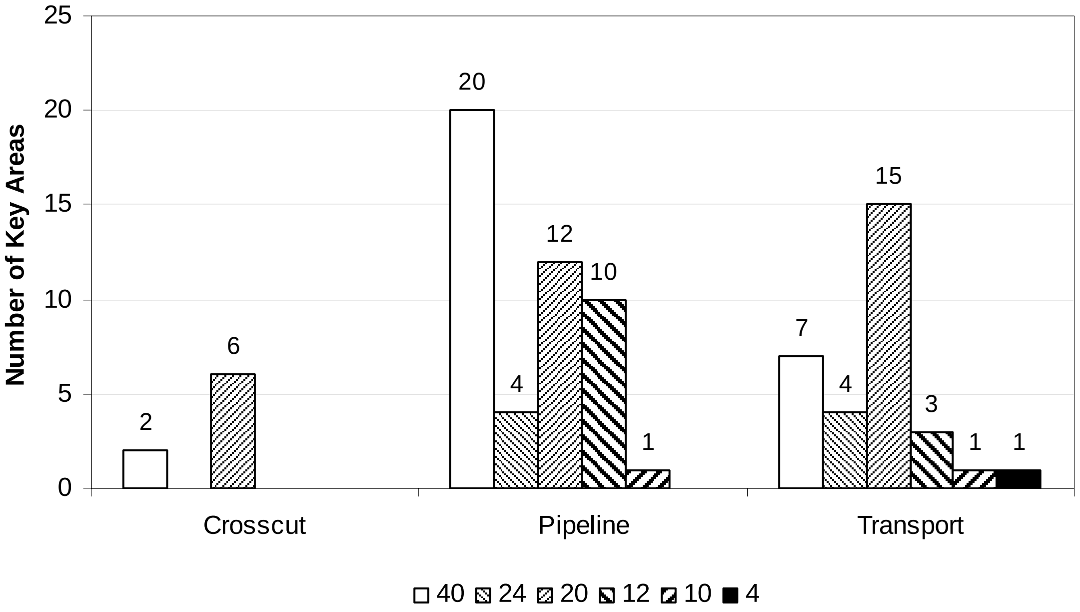


Figure 5. Distribution of Progress



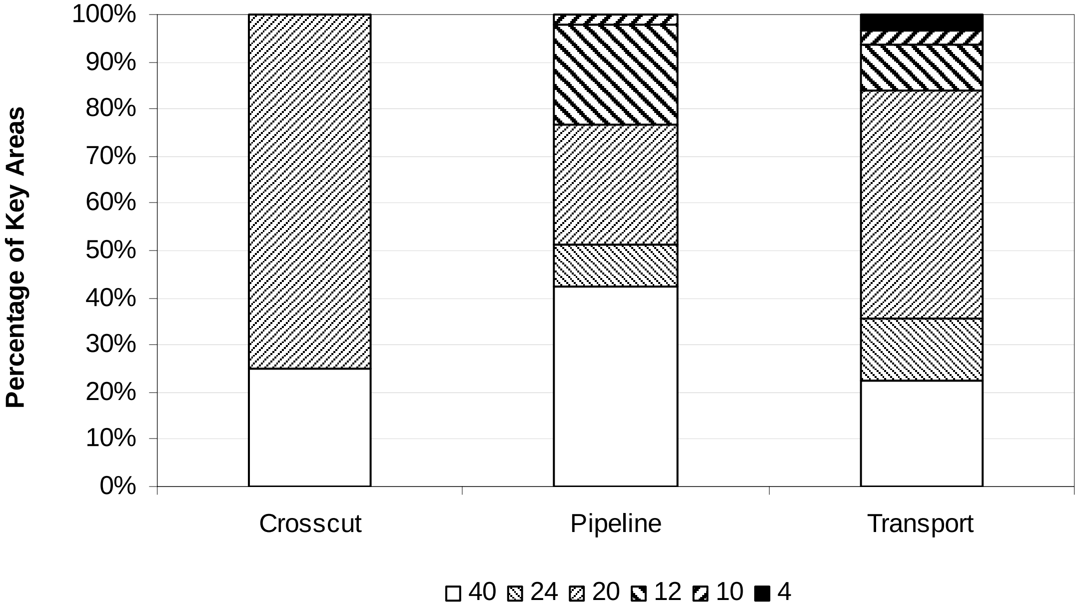


Figure 6. Distribution of Scores

The Pipeline group has the highest number of 40 scores, also representing the largest Key Area count for the scores both within the Pipeline and overall. The Crosscut group is mostly 20 scores, reflecting the progress assessment distribution for those items. For Transport, nearly half the items have 20 scores (High criticality and progress of Addressed, Not Adequately) as these items tend to be areas where applicable safety practices could be adapted to new transport technologies.

In terms of timeframe, 62 Key Areas have assessments of 0 to 5 years and 24 of 5 to 15 years. These are divided across the groups as shown in Figure 7. All the Crosscut items are short term while 60% to 80% of the Pipeline and Transport items, respectively, are short term. Most short term needs are either because the technologies are currently or shortly being deployed or because there is a long lead-time anticipated for development of safety practices for the item.

Examining the combination of score and timeframe, the distribution of items appears in Figure 8. There are 20 items in the short term with scores of 40, 3 items with scores of 24, and 29 items with scores of 20. The short term items with scores of 40 appear in Table 1, those with scores of 24 appear in Table 2, and those with scores of 20 appear in Table 3.

The average score within each group are approximately equal, with the average for Crosscut at 25, Pipeline at 27, and Transport at 23.

Specific recommendations are found in each Key Area Item Assessment. The Master Item Table below identifies each item with its criticality and progress assessments.

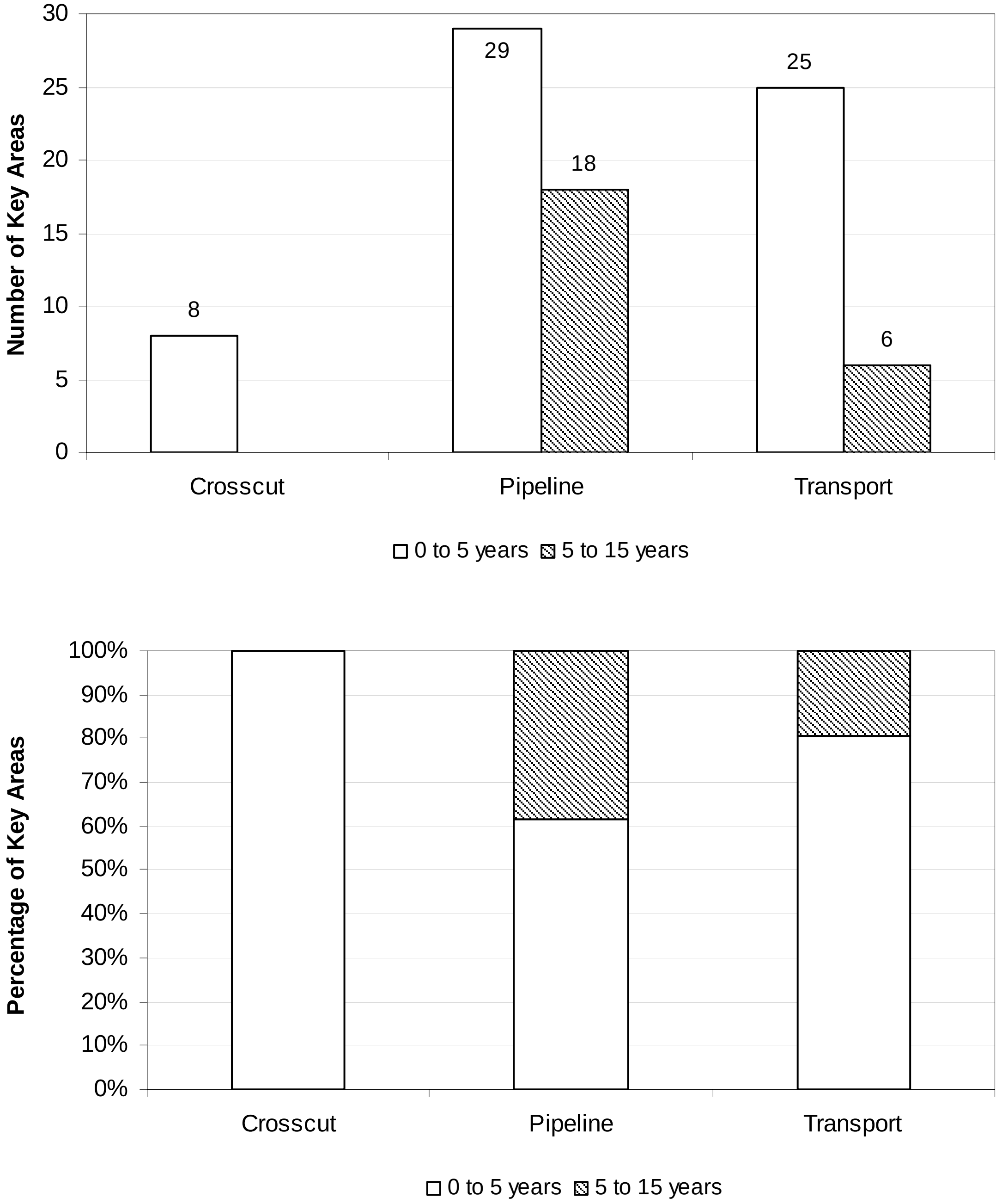


Figure 7. Distribution of Timeframes

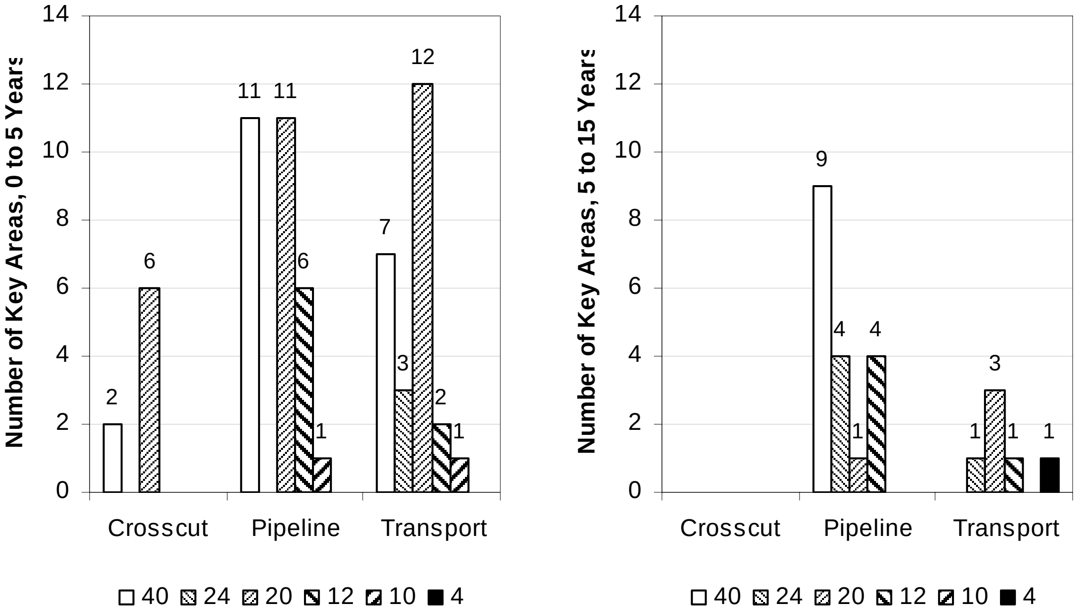


Figure 8. Distribution of Scores by Timeframe

Table 1. Short Term Items with Scores of 40

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed
1	Crosscut			Materials Compatibility					
1.5	Crosscut	●	40	Pressure and Temperature Interactions	High				X
1.8	Crosscut	●	40	Loss of Fatigue and Impact Strength	High				X
4	Pipeline	●	40	Conversion to Service	High				X
10	Pipeline	●	40	Joining Other than Welding	High				X
15	Pipeline	●	40	Uprating	High				X
16	Pipeline			Operations					
16.11	Pipeline	●	40	Odorization of Gas	High				X
16.12	Pipeline	●	40	Tapping Pipelines Under Pressure	High				X
16.13	Pipeline	●	40	Purging of Pipelines	High				X
17	Pipeline			Maintenance					
17.2	Pipeline	●	40	Transmission Lines: Leakage Surveys	High				X
17.5	Pipeline	●	40	Distribution Systems: Leakage Surveys	High				X
17.13	Pipeline	●	40	Prevention of Accidental Ignition	High				X
17.14	Pipeline	●	40	Qualification of Pipeline Personnel	High				X
17.15	Pipeline	●	40	Pipeline Integrity Management	High				X
18	Transport			Hazard and Packaging Class for Hydrides, Cryogas, Physisorption, Reactives					
18.2	Transport	●	40	Packaging Instructions for Micro Metal Hydride Hydrogen Storage Systems	High				X
18.3	Transport	●	40	Packaging Instructions for Portable Metal Hydride Hydrogen Storage Systems	High				X
25	Transport			Container Specifications					
25.1	Transport	●	40	Container Specifications for Composite Storage	High				X
25.2	Transport	●	40	Container Specifications For Metal Hydride Based Storage	High				X
29	Transport	●	40	Mobile Fuelers, Treatment of Gas Storage Containers	High				X
30	Transport			Aircraft Carriage					
30.1	Transport	●	40	Aircraft Carriage: Hydride Systems	High				X
30.2	Transport	●	40	Aircraft Carriage: Hydride Systems in Appliances	High				X

Table 2. Short Term Items with Scores of 24

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed
23	Transport	●	24	Filling and Purging Requirements for High Pressure Containers	Med				X
24	Transport	●	24	Loading and Unloading Requirements for Composite Containers	Med				X
25	Transport			Container Specifications					
25.3	Transport	●	24	Container Specifications For Reactive Type Storage	Med				X

Table 3. Short Term Items with Scores of 20

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed
1	Crosscut	▨	▨	Materials Compatibility					
1.1	Crosscut	●	20	Embrittlement	High			X	
1.2	Crosscut	●	20	Purity Effects	High			X	
1.3	Crosscut	●	20	Pressure Level	High			X	
1.4	Crosscut	●	20	Temperature Range	High			X	
1.6	Crosscut	●	20	Testing Methods	High			X	
1.7	Crosscut	●	20	Higher Strengths	High			X	
7	Pipeline	●	20	Pipe Design	High			X	
8	Pipeline	●	20	Pipeline Component Design	High			X	
9	Pipeline	●	20	Welding of Steel	High			X	
11	Pipeline	●	20	Construction Requirements	High			X	
14	Pipeline	▨	▨	Test Requirements					
14.2	Pipeline	●	20	Tensile Tests	High			X	
14.3	Pipeline	●	20	K_{IH} and K_{IC} Stress Intensity Factors	High			X	
14.4	Pipeline	●	20	Fatigue Crack Growth	High			X	
14.5	Pipeline	●	20	Burst	High			X	
16	Pipeline	▨	▨	Operations					
16.8	Pipeline	●	20	Maximum Allowable Operating Pressure: Steel and Polyethylene Pipelines	High			X	
17	Pipeline	▨	▨	Maintenance					
17.3	Pipeline	●	20	Transmission Lines: Repair of Leaks, Welds, etc.	High			X	
17.9	Pipeline	●	20	Compressor Stations: Gas Detection	High			X	
18	Transport	▨	▨	Hazard and Packaging Class for Hydrides, Cryogas, Physisorption, Reactives					
18.4	Transport	●	20	Reactive Hydrogen Storage May Be Mixtures	High			X	
19	Transport	▨	▨	Emergency Response					
19.2	Transport	●	20	Emergency Response Information: High Pressure Gas, Composite	High			X	
19.3	Transport	●	20	Emergency Response Information: Cryogenic	High			X	
19.4	Transport	●	20	Emergency Response Information: Metal Hydride	High			X	
19.8	Transport	●	20	Emergency Response Information: Reactive (Including Methanol)	High			X	
20	Transport	●	20	Training	High			X	
26	Transport	●	20	Composite/Novel Media Tube Trailer Specifications	High			X	
31	Transport	●	20	Pressure Relief Devices: High Pressure	High			X	
32	Transport	●	20	Pressure Relief Valves: High Pressure	High			X	
33	Transport	●	20	Valves: High Pressure	High			X	
34	Transport	●	20	Welding	High			X	
35	Transport	●	20	Tubing and Fittings: High Pressure	High			X	

Master Item Table

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed	Notes
1	Crosscut			Materials Compatibility						
1.1	Crosscut	●	20	Embrittlement	High			X		
1.2	Crosscut	●	20	Purity Effects	High			X		
1.3	Crosscut	●	20	Pressure Level	High			X		
1.4	Crosscut	●	20	Temperature Range	High			X		
1.5	Crosscut	●	40	Pressure and Temperature Interactions	High				X	
1.6	Crosscut	●	20	Testing Methods	High			X		
1.7	Crosscut	●	20	Higher Strengths	High			X		
1.8	Crosscut	●	40	Loss of Fatigue and Impact Strength	High				X	
2	Pipeline			Hydrogen Piping and Pipelines Codes and Standards						A
3	Pipeline	○	40	Class Locations	High				X	
4	Pipeline	●	40	Conversion to Service	High				X	
5	Pipeline	○	24	Customer Notification	Med				X	
6	Pipeline	○	24	Composite Reinforced Pipe	Med				X	
7	Pipeline	●	20	Pipe Design	High			X		A
8	Pipeline	●	20	Pipeline Component Design	High			X		
9	Pipeline	●	20	Welding of Steel	High			X		
10	Pipeline	●	40	Joining Other than Welding	High				X	
11	Pipeline	●	20	Construction Requirements	High			X		
12	Pipeline	○	24	Customer Meters, Regulators, and Service Lines	Med				X	
13	Pipeline	○	40	Corrosion Control	High				X	
14	Pipeline			Test Requirements						
14.1	Pipeline	●	10	ASTM F519 Hydrogen Embrittlement Test	High		X			
14.2	Pipeline	●	20	Tensile Tests	High			X		
14.3	Pipeline	●	20	K_{IH} and K_{IC} Stress Intensity Factors	High			X		
14.4	Pipeline	●	20	Fatigue Crack Growth	High			X		
14.5	Pipeline	●	20	Burst	High			X		
14.6	Pipeline	○	20	Composite Pipe	High				X	
14.7	Pipeline	○	40	Plastic Pipe	High				X	
15	Pipeline	●	40	Uprating	High				X	
16	Pipeline			Operations						
16.1	Pipeline	○	20	Procedural Manual for Operations, Maintenance, and Emergencies	High			X		
16.2	Pipeline	○	40	Change in Class Location	High				X	
16.3	Pipeline	○	40	Continuing Surveillance	High				X	
16.4	Pipeline	○	40	Damage Prevention Program	High				X	
16.5	Pipeline	●	12	Emergency Plans	Med			X		
16.6	Pipeline	○	24	Public Education: Emergencies	Med				X	
16.7	Pipeline	○	40	Investigation of Failures	High				X	
16.8	Pipeline	●	20	Maximum Allowable Operating Pressure: Steel and Polyethylene Pipelines	High			X		
16.9	Pipeline	●	12	Maximum Allowable Operating Pressure: High Pressure Distribution Systems	Med			X		
16.10	Pipeline	○	12	Maximum And Minimum Allowable Operating Pressure: Low Pressure Distribution Systems	Med			X		
16.11	Pipeline	●	40	Odorization of Gas	High				X	
16.12	Pipeline	●	40	Tapping Pipelines Under Pressure	High				X	
16.13	Pipeline	●	40	Purging of Pipelines	High				X	
17	Pipeline			Maintenance						
17.1	Pipeline	○	12	Transmission Lines: Patrolling	Med			X		
17.2	Pipeline	●	40	Transmission Lines: Leakage Surveys	High				X	B
17.3	Pipeline	●	20	Transmission Lines: Repair of Leaks, Welds, etc.	High			X		
17.4	Pipeline	○	12	Distribution Systems: Patrolling	Med			X		
17.5	Pipeline	●	40	Distribution Systems: Leakage Surveys	High				X	B

Hydrogen Infrastructure Safety Technical Assessment and Research Results Gap Analysis

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed	Notes
17.6	Pipeline	●	12	Test Requirements for Reinstating Service Lines	Med			X		
17.7	Pipeline	○	40	Abandonment or Deactivation of Facilities	High				X	
17.8	Pipeline	●	12	Compressor Stations: Reliefs and Combustible Storage	Med			X		
17.9	Pipeline	●	20	Compressor Stations: Gas Detection	High			X		
17.10	Pipeline	●	12	Pressure Limiting and Regulating Stations: Inspection, Testing, Reliefs, etc.	Med			X		
17.11	Pipeline	●	12	Valve Maintenance: Transmission and Distribution Lines	Med			X		
17.12	Pipeline	○	12	Vault Maintenance	Med			X		
17.13	Pipeline	●	40	Prevention of Accidental Ignition	High				X	
17.14	Pipeline	●	40	Qualification of Pipeline Personnel	High				X	
17.15	Pipeline	●	40	Pipeline Integrity Management	High				X	
18	Transport			Hazard and Packaging Class for Hydrides, Cryogas, Physisorption, Reactives						
18.1	Transport	●	12	Tests for Appropriate Class Determination	Med			X		C
18.2	Transport	●	40	Packaging Instructions for Micro Metal Hydride Hydrogen Storage Systems	High				X	
18.3	Transport	●	40	Packaging Instructions for Portable Metal Hydride Hydrogen Storage Systems	High				X	
18.4	Transport	●	20	Reactive Hydrogen Storage May Be Mixtures	High			X		
19	Transport			Emergency Response						
19.1	Transport	●	10	Emergency Response Information: High Pressure Gas, Steel	High		X			
19.2	Transport	●	20	Emergency Response Information: High Pressure Gas, Composite	High			X		
19.3	Transport	●	20	Emergency Response Information: Cryogenic	High			X		
19.4	Transport	●	20	Emergency Response Information: Metal Hydride	High			X		
19.5	Transport	○	20	Emergency Response Information: Cryogas	High			X		
19.6	Transport	○	20	Emergency Response Information: Physisorption	High			X		
19.7	Transport	○	20	Emergency Response Information: Complex Hydrides	High			X		
19.8	Transport	●	20	Emergency Response Information: Reactive (Including Methanol)	High			X		
20	Transport	●	20	Training	High			X		
21	Transport	●	12	Security Plans	Med			X		
22	Transport	○	24	Filling and Purging Requirements for Advanced Media	Med				X	
23	Transport	●	24	Filling and Purging Requirements for High Pressure Containers	Med				X	
24	Transport	●	24	Loading and Unloading Requirements for Composite Containers	Med				X	
25	Transport			Container Specifications						
25.1	Transport	●	40	Container Specifications for Composite Storage	High				X	C
25.2	Transport	●	40	Container Specifications For Metal Hydride Based Storage	High				X	C
25.3	Transport	●	24	Container Specifications For Reactive Type Storage	Med				X	C
26	Transport	●	20	Composite/Novel Media Tube Trailer Specifications	High			X		
27	Transport	○	12	Composite/Novel Media Portable Tank Specifications	Med			X		
28	Transport	○	4	Continuing Qualification and Maintenance	Low			X		
29	Transport	●	40	Mobile Fuelers, Treatment of Gas Storage Containers	High				X	
30	Transport			Aircraft Carriage						

Hydrogen Infrastructure Safety Technical Assessment and Research Results Gap Analysis

No.	Group	Timeframe	Score	Key Area	Criticality	Fully Addressed	Addressed, Monitoring	Addressed, Not Adequately	Not Addressed	Notes
30.1	Transport	●	40	Aircraft Carriage: Hydride Systems	High				X	
30.2	Transport	●	40	Aircraft Carriage: Hydride Systems in Appliances	High				X	
31	Transport	●	20	Pressure Relief Devices: High Pressure	High			X		
32	Transport	●	20	Pressure Relief Valves: High Pressure	High			X		
33	Transport	●	20	Valves: High Pressure	High			X		
34	Transport	●	20	Welding	High			X		
35	Transport	●	20	Tubing and Fittings: High Pressure	High			X		

●	Near term: 0 to 5 years
O	Long term: 5 to 15 years
A	Higher order--work in other areas will define requirements
B	Sensor technology will influence leak survey requirements
C	System-level consideration/requirements

Embrittlement (1.1)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Internal hydrogen embrittlement is when atomic hydrogen diffuses into and supersaturates the metal structure. The hydrogen acts to lower fracture resistance under applied stress and the concentration of hydrogen in the metal can increase over time. Environmental hydrogen embrittlement occurs with simultaneous hydrogen exposure and applied stress. Atomic hydrogen diffuses into the near-surface volume of metals and facilitates, over time, the propagation of surface defects propagation of surface flaws. The rate of sub-critical crack growth can be governed by hydrogen diffusion.

Increased crack propagation susceptibility degrades properties as ductility and fracture toughness. Impurities in the metal can affect the resistance of the metal to hydrogen-assisted fracture. Metals can be processed to have a wide range of strengths and resistance to hydrogen-assisted fracture generally decreases as the strength of the alloy increases.

The susceptibility to hydrogen-assisted fracture generally increases as hydrogen pressure increases. Temperature effects are not as clear. Some metals such as austenitic stainless steels exhibit a local maximum in hydrogen-assisted fracture susceptibility as a function of temperature.

Although not well understood, trace gases mixed with the hydrogen gas can also affect hydrogen-assisted fracture. Moisture, for example, may be detrimental to aluminum alloys since wet oxidation produces high-fugacity hydrogen, while in some steels moisture is believed to improve resistance to hydrogen-assisted fracture by producing surface films that serve as kinetic barriers to hydrogen uptake. An inverse strain rate effect is generally observed in the presence of hydrogen; in other words, metals are less susceptible to hydrogen-assisted fracture at high strain rates.

Sections 192.51 to 192.65 of Subpart B (Materials) of 49 CFR 192 “prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines.” Section 192.55 relates to steel pipe in particular.

Discussion of Criticality

Hydrogen pipelines have operated safely for years using X42 or X52 steels at pressures less than 6.9 MPa (1000 psi) with low cycling. A pipeline system built to serve a much larger market for hydrogen might operate at increased loads and pressure cycles. There is particular concern related to the heat affected zones of welds.

Discussion of Progress

Embrittlement studies have been performed and are currently ongoing. UIUC is currently investigating embrittlement issues and is coordinating with related work at SECAT, Inc., ORNL, and SRNL. A study of embrittlement of high strength fasteners for use on hydrogen systems has been completed by the Hendrix Group in 1998.

One ASTM standard does exist on this topic. It is ASTM F519, the Hydrogen Embrittlement Test.

Recommendations

Further research is needed on this key topic, especially related to embrittlement of base metal and of welds. A national database of embrittlement problems and incidents should be developed and maintained. A comprehensive listing of metals commonly used in piping should be created. The sequence of the listing should be in order of increasing tendency for embrittlement.

Purity Effects (1.2)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Purity requirements for hydrogen are most stringent for electronics industry consumers. Current industrial hydrogen grades are specified by both CGA (G-5.3 Commodity Specification for Hydrogen) and ISO (14687 Hydrogen fuel—Product specification) though industrial gas companies often establish their own grading systems. Vehicular fuel quality is being addressed by SAE and ISO. SAE has published J2719 "Information Report on the Development of a Hydrogen Quality Specification for Fuel Cell Vehicles" and is developing a hydrogen fuel specification though it is anticipated that it will be several years before one is complete. ISO is developing fuel cell application hydrogen specifications for incorporation into ISO 14687.

Subpart B (Materials) of 49 CFR 192 "prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines."

Discussion of Criticality

It is unclear precisely what the final fuel quality requirements will be in a more developed hydrogen economy.

Discussion of Progress

Sandia National Labs has identified this as a topic that must be researched if a full characterization of hydrogen effects on structural materials can be considered complete.

ASME B31.12 has no plans to incorporate purity issues at the present time.

Recommendations

Further research is needed on this key topic. Standards for hydrogen piping materials should take into account hydrogen purity effects. All standards established should be incorporated by reference into the federal code.

Pressure Level (1.3)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Most hydrogen pipelines in operation today operate at pressures less than 6.9 MPa (1000 psi) with low cycling. A pipeline system built to serve a much larger market for hydrogen might operate at increased loads and pressure cycles. Most discussions related to pipeline transport of hydrogen incorporate operating pressures up to 20.7 MPa (3000 psi).

Subpart B (Materials) of 40 CFR 192 “prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines.”

Discussion of Criticality

Current materials knowledge is sufficient for pressures up to 15.2 MPa (2200 psi) with 290 MPa (42 ksi) and 359 MPa (52 ksi) steels being used at 30% to 40% SMYS. With these steels in this pressure range, no embrittlement failures have been seen. Higher pressures may be required for more widespread hydrogen pipeline deployment. A maximum allowable operating pressure needs to be determined as well as a SMYS percentage.

Discussion of Progress

Sandia National Labs has spent a significant amount of time addressing these topics. Since the 1970s, Sandia has conducted high pressure hydrogen materials testing.

ASME B31.12 will include information equivalent to ASME B31.3, ASME B31.8 and NFPA 54 for natural gas. The anticipated operating range for hydrogen distribution piping is from full vacuum to 20.7 MPa (3000 psi).

Recommendations

For higher line pressures and/or or higher strength steels, the current knowledge base is insufficient. Research already underway related to embrittlement must be useable by engineers to write standards for which regulators can write clear rules.

Temperature Range (1.4)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

While it is generally true that higher pressures increase the susceptibility of metals to hydrogen-assisted fracture, temperature effects are not as systematic. For example, some metals such as austenitic stainless steels exhibit a local maximum in hydrogen-assisted fracture susceptibility as a function of temperature.

Subpart B (Materials) of 49 CFR 192 "prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines." The code further states that, "Materials for pipe and components must be able to maintain the structural integrity of the pipeline under temperature and other environmental conditions that may be anticipated."

Discussion of Criticality

Anticipated temperature operating ranges for hydrogen distribution piping may range between -40 and 150°C (-40 and 302°F). The temperature range should be consistent with 49 CFR 192.

Discussion of Progress

ASME B31.12 will include information equivalent to ASME B31.3, ASME B31.8 and NFPA 54 for natural gas.

Work is underway at SNL examining hydrogen-assisted fracture which includes an assessment of temperature effects.

Recommendations

Research is needed to compile data regarding temperature transition ranges from hydrogen embrittlement to hydrogen attack (lower temperature data on embrittlement exists and most of the lower temperature alloys like 316 stainless are not really affected by embrittlement). Engineering data is needed in order for proper design decisions to be made. Conclusions from research should be incorporated where necessary into the federal code.

Pressure and Temperature Interactions (1.5)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Pressure and temperature interactions are addressed under Subpart B (Materials) of 49 CFR 192. Per the Code, Subpart B on materials prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines.

Discussion of Criticality

This area is critical because loss of mechanical properties in the pipe due to pressure and temperature interactions can lead to pipe failure.

Discussion of Progress

During a presentation at the Materials and Components for the Hydrogen Economy Codes and Standards Workshop in Augusta, Georgia on August 29th to 30th, 2005, ASME identified the following knowledge gap: is there a correlation between pressure and temperature with the loss of mechanical properties of common pipe materials?

SNL is conducting hydrogen material compatibility studies. The focus is on material data for applications that involve the storage, distribution, and consumption of high-pressure hydrogen gas. Pertinent data include hydrogen-affected mechanical properties (yield, tensile strength, ductility, fracture toughness, threshold stress-intensity factor, fatigue crack growth rate, fatigue crack growth threshold, and impact fracture energy).

The ASME B31.12 hydrogen task group has undertaken a literature search which indicates that embrittlement seems to be most pronounced in carbon steels at about 20°C (68°F) and begins to become less of an issue starting at about 150°C (302°F). Above this temperature hydrogen attack becomes the primary problem. Hydrogen pipelines are not expected to operate above 150°C (302°F).

Recommendations

The ASME B31.12 hydrogen task group is considering adding cautionary statements about embrittlement and requires research data to provide more substantial guidance to code users. The work underway at Sandia needs to reflect the data needs of the ASME B31.12 hydrogen task group. Hydrogen standards for materials compatibility should be established and incorporated by reference into the federal code.

Testing Methods (1.6)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Subpart B (Materials) of 49 CFR 192 “prescribes the minimum requirements for the selection and qualification of pipe and components for use in pipelines.”

Discussion of Criticality

Most commonly used tests to determine the mechanical properties of metallic materials tend to overwhelm the effects of hydrogen embrittlement. The tests are too fast and the loss of properties is difficult to detect. Commonly used test seem to be strain rate sensitive when it comes to detecting embrittlement.

Discussion of Progress

ASTM Committee G01 on Corrosion of Metals has created a new task group, G01.06.08, to explore the cracking problems that materials exposed to hydrogen may encounter. The purpose of the new task group is to review potential problems with hydrogen as an energy source and to develop test methods and other standards that deal with the issues involved in using hydrogen in conjunction with other materials.

ASME B31.12 will reference test methods as needed to assure that materials used in the design of hydrogen systems have the proper mechanical properties.

Recommendations

Standards for testing methods for hydrogen pipelines and hydrogen storage containers should be established and incorporated by reference into the federal code.

Higher Strengths (1.7)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Because of hydrogen's low gravimetric and volumetric density, many hydrogen transport solutions are looking to higher pressures to increase storage/transport densities. Higher pressures lead to increased material needs for pipelines and containers. The ability to use higher strength materials can mitigate the need for increased material, reducing the cost and weight of hydrogen transportation technologies.

Discussion of Criticality

Metals can be processed to have a wide range of strengths and resistance to hydrogen-assisted fracture generally decreases as the strength of the alloy increases. Tensile strength is not the only influential factor. Steel chemistry can play a significant role relative to embrittlement. Many pipeline steels are "micro-alloyed" and initial indications are that they perform better than standard steels. Many pipe specifications are API standards which are performance based. They specify minimum yields without chemistry requirements.

Discussion of Progress

Embrittlement studies have been performed and are currently ongoing. UIUC is currently investigating embrittlement issues and is coordinating with related work at SECAT, Inc., ORNL, and SRNL. A study of embrittlement of high strength fasteners for use on hydrogen systems has been completed by the Hendrix Group in 1998.

One ASTM standard does exist on this topic. It is ASTM F519, the Hydrogen Embrittlement Test.

Recommendations

Research data on high strength steels needs to be completed. Chemistry reporting must be mandatory not just of the standard elements but also the trace elements from which are derived the "micro alloy" benefits. Confirm whether or not this topic will be addressed by ASME B31.12. Standards for materials of higher strength for use as hydrogen piping and containers should be established and incorporated by reference into the federal code.

Loss of Fatigue and Impact Strength (1.8)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.501 – §192.517

Description of Key Area

Hydrogen attack can lead to increased crack propagation susceptibility, which degrades properties such as ductility and fracture toughness. Subpart J of 49 CFR 192 prescribes the minimum leak test and strength test requirements for pipelines.

Discussion of Criticality

This area is critical because loss of mechanical properties in the pipe can lead to pipe failure.

Discussion of Progress

ASME has identified a research need for hydrogen testing requirements. This need was presented during the Materials and Components for the Hydrogen Economy Codes and Standards Workshop in Augusta, Georgia on August 29th to 30th, 2005. The research need identified was the following: "Testing is needed of all commonly used piping and pipeline materials for loss of fatigue and impact strength in a high pressure hydrogen environment. Research of the effects of pressure cycling on mechanical properties is needed."

SNL is conducting hydrogen compatible materials studies. The focus is on material data for applications that involve the storage, distribution, and consumption of high-pressure hydrogen gas. Pertinent data include hydrogen-affected mechanical properties (yield, tensile strength, ductility, fracture toughness, threshold stress-intensity factor, fatigue crack growth rate, fatigue crack growth threshold, and impact fracture energy).

Work underway at UIUC has indicated that fatigue cracking appears to be more of prevalent in low cycle rate, low stress situations than in high cycle rate, higher stress situations.

Recommendations

The ASME B31.12 hydrogen task group is considering the addition of cautionary statements on fatigue in hydrogen pipelines and piping. Appropriate tests for hydrogen pipe should be devised including pressure cycling. Once this research has been completed, current standards should be amended based on this research and these amendments incorporated by reference into the federal code.

Class Locations (3)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.5

Description of Key Area

Class location comprises a portion of Subpart A (General) of 49 CFR 192. Class location refers to the distance a structure must be located from the pipeline. A "class location unit" is defined in 49 CFR 192 as "an on-shore area that extends 220 yards on either side of the centerline of any continuous 1-mile length of pipeline."

Discussion of Criticality

The parameters for class location are based on natural gas considerations. The underlying definition of class location must be redefined for hydrogen.

Discussion of Progress

The current plans of the ASME B31.12 hydrogen task group call for using only the location class 3 and 4 to maintain a classification designation familiar to pipeline operators and designers. This will increase the level of conservatism in the design of new lines and require more frequent inspections in the integrity management process. The ASME B31.12 hydrogen task group is also reviewing a new DOT report, TTO13, entitled "Potential Impact Radius Formulae for Flammable Gasses Other Than Natural Gas, June 2005". If the task group agrees with the report results, it will change the "potential impact area" equation for radius of impact calculations and use this in conjunction with ASME B31.8S (equation 1 in ASME B31.8S, section 3.2).

Recommendations

The ASME effort should be monitored and its recommendations assessed for potential incorporation by reference into the federal code.

Conversion to Service (4)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.14

Description of Key Area

A number of hydrogen pipelines in use today have been converted from earlier oil or gas use. Generally, these are derated relative to allowable percentage of SMYS. Under Subpart A (General) of 49 CFR 192, conversion of service refers to using existing in-ground pipe for service.

Discussion of Criticality

A number of assessments are typically performed prior to conversion, including research into service history, previous replacement and repair work, metallurgical analyses, reviews of right-of-way documents, etc. Parameters must be defined for standards for using existing in-ground oil or gas pipe for hydrogen service.

Discussion of Progress

Requirements have been developed by a number of companies internally but there are not yet any public guidelines.

Recommendations

The ASME B31.12 task group has included a section on pipeline conversion in their draft document. Standards for conversion of service to hydrogen should be established and incorporated by reference into the federal code.

Customer Notification (5)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§192.16

Description of Key Area

Customer notification is addressed under Subpart A (General) of 49 CFR 192. Per the Code, if the gas operator does not maintain the customer's buried piping up to a certain point of entry, the operator must notify the customer in writing to let them know and also to advise them of the need of periodic inspections for leaks and corrosion.

Discussion of Criticality

For hydrogen, the term "customer's buried piping" should be defined. Is there special notification that must be conveyed to the customer above the information which is currently listed in the federal code? A determination is needed as to where notices might need to be posted, such as fill stations, etc.

Discussion of Progress

No information found.

Recommendations

Hydrogen standards for customer notification should be established and incorporated by reference into the federal code.

Composite Reinforced Pipe (6)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	

Description of Key Area

Because of hydrogen's low gravimetric and volumetric density, many hydrogen transport solutions are looking to higher pressures to increase storage/transport densities. Higher pressures lead to increased material needs for pipelines and containers. The ability to use composite reinforcement can mitigate the need for increased material, reducing the cost of hydrogen transportation technologies.

Discussion of Criticality

Composite reinforced pipe technology is being examined for hydrogen transport to address a number of issues related to metallic pipeline materials: embrittlement, welding heat affected zones, reduction in the quantity of pipe joins, etc. While potentially avoiding some of the problems associated with metallic materials, composite pipe technology faces its own hurdles, including lack of design specifications, qualification of joining methods, permeation rates, robustness from external mechanical damage, etc.

Discussion of Progress

A limited number of composite reinforced pipe installations exist but none in hydrogen service. Work is underway at ORNL to examine a number of issues related to development and deployment of composite reinforced pipe for hydrogen service.

Recommendations

When information is made available it will be added to the ASME B31.12 code. At that time, ASME B31.12 may specify a minimum burst to operating pressure ratio for composite piping. Standards for composite reinforced materials for use as hydrogen piping should be established and incorporated by reference into the federal code.

Pipe Design (7)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.101 – §192.125

Description of Key Area

Pipe design is addressed under Subpart C (Pipe Design) of 49 CFR 192. Per the Code, Subpart C prescribes the minimum requirements for the design of pipe.

Discussion of Criticality

Pipe design of hydrogen pipelines will encompass topics such as design formulae, wall thickness, design factor, joint factor, and derating. MAOP for high pressure hydrogen pipelines must be determined as well as the SMYS percentage. The MAOP and SMYS percentage should be consistent with materials to be used for pipe design.

Discussion of Progress

ASME STP/PT-003 was a 2005 study that evaluated the potential use of four piping and pipeline codes (ASME B31.1, ASME B31.3, ASME B31.8, and 49 CFR 192) for up to 103 MPa (15000 psi) hydrogen service. ASME B31.12 will address hydrogen piping standards specifically.

CGA G-5.6 is a non-mandatory standard for hydrogen pipes for the design, construction, pre-service, operation and monitoring, and safety of hydrogen pipes.

Recommendations

Standards for hydrogen pipe design, MAOP, and percentage SMYS should be established and the ASME B31.12 code is in development at this time. Standards established should be incorporated by reference into the federal code.

Pipeline Component Design (8)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.141 – §192.161

Description of Key Area

Pipeline component design is addressed under Subpart D of 49 CFR 192. Per the code, "This subpart prescribes minimum requirements for the design and installation of pipeline components and facilities. In addition, it prescribes requirements relating to protection against accidental overpressurization.

Discussion of Criticality

This category includes components such as valves, flanges, fittings, vaults, etc. It also should encompass processes such as tapping, and should address compressor station components as well.

Discussion of Progress

CGA has created a non-mandatory standard for hydrogen pipes that addresses design, construction, pre-service, operation and monitoring and safety.

SRNL is working on a project currently that "provide(s) a facility for the testing of safety codes and standards with emphasis on the development of components, materials, and repair techniques for piping in high pressure hydrogen service." One of the key issues for the project is to address design concerns regarding hydrogen pipeline components, such as leakage of mechanical joints.

Recommendations

Recommendations should be made for tests of pipeline component designs to verify design integrity. The primary issues for component design are the material of construction and sealing mechanisms. Also, new standards will be needed for any new components developed specifically for hydrogen. These standards, once established, should be incorporated by reference into the federal code.

Welding of Steel (9)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.221 – §192.245

Description of Key Area

Welding of steel in pipelines is addressed under Subpart E of 49 CFR 192. Per the federal code, the scope of this section is as follows: “This subpart prescribes minimum requirements for welding steel materials in pipelines. This subpart does not apply to welding that occurs during the manufacture of steel pipe or steel pipeline components. “

Discussion of Criticality

Modifications to the CFR may be needed to account for welding of steel pipe to be used in hydrogen applications. It is important that all joining methods used are adequate to prevent leakage, permeation of hydrogen, pipe weld and HAZ embrittlement.

Discussion of Progress

Over the years, organizations such as the SRNL, SNL, ORNL, and ASME have studied different aspects of welding of steel pipe for hydrogen use. The research categories studied include crack growth, procedures for welding, welding qualification, weld inspection, and appropriate weld hardness levels.

ASME has identified a knowledge gap in the study of welds for hydrogen pipe. ASME is concerned about the effect of pressure on sustained load cracking in welds and weld HAZs.

Recommendations

Current research regarding hydrogen pipe welds should be expanded to include a more in-depth analysis of the research areas mentioned above. Standards for hydrogen pipe welds should be established and incorporated by reference into the federal code. It is important that all joining methods used are adequate to prevent leakage, permeation of hydrogen, pipe weld and HAZ embrittlement. These standards should address procedures for welding, welding qualification, weld inspection, appropriate weld hardness levels, acceptable rates of crack growth (if any), and testing of welds. Without research data, all that the ASME B31.12 task group can do at the present is to add cautionary notes for welding for hydrogen service and require a maximum hardness limit that comes from NACE recommendations for sour service.

Joining Other than Welding (10)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.271 – §192.287

Description of Key Area

Subpart F of 49 CFR 192 refers to requirements for joining materials in pipelines other than by welding. It does not apply to joining during the manufacture of pipe or pipeline components. Joining by welding is addressed in subpart E (Welding of Steel in Pipelines, §192.221 to §192.245). Joining, in general, may take place by welding of steel, or joining of pipes other than steel, such as plastic pipe or composite pipe. Plastic pipe is joined by fusion. Composite pipe might be joined by combinations of mechanical joining and some type of fusion.

Discussion of Criticality

It is important that all joining methods used be adequate to prevent leakage, permeation of hydrogen, or pipe embrittlement.

Discussion of Progress

No information found.

Recommendations

Appropriate joining techniques must be documented and tested for hydrogen applications. In addition, standards for flange gaskets and other sealant materials for steel pipe used for hydrogen applications need to be established. A definition for a qualified joint must be created. Operator training and qualification must be developed for the joining methods. Standards for joining (other than by welding) must be established and incorporated by reference to the federal code.

ASME B31.12 will reference consensus standards that adequately cover the mechanical joining of pipes in hydrogen service. Performance testing is required and should be performed to a national standard. System design and joint design may dictate what can and can not be mechanically joined.

Construction Requirements (11)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.301 – §192.327

Description of Key Area

Subpart G (General Construction Requirements for Transmission Lines and Mains) of 49 CFR 192 "prescribes minimum requirements for constructing transmission lines and mains.

Discussion of Criticality

The category of construction requirements includes the subjects of mechanical testing, creation of a material properties database, and evaluation methodologies.

Discussion of Progress

CGA has created hydrogen pipeline non-mandatory standards addressing piping and piping component design, construction, pre-service, operation and monitoring, and safety.

SRNL has identified key needs for properties and Applications to Construction Codes which include standards for hydrogen mechanical testing, a database of material properties, evaluation methodologies such as a fracture control plan, and a qualification plan for service-experienced materials/systems.

Recommendations

Additional research should be performed to address factors relating to construction requirements. Construction requirements for hydrogen pipelines will be included in ASME B31.12 and once established should be considered for incorporated by reference into the federal code.

Customer Meters, Regulators, and Service Lines (12)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§192.351 – §192.383

Description of Key Area

Subpart H (Customer Meters, Service Regulators, and Service Lines) of 49 CFR 192 “prescribes minimum requirements for installing customer meters, service regulators, service lines, service line valves, and service line connections to mains.

Discussion of Criticality

The criticality is listed as medium because distribution mains are considered to be the highest priority, and sequentially the first item to be addressed when changing from gas pipelines to hydrogen pipelines.

Discussion of Progress

No information found.

Recommendations

ASME B31.12 requirements are the same as those for ASME B31.8. Different pressures for hydrogen service may require special attention. It is presumed that any unique requirements would be derived from natural gas standards. Standards for hydrogen pipelines should be established and incorporated by reference into the federal code.

Corrosion Control (13)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.451 – §192.491

Description of Key Area

Corrosion control refers to minimum requirements for the protection of metallic pipelines from external, internal and atmospheric corrosion.

Discussion of Criticality

An analysis of corrosion control for hydrogen pipe must begin with the pipe itself and take into consideration not only factors about the pipe but also those things that impact the pipe, such as type of welding process, procedure, post weld heat treatment and the internal and external environment to which the piping system is subjected. The presence of moisture in hydrogen gas is detrimental and generally "dry" hydrogen is typically a minimum requirement (dew point of -48°C (-54°F)).

Discussion of Progress

No information found.

Recommendations

Research should be conducted on corrosion control of hydrogen pipe including studies of coatings to be used, cathodic protection, electrical isolation, and interference currents. Standards should be established and incorporated by reference into the federal code. These standards should address the use of coatings, cathodic protection, external electrical isolation, external interference currents, internal and external monitoring, external test stations, test leads, atmospheric corrosion control and monitoring and remedial measures for both transmission and distribution lines for steel pipes used for hydrogen transmission and distribution lines.

ASTM F519 Hydrogen Embrittlement Test (14.1)

Criticality: High
Score: 10
Progress: Addressed, Monitoring
DOT Relevance: §192.501 – §192.517

Description of Key Area

Hydrogen pipe embrittlement testing falls under Subpart J (Test Requirements) of 49 CFR 192. Per the Code, "This subpart prescribes minimum leak-test and strength-test requirements for pipelines."

Discussion of Criticality

An ASTM standard (ASTM F519) has been created to provide for hydrogen pipeline embrittlement evaluation.

Discussion of Progress

As this is a relatively new topic, even though an ASTM document has been established, the subject should still be monitored.

Recommendations

Once the adequacy of ASTM F519 has been evaluated against the ongoing embrittlement research, the established standard should be incorporated by reference into the federal code.

Tensile Tests (14.2)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.501 – §192.517

Description of Key Area

Tensile testing falls under Subpart J (Test Requirements) of 49 CFR 192. Per the Code, "This subpart prescribes minimum leak-test and strength-test requirements for pipelines."

Discussion of Criticality

Tensile testing is a critical area because it is one of the procedures to test the integrity of the material to be used for hydrogen pipe. Tensile testing is a recommended test for hydrogen piping and a recommended test in general for any material.

If composite materials are used for hydrogen pipelines, tensile tests may not be relevant. Other forms of testing may be more appropriate for composite materials and polyethylene pipe materials.

Discussion of Progress

No information found.

Recommendations

ASME B31.12 will incorporate tensile tests if they are necessary for design safety. Standards for test requirements for hydrogen pipe should be established and incorporated by reference into the federal code.

K_{IH} and K_{IC} Stress Intensity Factors (14.3)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.501 – §192.517

Description of Key Area

Material testing falls under Subpart J (Test Requirements) of 49 CFR 192. Per the Code, “This subpart prescribes minimum strength-test requirements for pipelines.”

Discussion of Criticality

Typical pipe specifications to not have specific steel chemistry requirements and therefore it will be difficult to establish a standard (K) factor when characteristics vary from mill to mill.

Discussion of Progress

SRNL advises that stress intensity factors (K) should be identified and evaluated for materials to be used for hydrogen pipelines though there is a diversity of opinion on this need particularly for lower strength steels.

Recommendations

The ASME B31.12 hydrogen task group is currently discussing a fracture mechanics approach for piping and pipeline design and fatigue analysis. Standards for hydrogen pipelines should be established and incorporated by reference into the federal code.

Fatigue Crack Growth (14.4)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.501 – §192.517

Description of Key Area

Material testing falls under Subpart J (Test Requirements) of 49 CFR 192. Per the Code, “This subpart prescribes minimum leak-test and strength-test requirements for pipelines.”

Discussion of Criticality

There is little knowledge other than that fatigue cracks grow 10 to 30 times faster in hydrogen embrittled materials than under the same conditions in air.

Discussion of Progress

SRNL advises that fatigue crack growth should be identified and evaluated for materials to be used for hydrogen pipelines.

Recommendations

ASME B31.12 will address this issue within the limits of available data. Further research is necessary and appropriate fatigue crack growth testing methods should be identified and documented. A database of fatigue related incidents should be established. Standards for hydrogen pipelines should be established and incorporated by reference into the federal code.

Burst (14.5)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.501 – §192.517

Description of Key Area

Material testing falls under Subpart J (Test Requirements) of 49 CFR 192. Per the Code, "This subpart prescribes minimum leak-test and strength-test requirements for pipelines."

Discussion of Criticality

Burst testing is one mechanism to verify design parameters and assumptions.

Discussion of Progress

SRNL recommends that mechanical tests for materials to be used for hydrogen service include burst testing.

Recommendations

Burst testing as a topic is not covered in ASME B31.12. Standards for burst testing of materials and structures to be used for hydrogen pipelines should be established and incorporated by reference into the federal code.

Composite Pipe (14.6)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.51 – §192.65

Description of Key Area

Although Subpart B (Materials) of 49 CFR 192 "prescribes minimum requirements for the selection and qualification of pipe and components for use in pipelines," composite pipes are not used at this time in the United States for natural gas applications. Studies are ongoing as to whether composite pipes could be a candidate for hydrogen applications.

Discussion of Criticality

Composite pipe materials are not currently referenced in 49 CFR192. There are two rationales for composite pipe applications: the avoidance of metallic material limitations at higher pressures and the potential for reduced installation cost through longer pipe segments relative to steel pipe.

Discussion of Progress

Although composite materials are widely used today for many applications, their adequacy for use as hydrogen pipe must assessed. Composite pipe is used in natural gas applications in Europe. One example of this is reinforced thermoplastic pipe (RTP) developed by Soluforce under the brand name of PipeLife. For hydrogen applications, composite pipe materials must be adequate to prevent or minimize leakage or permeation of hydrogen. TransCanada Pipeline has an ongoing project using composite pipe in natural gas service in Canada with test loop in operation.

Research must be conducted into materials to be used for composite pipe for hydrogen applications. In Europe, reinforced thermoplastic pipe (RTP) is used for gas transportation applications. This pipe was designed according to ISO 9080 and ASTM 2992. This type of pipe must be tested for hydrogen applications. Research has been conducted in the United States on fiber reinforced plastic (FRP) pipe and the implications for its use for hydrogen applications.

The areas of greatest concern relative to composite pipe include joining methods (e.g., mechanical and fusion), exterior mechanical damage tolerance, design analysis methods, permeation, and composite structural integrity.

Key/Sub Area Assessment Summaries

During a presentation at the Materials and Components for the Hydrogen Economy Codes and Standards Workshop in Augusta, Georgia on August 29th to 30th, 2005, ASME has identified the subject of composite pipes as a "knowledge gap."

SNL is conducting hydrogen compatible materials studies. The focus is on material data for applications that involve the storage, distribution, and consumption of high-pressure hydrogen gas. Pertinent data include hydrogen-affected mechanical properties (yield, tensile strength, ductility, fracture toughness, threshold stress-intensity factor, fatigue crack growth rate, fatigue crack growth threshold, and impact fracture energy).

ASME B31.12 will include the use of composite pipe and plastic pipe when research shows that it is a viable alternative to metallic pipe.

Recommendations

Potential composite pipe materials and structures, including potential joining methodologies, should be researched and tested. Research should include topics regarding permeation and rapid purge methods. Operator qualifications for composite pipe should be determined. Composite pipe standards should be established and incorporated by reference into the federal code.

Plastic Pipe (14.7)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.59; §192.501 – .517

Description of Key Area

The subject of use of plastic pipe for hydrogen pipelines falls under Subpart B (Materials) of 49 CFR 192 as well as Subpart J (Test Requirements).

Discussion of Criticality

Large scale distribution of hydrogen via a pipeline network would likely require both transmission and distribution network components. The natural gas industry has found plastic pipe to be a cost-effective and safe technology for the lower pressures and flow encountered in the distribution system. Deploying steel at the distribution level could prove to be costly.

Discussion of Progress

To assess the viability of plastic distribution pipe for hydrogen service, material and structure testing needs to be completed as well as testing of common joining methods (bonding and fusion). These needs were expressed by ASME during its presentation at the Materials and Components for the Hydrogen Economy Codes and Standards Workshop held on August 29th to 30th, 2005, in Augusta, GA. ASME B31.12 will incorporate plastic pipe coverage as soon as more data becomes available.

Recommendations

A standard for acceptable plastic material should be defined. This may include polyethylene, polyvinyl, polyamid, and other materials. Research and testing should be conducted on plastic pipe to investigate its compatibility with hydrogen. Specifically, materials suitable for use as hydrogen pipe must be identified, and acceptable joining methods for plastic pipe and fittings must be identified. Current plastic pipe standards should be amended to include hydrogen plastic pipe and these amendments should be incorporated by reference into the federal code.

Uprating (15)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.551 – §192.557

Description of Key Area

Under Subpart K of 49 CFR 192, the minimum requirements for increasing maximum allowable operating pressure for pipelines are prescribed.

Discussion of Criticality

Today’s hydrogen pipelines operate at stress levels generally between 30% and 40% of SMYS. To increase pipeline capacity, increased pressures may be required. Increased allowable stress levels can, in part, lead to cost-effective designs at higher pressures.

Discussion of Progress

ASME B31.12 will use only location class 3 and 4 for pipeline design. This will limit the percentage SMYS utilized in design or uprating. The new code will provide location class limits and incorporate “design factors” to maintain design conservatism until actual research data on material properties is available. The design factors will be used to restrict pipe stresses as the pressure increases and/or the tensile strength of the pipe material is increased or both.

Recommendations

Research needs to be performed to produce research data on material properties so that accurate class limits can be set. Standards and procedures for the uprating of hydrogen pipe should be established and incorporated by reference into the federal code.

Procedural Manual for Operations, Maintenance, and Emergencies (16.1)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.605

Description of Key Area

The topic of procedures for operations falls under Subpart L (Operations) of 49 CFR 192. Per the Code, "This subpart prescribes minimum requirements for the operation of pipeline facilities."

Discussion of Criticality

Procedures must be documented and training programs must be created.

Discussion of Progress

Hydrogen pipeline operations and maintenance requirements have been developed by a number of companies internally but there are not yet any public guidelines.

In 2005, the NASFM and DOT's RITA established the Hydrogen Executive Leadership Panel (HELP). HELP's mission is "…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources." HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

NREL has plans to establish a condensed version of training related material for code officials and fire marshals.

ASME B31.12 will incorporate by reference ASME B31.8S to address the more comprehensive concept of integrity management and not just maintenance. ASME B31.12 will incorporate by reference ASME B31Q when it is published to address the training, examination, and certification of system operators.

Recommendations

Generally, a complete public specification for operation and maintenance may not be necessary but, at a minimum, best practices should be disseminated. The ongoing efforts related to procedure development should be monitored and appropriate learning considered for incorporation by reference into the federal code.

Change in Class Location (16.2)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.609 – §192.611

Description of Key Area

The subject of change in class location falls under the Subpart L (Operations) of 49 CFR 192. Class location refers to the distance a structure must be located from the pipeline. A “class location unit” is defined in 49 CFR 192 as “an on-shore area that extends 220 yards on either side of the centerline of any continuous 1-mile length of pipeline.”

Discussion of Criticality

The parameters for class location are based on natural gas considerations. The underlying definition of class location should be reviewed for hydrogen.

Discussion of Progress

ASME B31.12 plans on following the ASME B31.8 code with input from the modified section 3.2 of ASME B31.8S.

Recommendations

Standards should be established for change in class location of hydrogen pipelines and incorporated by reference into the federal code including what the maximum allowable operating pressure of the hydrogen pipe should be and at what population density is a change in class location warranted. The class location unit needs to be revisited to confirm whether it is appropriate for hydrogen. The change in class location criteria in 49 CFR 192 also should be revisited.

Continuing Surveillance (16.3)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.613

Description of Key Area

Continuing surveillance falls under the heading of Operations in Subpart L of 49 CFR 192. Per the code, “each operator shall have a procedure for continuing surveillance of its facilities to determine and take appropriate action concerning changes in class location, failures, leakage history, corrosion, substantial changes in cathodic protection requirements, and other unusual operating and maintenance conditions.”

Discussion of Criticality

A determination of action needed must be defined for changes in operating and maintenance conditions for hydrogen pipe.

Discussion of Progress

ASME B31.12 will incorporate the requirements of ASME B31.8S as mandatory and modify selected sections to adapt this standard to hydrogen use.

Recommendations

Because of the unique characteristics of hydrogen, this section of 49 CFR 192 may need to be changed. Standards for continuing surveillance of hydrogen pipe should be established and incorporated by reference into the federal code. The standard should include guidelines to determine the proper time for pipe replacement, and when reduction in the maximum allowable operating pressure should occur.

Damage Prevention Program (16.4)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.614

Description of Key Area

Damage prevention is considered in Subpart L (Operations) of 49 CFR 192.

Discussion of Criticality

A hydrogen damage prevention program is needed for hydrogen transmission and distribution systems to prevent damage to pipelines from excavation activities such as excavation, blasting, boring, tunneling, backfilling, removal of aboveground structures and other earth moving operations.

Discussion of Progress

This topic will be covered in ASME B31.12. ASME B31.8 and ASME B31.8S will be used as models or by reference.

Recommendations

Standards for a hydrogen pipeline damage prevention program need to be established and incorporated by reference into the federal code. Hydrogen pipeline systems need to be incorporated into existing one-call systems.

Emergency Plans (16.5)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.601 – §192.629

Description of Key Area

Emergency plans fall under Subpart L (Operations) of 49 CFR 192. Per the Code, "This subpart prescribes minimum requirements for the operation of pipeline facilities."

Discussion of Criticality

Procedures must be documented and training programs must be created.

Discussion of Progress

In 2005, the NASFM and DOT's RITA established the Hydrogen Executive Leadership Panel (HELP). HELP's mission is "…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources." HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

ASME B31.12 will provide an outline as in ASME B31.8 for emergency plans.

Recommendations

Procedures for emergencies related to hydrogen pipelines must be established and incorporated by reference into the federal code.

Public Education: Emergencies (16.6)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§192.601 – §192.629

Description of Key Area

Public education on emergencies falls under Subpart L (Operations) of 49 CFR 192. Per the Code, “This subpart prescribes minimum requirements for the operation of pipeline facilities.”

Discussion of Criticality

Customers must be educated to recognize where a hydrogen pipeline exists and to recognize emergency conditions.

Discussion of Progress

ASME B31.12 will not address public education. ASME has proposed a cooperative effort between DOE and ASME to plan and implement a public education process.

Recommendations

Policies on public education on emergencies related to hydrogen pipelines must be established and incorporated by reference into the federal code. Notification requirements in 49 CFR 192 will need to be followed.

Investigation of Failures (16.7)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.617

Description of Key Area

Investigation of failures is addressed under Subpart L (Operations) of 49 CFR 192. As per the current 49 CFR 192, procedures must be established "for analyzing accidents and failures, including the selection of samples of the failed facility or equipment for laboratory examination, where appropriate, for the purpose of determining the causes of the failure and minimizing the possibility of a recurrence."

Discussion of Criticality

Investigation processes of failures for hydrogen of hydrogen transportation systems need to be established as new materials and construction methods are tested and deployed so that increased understanding of failure modes can be obtained.

Discussion of Progress

SNL, in coordination with NREL, is currently developing benchmark experiments and analysis strategy for risk assessment of hydrogen systems. The application of risk assessment studies is being cooperatively developed with the assistance of industry, government agencies and laboratories, insurance companies, and other stakeholders. ASME B31.12 will also address this area.

Recommendations

Risk assessments are an essential tool for methodically evaluating technologies and their application. It is necessary to establish standards and incorporate them by reference into the federal code. These standards should include specific instructions regarding investigation of failures.

Maximum Allowable Operating Pressure: Steel and Polyethylene Pipelines (16.8)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.619

Description of Key Area

Section 192.619 details the maximum allowable operating pressures for steel and polyethylene pipelines.

Discussion of Criticality

It is not yet clear if MAOP determination methods need to be altered for hydrogen pipelines.

Discussion of Progress

ASME B31.12 will only allow location class 3 or 4 designs for hydrogen pipelines at this time (50% and 40% SMYS respectively). Pipe design may be changed from a stress based design to a strain based design. Discussions are scheduled for March of 2006.

Recommendations

Standards for maximum allowable operating pressure for hydrogen pipelines must be incorporated by reference into the federal code.

Maximum Allowable Operating Pressure: High Pressure Distribution Systems (16.9)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.621

Description of Key Area

Section 192.621 details the maximum allowable operating pressures for high pressure distribution systems.

Discussion of Criticality

It is not yet clear if MAOP determination methods need to be altered for hydrogen high pressure distribution systems.

Discussion of Progress

ASME B31.12 will only allow location class 3 or 4 designs for hydrogen pipelines at this time (50% and 40% SMYS respectively). Pipe design may be changed from a stress based design to a strain based design. Discussions are scheduled for March of 2006.

Recommendations

Standards for maximum allowable operating pressure for hydrogen pipelines must be incorporated by reference into the federal code.

Maximum Allowable Operating Pressure: Low Pressure Distribution Systems (16.10)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.623

Description of Key Area

Section 192.623 details the maximum allowable operating pressures for low pressure distribution systems.

Discussion of Criticality

It is not yet clear if MAOP determination methods need to be altered for hydrogen high pressure distribution systems.

Discussion of Progress

At this time, no change is anticipated in ASME B31.12 relative to ASME B31.8.

Recommendations

Standards for maximum allowable operating pressure for hydrogen pipelines must be incorporated by reference into the federal code.

Odorization of Gas (16.11)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.625

Description of Key Area

Odorization of gas is considered under Subpart L (Operations) of 49 CFR 192. The Code states that "a combustible gas in a distribution line must contain a natural odorant or be odorized so that at a concentration in air of one-fifth of the lower explosive limit, the gas is readily detectable by a person with a normal sense of smell."

Discussion of Criticality

Odorants compatible with hydrogen have not yet been found. The sulfur found in traditional natural gas odorants can, even at very low concentrations, damage fuel cells. It is also impractical to implement odorant removal equipment at each point of use.

Discussion of Progress

A successful, efficient, and cost effective method of hydrogen odorization has not yet been identified. Although there are odorants compatible with hydrogen, it is difficult to envision odorizing of hydrogen with sulfur-containing compounds. The Japanese Auto Research Institute (JARI) is working on a non-sulfur based odorant for hydrogen. Other organizations are also actively conducting research on different classes of odorants to make hydrogen leaks detectable by humans. ASME B31.12 will not address this topic.

Recommendations

Current research for hydrogen odorants must address the odorant's potential impact on transportation technologies and on end use technologies. Once research is completed, standards for hydrogen odorants must be established and incorporated by reference into the federal code. It may be necessary to re-examine odorant detection limits that are incorporated into 49 CFR 192.

Tapping Pipelines Under Pressure (16.12)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.627

Description of Key Area

The tapping of pipelines under pressure is addressed in Subpart L (Operations) of 49 CFR 192. The Code states that “each tap made on a pipeline under pressure must be performed by a crew qualified to make hot taps.”

Discussion of Criticality

Operator qualification for crews to make taps on hydrogen pipes and pipelines must be established. This is a critical area because of pressure considerations. If, during the tapping process, proper procedures are not followed there is a potential for an uncontrolled release of gas.

Discussion of Progress

No information found.

Recommendations

Confirm whether or not this topic will be addressed by ASME B31.12. Standards for tapping hydrogen pipelines under pressure must be established and incorporated by reference into the federal code. These standards must include specific tapping processes and methods, as well as tooling or equipment to be used. Tapping should be conducted under “no-blow” conditions. The term “hot taps” should be defined. In general, there must be operator qualification standards for hydrogen work. These standards should be based on current standards but there may be specific tasks to be added for hot tapping of hydrogen pipelines.

Purging of Pipelines (16.13)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.629

Description of Key Area

Purging of pipelines is considered under Subpart L (Operations) of 49 CFR 192. This section discusses the purging of gas in such a way as to prevent "the formation of a hazardous mixture of gas and air."

Discussion of Criticality

This area is critical because of the wider flammability range of hydrogen relative to natural gas. For crew safety and public safety, in terms of accidental ignition and asphyxiation, purging practices for hydrogen pipelines needs to be examined.

Discussion of Progress

No information found.

Recommendations

Confirm whether or not this topic will be addressed by ASME B31.12. Standards for safe and effective purging (by gas purge or flaring) of hydrogen pipelines, including inert purge gas procedures and tooling to be used, must be established and incorporated by reference into the federal code.

Transmission Lines: Patrolling (17.1)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.705

Description of Key Area

Section 192.705 (Transmission Lines: Patrolling) of Subpart M (Maintenance) of 49 CFR 192 states, "Each operator shall have a patrol program to observe surface conditions on and adjacent to the transmission line right-of-way for indications of leaks, construction activity, and other factors affecting safety and operation.

Discussion of Criticality

Transmission line operators must have a patrol program in place. There must be a certain frequency of patrols and in addition a method of patrol must be established. The frequency of patrols may or may not be the same as that for natural gas.

Discussion of Progress

This topic will be addressed by ASME B31.12.

Recommendations

Standards for patrolling (and frequency of patrols) of hydrogen transmission lines must be established and incorporated by reference into the federal code.

Transmission Lines: Leakage Surveys (17.2)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.706

Description of Key Area

Leakage surveys for transmission lines fall under Subpart M (Maintenance) of 49 CFR 192. This subpart lists the minimum intervals at which leak surveys on transmission lines should be conducted.

Discussion of Criticality

Because of the increased flammability range of hydrogen relative to natural gas, special leak surveys are likely appropriate for hydrogen pipelines. The adequacy of current combustible gas and hydrogen-specific detection methods and equipment need to be assessed relative to industry leak survey practices.

Discussion of Progress

This topic will be part of the integrity management process that will be mandatory in ASME B31.12.

Recommendations

Current work should continue on hydrogen sensors and detectors. Standards for hydrogen transmission line leak surveys must be established and incorporated by reference into the federal code.

Transmission Lines: Repair of Leaks, Welds, etc. (17.3)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.706, §192.711 – .719

Description of Key Area

The sections listed above can be found under Subpart M (Maintenance) of 49 CFR 192. The Code states requirements for various types of pipeline repair.

Discussion of Criticality

It is important to know what types and extents of damage or leaks can be repaired without replacements being performed.

Discussion of Progress

There are currently several potential repair techniques that may be suitable for hydrogen pipe such as using clock spring techniques or other permanent repair methods.

ASME B31.12 is considering the need for full cylinder replacement for defects that must be repaired.

Recommendations

Standards for repairs of leaks, welds, etc. for hydrogen transmission lines must be established and incorporated by reference into the federal code.

Distribution Systems: Patrolling (17.4)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.721

Description of Key Area

Section 192.721 (Distribution Systems: Patrolling) of Subpart M (Maintenance) of 49 CFR 192 states, "The frequency of patrolling mains must be determined by the severity of the conditions which could cause failure or leakage, and the consequent hazards to public safety."

Discussion of Criticality

The frequency of patrols must be determined as well as what locations to patrol (business districts, outside of business districts, etc.). The frequency of patrols may or may not be the same as that for natural gas.

Discussion of Progress

This topic will be addressed by ASME B31.12.

Recommendations

Standards for patrolling (including frequency of patrol) of hydrogen distribution systems must be established and incorporated by reference into the federal code.

Distribution Lines: Leakage Surveys (17.5)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.723

Description of Key Area

Leakage surveys for distribution lines fall under Subpart M (Maintenance) of 49 CFR 192. This subpart lists the minimum intervals at which leak surveys on distribution lines should be conducted.

Discussion of Criticality

Because of the increased flammability range of hydrogen relative to natural gas, special leak surveys are likely appropriate for hydrogen distribution systems. The adequacy of current combustible gas and hydrogen-specific detection methods and equipment need to be assessed relative to industry leak survey practices.

Discussion of Progress

This topic will be part of the integrity management process that will be mandatory in ASME B31.12.

Recommendations

Standards for hydrogen distribution line leak surveys must be established and incorporated by reference into the federal code.

Test Requirements for Reinstating Service Lines (17.6)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.725

Description of Key Area

Section 192.725 (Test Requirements for Reinstating Service Lines) of Subpart M (Maintenance) of 49 CFR 192 states, "…each disconnected service line must be tested in the same manner as a new service line, before being reinstated."

Discussion of Criticality

Rules regarding testing of disconnected hydrogen service lines and hydrogen service lines temporarily disconnected from the main must be formulated. Also, rules must be made regarding the need to test bypass line installations on hydrogen service lines. There may be additional considerations for higher pressure capable materials and structures that have not yet been identified.

Discussion of Progress

This topic will be addressed by ASME B31.12.

Recommendations

Standards for test requirements for reinstating services must be established and incorporated by reference into the federal code.

Abandonment or Deactivation of Facilities (17.7)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.727

Description of Key Area

Abandonment or deactivation of facilities is considered under Subpart M (Maintenance) of 49 CFR 192. It defines the rules for abandoning pipelines.

Discussion of Criticality

Abandonment methods for hydrogen pipelines must be established to ensure public safety.

Discussion of Progress

This topic will be covered in ASME B31.12.

Recommendations

Standards for abandonment or deactivation of hydrogen facilities must be established and incorporated by reference into the federal code. These standards should include methods of purging, purging gases, gas detection and abandonment procedures. Material and fitting specifications should be considered. Determinations should be made as to what materials and fittings are acceptable for use in the procedures and how acceptable fittings should be tested.

Compressor Stations: Reliefs and Combustible Storage (17.8)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.731 – §192.735

Description of Key Area

Section 192.731 (Compressor Stations: Inspection and Testing of Relief Devices) of Subpart M (Maintenance) of 49 CFR 192 states, “Except for rupture discs, each pressure relieving device in a compressor station must be inspected and tested in accordance with Section 192.739 and 192.743, and must be operated periodically to determine that it opens at the correct set pressure.”

Section 192.735 (Compressor Stations: Storage of Combustible Materials) of Subpart M (Maintenance) of 49 CFR 192 states, “Flammable or combustible materials in quantities beyond those required for everyday use, or other than those normally used in compressor buildings, must be stored a safe distance from the compressor building.”

Discussion of Criticality

Plans and procedures must be established to promptly repair or replace defective equipment. It must be determined how often to test relief devices. Finally, it must be determined if there are any special requirements for storage of combustible materials at compressor stations.

Discussion of Progress

Compressor station design will be covered in ASME B31.12.

Recommendations

Standards must be established relating to hydrogen compressor stations. These standards must be incorporated by reference into the federal code.

Compressor Stations: Gas Detection (17.9)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§192.736

Description of Key Area

Section 192.736 (Compressor Stations: Gas Detection) of Subpart M (Maintenance) of 49 CFR 192 states that "…each compressor building in a compressor station must have a fixed gas detection alarm system……."

Discussion of Criticality

The gas detection system should continuously monitor the compressor building for a certain concentration of hydrogen in air. This concentration must be established. There is an ongoing discussion in the hydrogen community regarding the need to distinguish between hydrogen and other combustible gases in certain applications.

Discussion of Progress

This topic will be addressed by ASME B31.12 as part of compressor station requirements.

Recommendations

The need for hydrogen-specific sensors at compressor stations needs to be evaluated. If required, current sensor development efforts should be evaluated for applicability. Standards must be established relating to hydrogen compressor stations. These standards must be incorporated by reference into the federal code.

Pressure Limiting and Regulating Stations: Inspection, Testing, Reliefs, etc. (17.10)

Criticality: Medium
Score: 12
Progress: Addressed, Not Adequately
DOT Relevance: §192.739 – §192.743

Description of Key Area

Sections 192.739 to 192.743 of Subpart M (Maintenance) of 49 CFR 192 address pressure limiting and regulating stations. The equipment at the stations must be inspected at certain and regular time intervals to make sure that their condition is adequate and can support the capacity required. The equipment must also be checked to make sure that it is set at the correct pressure. Sometimes, the regulating stations must be equipped with telemetering or recording pressure gauges to indicate the gas pressure in the district. If there is an indication of an abnormally high or low pressure, corrective measures are taken. Pressure relief devices must be tested “in place” at regular intervals.

Discussion of Criticality

For hydrogen pipeline purposes, relief devices are important. Regulations as to the frequency of inspection must be determined. The necessity of telemetering to indicate gas pressure on the hydrogen pipeline must be determined. Necessary steps must be put in place when there are indications of abnormally high or low pressure in the hydrogen system. The frequency of testing needs to be confirmed.

Discussion of Progress

This topic will be addressed by ASME B31.12.

Recommendations

Standards must be established relating to hydrogen regulating stations and pressure limiting systems. These standards must be incorporated by reference into the federal code.

Valve Maintenance: Transmission and Distribution Lines (17.11)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.745 – §192.747

Description of Key Area

Sections 192.745 to 192.747 of Subpart M (Maintenance) of 49 CFR 192 address valve maintenance for transmission and distribution lines. The Code states the frequency at which these valves must be inspected.

Section 192.745 (Valve Maintenance: Transmission Lines) states, “Each transmission line valve that might be required during any emergency must be inspected and partially operated at intervals not exceeding 15-months, but at least once each calendar year.”

Section 192.747 (Valve Maintenance: Distribution Systems) states, “Each valve, the use of which may be necessary for the safe operation of a distribution system, must be checked and serviced at intervals not exceeding 15 months, but at least once each calendar year.”

Discussion of Criticality

For hydrogen pipeline purposes, regulations as to the frequency of inspection valves for transmission and distribution lines must be determined.

Discussion of Progress

This topic will be addressed in ASME B31.12.

Recommendations

Standards must be established relating to valve maintenance on hydrogen transmission lines and hydrogen distribution systems. These standards must be incorporated by reference into the federal code.

Vault Maintenance (17.12)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§192.749

Description of Key Area

Section 192.749 (Vault Maintenance) of Subpart M (Maintenance) of 49 CFR 192 states the frequency at which vaults must be inspected, and steps to follow if gas is found in the vault.

Discussion of Criticality

For hydrogen pipeline purposes, regulations as to the frequency of vault inspections must be determined. Regulations must also be put in place for the inspection of ventilating equipment and vault covers. Any areas of confined space must be addressed with regard to operator safety and maintenance. Atmospheric testing may also be appropriate.

Discussion of Progress

No information found.

Recommendations

Confirm whether or not this topic will be addressed by ASME B31.12. Standards must be established relating to vault maintenance on hydrogen pressure regulating and pressure limiting equipment. These standards must be incorporated by reference into the federal code.

Prevention of Accidental Ignition (17.13)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.751

Description of Key Area

Prevention of accidental ignition falls under Subpart M (Maintenance) of 49 CFR 192. §192.751 states that "each operator shall take steps to minimize the danger of accidental ignition of gas in any structure or area where the presence of gas constitutes a hazard of fire or explosion…"

Discussion of Criticality

Appropriate standards are necessary for prevention of accidental ignition of hydrogen pipelines.

Discussion of Progress

SNL is currently conducting research on hydrogen release scenarios, cloud formation and ignition, and flame jet characteristics.

Recommendations

Confirm whether or not this topic will be addressed by ASME B31.12. Research into prevention of accidental ignition for hydrogen pipeline applications must be expanded. This may mean development of tools, equipment, sensors, training programs, etc. Standards need to be developed and incorporated by reference into the federal code.

Qualification of Pipeline Personnel (17.14)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.801 – §192.809

Description of Key Area

Qualification of pipeline personnel is defined under Subpart N (Qualification of Pipeline Personnel) of 49 CFR 192. As per §192.801, "this subpart prescribes the minimum requirements for operator qualification of individuals performing covered tasks on a pipeline facility." A "covered task" is defined in 49 CFR 192 as "an activity…that is performed on a pipeline facility; is an operations or maintenance task; is performed as a requirement of this part; and affects the operation or integrity of the pipeline."

Discussion of Criticality

As qualified personnel, individuals must be able to "recognize and react to abnormal operating conditions."

Discussion of Progress

ASME B31Q has been drafted to address operator training, qualification, and certification. It is expected to be published in 2006.

Recommendations

Standards for hydrogen pipeline operator qualification must be incorporated by reference into the federal code. There may be the need for a national training program for hydrogen pipeline operators.

Pipeline Integrity Management (17.15)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§192.901 – §192.951

Description of Key Area

Pipeline integrity management falls under Subpart O (Pipeline Integrity Management) of 49 CFR 192. As per §192.901, “this subpart prescribes minimum requirements for an integrity management program on any gas transmission pipeline covered under this part.”

Discussion of Criticality

Integrity management of any pipeline system is of fundamental importance for safe and efficient pipeline operation.

Discussion of Progress

ASME B31.8S will be incorporated by reference into ASME B31.12. There will be exceptions taken to sections and alternate language will be provided to make these sections specific to hydrogen. Equations for impact areas will be restated for hydrogen by using DOT report TT013 from June 2005.

Recommendations

Standards for system integrity management of hydrogen pipelines must be incorporated by reference into the federal code. It is expected that new standards will follow the stated procedures within §192.901 – §192.951.

Tests for Appropriate Class Determination (18.1)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§173 Subpart D

Description of Key Area

DOT hazardous materials regulations for transportation are based on the performance of the material when subjected to various tests. The definitions and requirements classification and packing group assignments are found in 49 CFR 173 of the hazardous materials regulations, specifically §173.50 through §173.156. The classification and packing group assignment are, for the most part, based on tests found in the UN Manual of Tests and Criteria and are essentially “open air” tests. Testing of this type for the determination of the potential hazards associated with a metal hydride-based hydrogen storage system may not be appropriate.

There are two broad types of metal hydride hydrogen storage systems that are being developed and need to be considered, rechargeable and non-rechargeable systems; where rechargeable systems contain a reversible metal hydride are refilled by applying hydrogen to the system and non-rechargeable systems are refilled by removing the spent hydrogen-depleted material and replacing it with fresh hydrogen-containing material.

For non-rechargeable systems, the current material testing for determination of hazard class and division may satisfactory address the actual hazards presented by the hydrogen storage system. The systems may contain a mixture of hazardous materials, such as a liquid phase that may or may not contain a solid phase in slurry and possibly gaseous hydrogen. Each of the various materials could be tested by the appropriate test methods and the hazard class/division determined; the overall system classification and division set according to 49 CFR 173.2a for mixtures and materials having more than one hazard.

Rechargeable metal hydride systems will normally contain gaseous hydrogen and a solid phase. While it might seem logical to classify them as a mixture of hazardous materials: gaseous hydrogen (a 2.1 flammable gas) and a solid material, which might be non-hazardous, a 4.1 flammable solid, a 4.2 self-heating solid or a 4.3 water reactive solid, this approach might not represent the actual hazard represented by the overall hydrogen storage system. The independent, separate hazards testing of the solid materials in the absence of hydrogen gas does not accurately represent the state of the materials in a hydrogen storage system in the presence of hydrogen gas. When charged with hydrogen, the hydrogen is bonded to the solid phase, forming a distinctly different chemical species. Reversible hydrogen storage materials, by design, decompose under the operational conditions of the storage system to release gaseous hydrogen. This process is normally endothermic, requiring an input of heat, thus the materials cool upon hydrogen desorption. Also the hydrogen gas might provide a barrier, slowing the diffusion of oxygen-containing air to the material. Therefore the reactivity of the solid material in the presence of hydrogen gas will be different than the combustion or oxygen reactivity of the solid material at ambient temperature when in the totally desorbed state in the absence of air. An extreme example of the difference between the hydrided and non-hydrided state could be shown with titanium, which forms a stable hydride, decomposing to release hydrogen only at high (600°C (1112°F)) temperatures. Dry titanium powder (UN 2546) is a 4.2 self-heating solid assigned to packing group I or II (i.e., either pyrophoric or at least produces moderate heat on air exposure); whereas titanium hydride (UN 1871) is a moderate (packing group II) 4.1 flammable solid.

Additionally hydrogen storage systems that utilize metal hydrides are more complex than simple storage containers. For example two engineered features that these systems will likely contain for proper and optimal operation include a manner to transfer heat between the contained solid phase and an external heat sink and a method of preventing the solid phase from being redistributed within the container. This second feature is to prevent compaction of the solid which could over-stress the container. These engineered features may mitigate potential hazards in case of an accident by minimizing release of material or restricting the ability of air to diffuse to the solid phase. Therefore again the hazard presented by the total system may not be appropriately represented by the individual, open air material tests.

Discussion of Criticality

This item has been assigned a criticality of medium for several reasons. Currently hydrogen storage systems where the hydrogen is absorbed in a metal hydride are allowed for transport under special permits. The UN has approved a listing in the dangerous goods table, UN 3468, and the US DOT issued NA 9279, both of which classifies these systems as 2.1 flammable gas systems. With review and approval of individual systems and manufacturers, potential risks associated with these systems are minimized.

Low power fuel cell systems for portable power applications are entering the commercial marketplace. Today the volumes are relative low with few manufacturers. However it is expected that these applications will be the first to achieve mass market status, with more products, manufacturers, and higher volumes expected within the next few years.

Before packing instructions are put into regulations and some of the materials currently under investigation are introduced into commercial systems, it is recommended that a revised method to determine the true potential hazards presented total system be considered.

Discussion of Progress

In the last several years, the US DOT issued hazardous materials table listing NA 9279, *Hydrogen absorbed in metal hydride* and the UN SCETDG approved entry UN 3468, *Hydrogen in a metal hydride storage system* to the List of Dangerous Goods. Both of these listings assign a hazard classification to the systems of 2.1 flammable gas. Currently these identifications can only be used with approval from the OHMS after review and approval of the packaging. No packaging instructions have been adopted in either the US regulations or the international Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems. All of the systems that allow recharging use NA 9279 and/or UN 3468 with a 2.1 flammable gas classification.

Progress on developing consensus standards that might be used as packaging instructions include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (document 16111). This document is currently in the approval stage as a committee draft (“CD”) for advancement to the draft international standard stage (“DIS”). In parallel to the CD approval, the document is being considered for publication as a technical specification; this will allow publishing of a consensus document at an earlier date than is possible with the International Standard. Once the international standard is approved, the technical specification will be withdrawn.

2. CGA has also considered developing a standard for portable metal hydride hydrogen storage systems. The current status of this effort is not known at this time.

3. Once approved and published, either the ISO or CGA document might be used as the basis for packaging instructions for NA 9279 or UN 3468. However it is expected that neither will explicitly address the hazardous classification of the materials or system.

Proposals have been submitted to ICAO and the UN SCETDG for approval of metal hydride hydrogen storage systems of limited size being transported aboard aircraft, both cargo and passenger, including within the passenger cabin. ICAO has approved part of the request to allow transport aboard cargo aircraft. These proposals have included introducing system level tests of the systems and/or reference to ISO 16111 to approve packaging.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing metal hydride vessel design in a code case to Section VIII-1.

Recommendations

Currently metal hydride hydrogen storage systems can be transported upon review and approval by the OHMS of the packaging. NA 9279 and UN 3468 are available for use as identifications, both with a hazard classification of 2.1 flammable gas. This classification ignores any hazard that might be presented by the solid phase material and/or combination of hydrogen gas with the solid phase material.

Due to the nature of reversible metal hydride hydrogen storage systems, it is recommended that they be considered as articles and system level tests be developed that could predict the potential hazards associated with the total systems under simulated real-life conditions. An example of the testing that could be performed is catastrophic penetrations under several states of charge. This test could include a measurement of the energy that is released and that used to determine restrictions on mode and quantities for transportation. This would not penalize manufacturers that use a material that might appear to be more hazardous according to current test methods but mitigates risk with system design.

While there is a lot of information available about the traditional intermetallic metal hydrides, there is not a lot of public information available about total system performance and their hazards in accident scenarios. Also there are many materials under development that might have very different properties, and thus hazards. By developing system level tests to determine potential hazards, new materials and new designs will be able to be introduced and appropriately classified without the risk of misclassified.

Packaging Instructions for Micro Metal Hydride Hydrogen Storage Systems (18.2)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§173 Subpart D

Description of Key Area

UN SCETDG has approved entry UN 3468, *Hydrogen in a metal hydride storage system*, to the Dangerous Goods List in the UN Model Regulation for the Transport of Dangerous Goods. This entry has been adopted by the US DOT and is included in the Hazardous Materials table in 49 CFR 172.101. Packaging instructions for UN 3468 require approval by the Associate Administrator prior to first shipment (49 CFR 173.214). The Hazardous Materials table also includes entry NA 9279, *Hydrogen absorbed in metal hydride*, which includes no packaging instructions and requires a special permit for transport. Without any guidance on packaging, the OHMS must individually review and issue an approval or special permit for each system design and manufacturer/offeror for all metal hydride-based hydrogen storage systems.

This discussion applies to both entries, UN 3468 and NA 9279. Systems which are appropriately identified by these entries can be divided into two broad groups that really only differ in where and how they might be used and transported. This section will discuss “Micro” systems and Item 18.3 will discuss “Portable” systems. Micro systems are ones that are expected to be transported both as stand-alone storage containers and as storage containers connected to and in use with fuel cell systems. It is anticipated that Micro systems will be approved for transport and use with all modes of transport including the passenger cabin of aircraft. Portable systems are not expected to be transported or used within the passenger cabin of aircraft. Micro systems will likely have a maximum size limitation applied to them. Current proposed size limitations have been arbitrarily chosen and will likely be revised as a natural safety or application-based limit becomes apparent.

Today travelers expect to be allowed to carry and use a host of electronic devices while traveling by road, rail, ship, and air. These devices include laptop computers, cellular phones, PDAs, video games, DVD players, cameras, video recorders, and others. Many devices combine several functions into a single device. As the number of functions a device performs increases, as their overall performance is enhanced and as customer expectations rise, the power and energy requirements for the devices become greater. This has lead to a widening gap between device power and energy demand and the ability of current battery technology to meet demand. One technology that is expected to be able to provide better power and energy capabilities in these applications is hydrogen fuel cells. Fuel cells are similar to batteries in that they convert chemical potential energy into electrical power and energy. However unlike batteries, the fuel and oxidant are supplied from external sources and the by-products exhausted. With hydrogen fuel cells, the fuel is hydrogen and the by-product is water.

Currently there are a lot of development activities being carried out by various companies and organizations around the world on these technologies. Advanced prototypes and early entry products are starting to leave the laboratory environments and enter the marketplace. The number of products and designs available are expected to increase dramatically over the next few years. Without packaging instructions being included in the hazardous materials regulations and without at least a template or set of guidelines for use by the OHMS for evaluating these systems, the effort required to review and approve or issue special permits for each may be burdensome.

Micro systems have additional complexities in their review since it will also need to consider the implications of when they are attached to or detached from a fuel cell appliance. This becomes even more critical in light of their expected transport and use within the passenger cabin of aircraft in today’s environment of heightened concern of potential terrorism.

Discussion of Criticality

This item has been assigned a criticality of high. Without packaging instructions being developed for metal hydride-based hydrogen storage systems, there is no set of consistent minimum requirements to manufacturers and offerors follow. The absence of packaging instructions requires that OHMS personnel review and approve each system from each offeror and manufacturer. This could present a burdensome work load on the OHMS if this technology is found to be able to meet current expectations leading to many requests for approval.

While it is considered critical that packaging instructions be developed for systems identified by UN 3468 and NA 9279, it is also recommended that the packaging instructions be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The packaging instructions should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

The hazardous materials table currently includes two listings: NA 9279, *Hydrogen absorbed in metal hydride* and UN 3468, *Hydrogen in a metal hydride storage system*. Currently these identifications can only be used with approval from the OHMS after review and approval of the packaging. No packaging instructions have been adopted in either the US regulations or the UN Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems that are identified by either one or both of these identifiers.

Progress on developing consensus standards that might be used as packaging instructions include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (ISO 16111). This document is currently in the approval stage as a committee draft (“CD”) for advancement to the draft international standard stage (“DIS”). In parallel to the CD approval, the document is being considered for publication as a technical specification; with possible publication of the TS much earlier than possible for the International Standard. Once the international standard is approved, the technical specification will be withdrawn. This document only considers stand-alone containers.

2. IEC TC 105 has drafted and is currently reviewing a draft publicly available standard for Micro Fuel Cell Systems (IEC PAS 62282-6-1). This document includes sections on fuel storage containers and complete integrated fuel cell appliances with fuel containers. This standard is expected to reference ISO 16111 for metal hydride-based hydrogen storage container design and testing.

3. UL is developing a consensus standard (UL 2265) on micro fuel cell systems. An effort is being made to keep UL 2265 consistent with IEC 62282 and its development is therefore trailing that of IEC 62282.

4. CGA has also considered developing a standard for portable metal hydride hydrogen storage systems. This effort is early in development and the expected publication date is unknown.

Proposals have been submitted to ICAO and the UN SCETDG for approval of metal hydride hydrogen storage systems of limited size being transported aboard aircraft, both cargo and passenger, including within the passenger cabin. ICAO has approved part of the request to allow transport aboard cargo aircraft. These proposals have included introducing system level tests of the systems and/or reference to ISO 16111 to approve packaging.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing metal hydride vessel design in a code case to Section VIII-1.

Recommendations

It is recommended that the OHMS develop a minimum set of design and test criteria for packaging of systems that meet the UN 3468 and NA 9279 hazard descriptions and that meet the micro system definition used in this report. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. It is preferred that these criteria be performance-based. Ideally they would be based on the ISO and IEC standards underdevelopment by international expert committees (ISO 16111 and IEC 62282-6-1).

To help ensure that the standards being developed for metal hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on the applicable development committees. These would include ISO TC 197 working group 10, IEC TC 105 working group 8, the CGA Hydrogen Fuel Technology committee and UL’s 2265 technical committee.

From experience obtained from systems approved under these guidelines, they could, at an appropriate future time, be refined and used as a basis for a New Rule Making Proposal for conversion into regulations and incorporated into 49 CFR 173.

Packaging Instructions for Portable Metal Hydride Hydrogen Storage Systems (18.3)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§173 Subpart D

Description of Key Area

UN SCETDG has approved entry UN 3468, *Hydrogen in a metal hydride storage system*, to the Dangerous Goods List in the UN Model Regulation for the Transport of Dangerous Goods. This entry has been adopted by the US DOT and is included in the Hazardous Materials table in 49 CFR 172.101. Packaging instructions for UN 3468 require approval by the Associate Administrator prior to first shipment (49 CFR 173.214). The Hazardous Materials table also includes entry NA 9279, *Hydrogen absorbed in metal hydride,* which includes no packaging instructions and requires a special permit for transport. Without any guidance on packaging, the OHMS must individually review and issue an approval or special permit for each system design and manufacturer/offeror for all metal hydride-based hydrogen storage systems.

This discussion applies to both entries, UN 3468 and NA 9279. Systems which are appropriately identified by these entries can be divided into two broad groups that really only differ in where and how they might be used and transported. This section will discuss “Portable” systems and Item 18.2 discussed “Micro” systems. Micro systems are ones that are expected to be transported both as stand-alone storage containers and as storage containers connected to and in use with fuel cell systems. It is anticipated that Micro systems will be approved for transport and use with all modes of transport including the passenger cabin of aircraft. Portable systems are not expected to be transported or used within the passenger cabin of aircraft. In most instances portable systems will be stand-alone; however there may be specific applications where the portable systems will be attached to a fuel cell appliance during transportation.

Today electronic appliances are ubiquitous and there is ever greater demand to un-tether them from the grid, i.e., to use them without always having a cord running to a grid-connected electrical outlet. Today this is accomplished by the use of batteries. However a gap has been developing between application power and energy demand and the ability of current battery technology to meet demand. Hydrogen fuel cell technology is expected to be able to provide better power and energy capabilities in these applications. Fuel cells are similar to batteries in that they convert chemical potential energy into electrical power and energy. However unlike batteries, the fuel and oxidant are supplied from external sources and the by-products exhausted. With hydrogen fuel cells, the fuel is hydrogen and the by-product is water. Another advantage of hydrogen fuel cells is that they do not need electricity to be "recharged" as batteries do. This advantage can provide tremendous benefits under certain circumstances such as what was experienced by emergency responders on the Gulf Coast after hurricane Katrina in 2005 when there was no operational electrical grid to recharge batteries for radios and other equipment.

Portable metal hydride-based hydrogen storage systems will find use in many applications, not all of which will be with fuel cells. Since these systems can provide a very compact, low-pressure storage option for hydrogen gas, they may be used in laboratories which need hydrogen for equipment, such as gas chromatographs. They may be used as exchangeable fuel tanks on mobility devices such as wheel-chairs, scooters, golf carts, etc., which may be propelled by either fuel cells or internal combustion engines. Portable systems are expected to be used with portable generators for backup power and for auxiliary power units (APUs), which is an example of an application where they might be connected to an appliance and operating while being transported.

Currently there are a lot of development activities being carried out by various companies and organizations around the world on these technologies. Entry level products have started entering the marketplace. The number of products and designs available are expected to increase dramatically over the next few years. Without packaging instructions being included in the hazardous materials regulations and without at least a template or set of guidelines for use by the OHMS for evaluating these systems, the effort required to review and approve or issue special permits for each may be burdensome.

Discussion of Criticality

This item has been assigned a criticality of high. Without packaging instructions being developed for metal hydride-based hydrogen storage systems, there is no set of consistent minimum requirements to manufacturers and offerors follow. The absence of packaging instructions requires that OHMS personnel review and approve each system from each offeror and manufacturer. This could present a burdensome work load on the OHMS if this technology is found to be able to meet current expectations leading to many requests for approval.

While it is considered critical that packaging instructions be developed for systems identified by UN 3468 and NA 9279, it is also recommended that the packaging instructions be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The packaging instructions should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

The hazardous materials table currently includes two listings: NA 9279, *Hydrogen absorbed in metal hydride* and UN 3468, *Hydrogen in a metal hydride storage system*. Currently these identifications can only be used with approval from the OHMS after review and approval of the packaging. No packaging instructions have been adopted in either the US regulations or the UN Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems that are identified by either one or both of these identifiers.

Progress on developing consensus standards that might be used as packaging instructions include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (ISO 16111). This document is currently in the approval stage as a committee draft (“CD”) for advancement to the draft international standard stage (“DIS”). In parallel to the CD approval, the document is being considered for publication as a technical specification; with possible publication of the TS much earlier than possible for the International Standard. Once the international standard is approved, the technical specification will be withdrawn. This document only considers stand-alone containers.

2. CGA has also considered developing a standard for portable metal hydride hydrogen storage systems. This effort is early in development and the expected publication date is unknown.

Proposals have been submitted to ICAO for approval of metal hydride-based hydrogen storage systems to be transported aboard aircraft. ICAO approved transport aboard cargo aircraft. It is expected that future requests to ICAO for transport in the cargo space of passenger aircraft will be made once a published document on system design and testing is available for reference. The OHMS granted special permit DOT-E 13598, issued to Jadoo Power Systems, that allows up to 90.7 kg (200 lb) to be transported aboard cargo aircraft.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing metal hydride vessel design in a code case to Section VIII-1.

Recommendations

It is recommended that the OHMS develop a minimum set of design and test criteria for packaging of systems that meet the UN 3468 and NA 9279 hazard descriptions and that meet the portable system definition used in this report. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. It is preferred that these criteria be performance-based. Ideally they would be based on ISO 16111, underdevelopment by an international committee of experts.

To help ensure that the standards being developed for metal hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on the applicable development committees. These would include ISO TC 197 working group 10 and the CGA Hydrogen Fuel Technology committee.

From experience obtained from systems approved under these guidelines, they could, at an appropriate future time, be refined and used as a basis for a New Rule Making Proposal for conversion into regulations and incorporated into 49 CFR 173.

Reactive Hydrogen Storage May Be Mixtures (18.4)

Criticality: High **Progress:** Addressed, Not Adequately
Score: 20 **DOT Relevance:**

Description of Key Area

DOT hazardous materials regulations for transportation are written to provide a minimum level of safety when transporting materials that are dangerous and could pose a hazard if not appropriately controlled. Materials are divided by their potential hazard classification, defined in 49 CFR 173 of the hazardous materials regulations. This part also contains criteria to be followed for packaging the materials, including prohibitions on combining certain types of materials that could react together. The current packaging specifications, and especially the prohibitions on mixtures, may not be appropriate for metal hydride-based hydrogen storage systems and may forbid their transport as currently written.

There are two broad types of metal hydride hydrogen storage systems that are being developed and need to be considered, rechargeable and non-rechargeable systems; where rechargeable systems contain a reversible metal hydride and are refilled by applying hydrogen to the system and non-rechargeable systems are refilled by removing the spent hydrogen-depleted material and replacing it with fresh hydrogen-containing material. Any regeneration of the hydrogen-containing material from the hydrogen-depleted material in non-rechargeable systems is done independent of the storage system.

Non-rechargeable systems may contain a mixture of hazardous materials that are selected such that they combine or react to produce hydrogen gas. These systems may contain mixed solids, mixed liquid and solid phases, liquids with dissolved solids, gaseous and liquid or solid phases, etc. They may also contain gaseous hydrogen during part of the time or at all times in at least part of the packaging.

A number of different types of non-rechargeable systems have been developed and/or proposed. Three examples include:

1. Reacting alkali (e.g., sodium and potassium) or alkaline earth metals (e.g., calcium) or their hydrides with water to produce hydrogen gas. For example with sodium metal the reaction would be:

$$Na_{(s)} + H_2O_{(l)} \rightarrow \frac{1}{2} H_{2(g)} + NaOH_{(aq)}$$

Various method of containing reactants and controlling reaction have been proposed, such as making a slurry of the metals in an organic or inorganic oil and controlling the addition of water and encapsulating the solids in with a non-reactive coating and placing them in a container with water—the encapsulating coating are then mechanically breached as required to liberate gaseous hydrogen.

2. Reacting ammonia with an aluminum hydride, such as $LiAlH_4$, to produce hydrogen gas and various amines and amides as by-products. In one system developed for and tested by the military, the ammonia, which is contained in one pressurized compartment, passes through a valve into a second compartment that contains the solid hydride phase. In the second compartment the reaction occurs, producing gaseous hydrogen. The hydrogen gas pressure is used to control the rate of ammonia passing into the second compartment.

3. Reacting sodium borohydride catalytically with water to produce hydrogen and sodium borate. The reaction is:

$$NaBH_{4(aq)} + 2\ H_2O_{(l)} \text{ –(cat.)}\rightarrow 4\ H_{2(g)} + NaBO_{2(aq)}$$

   If not taken to completion, the reaction by-product could be $NaB(OH)_4$. In one version of this type of system, the aqueous solution of sodium borohydride is stabilized by buffering the solution to a high pH, typically in the 12 to 14 range. The stabilized solution is then passed through a second chamber containing the catalyst where the reaction rapidly occurs, liberating gaseous hydrogen. The spent solution is collected in a third chamber.

Rechargeable metal hydride systems will normally contain gaseous hydrogen and a solid phase. Reversible hydrogen storage materials, by design, decompose under the operational conditions of the storage system to release gaseous hydrogen through a reversible decomposition reaction. By changing conditions, such as increasing the hydrogen gas pressure or reducing temperature, the reverse formation reaction occurs producing the hydrogen-containing solid phase once more. This process is normally endothermic (absorbing heat) for the decomposition reaction and exothermic (producing heat) for the formation reaction.

Metal hydride-based hydrogen storage systems are more complex than simple storage containers. For example two engineered features that reversible systems will likely contain for proper and optimal operation include a manner to transfer heat between the contained solid phase and an external heat sink and a method of preventing the solid phase from being redistributed within the container. Non-rechargeable system may include multiple compartments, heat exchangers, valve and manifolds, etc. Such engineered features are normally not found in simple packaging for transport and may mitigate potential hazards in case of an accident by minimizing release of material or restricting the ability of them to react together or with air.

When the requirements of 49 CFR 173 are examined for the example hydride-based hydrogen storage systems, several conflicts are readily apparent. First, the systems contain materials that react to produce hydrogen, a flammable gas—not allowed by §173.21(e), §173.21(g) and §173.24(e)(4). Second, the systems may not use DOT specification packaging as required §173.24(c) nor be able to use a metal cylinder (even though they may have hydrogen gas present) as required by §173.301(a)(1). If not properly designed and engineered, they might also not be allowed by paragraph §173.301(d).

Discussion of Criticality

The hazardous materials table currently includes two listings: NA 9279, *Hydrogen absorbed in metal hydride* and UN 3468, *Hydrogen in a metal hydride storage system* that may be used for the rechargeable (reversible) systems. These identifications can only be used with approval from the OHMS after review and approval of the packaging since no packaging instructions have been adopted in either the US regulations or the UN Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems that are identified by either one or both of these identifiers.

The two identifiers, UN 3468 and NA 9279, are not suitable for most of the non-rechargeable systems. They might be best identified as mixed hazard systems based on the contained materials, reactants and by-products. Paragraphs §§173.155, 173.156 and 173.222 (for Exceptions for Class 9 (miscellaneous hazardous materials), Exceptions for ORM materials and Dangerous goods in equipment, machinery or apparatus, respectively) might be applicable to these systems. Guidelines for packaging and testing of these systems will need to be developed. However it will be necessary to develop exceptions to certain restrictions, as listed previously, to allow these systems for transport.

While it is considered critical that packaging instructions be developed for hydride-based hydrogen storage systems, it is also recommended that the packaging instructions be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The packaging instructions should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

In the last several years, the US DOT issued hazardous materials table listing NA 9279, *Hydrogen absorbed in metal hydride* and the UN SCETDG approved entry UN 3468, *Hydrogen in a metal hydride storage system* to the List of Dangerous Goods. Both of these listings assign a hazard classification to the systems of 2.1 flammable gas. Currently these identifications can only be used with approval from the OHMS after review and approval of the packaging. No packaging instructions have been adopted in either the US regulations or the international Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems, essentially approving the packaging and exempting them from §173.301(d).

Currently there are no known special permits issued for non-reversible hydride-based hydrogen storage systems. However there are numerous companies and organizations that are developing various types of systems. Systems of this type have been tested by the military, government laboratories and corporations over a number of years. Commercially available products are expected to become available within the next few years. DOE—through its Hydrogen, Fuel Cells and Infrastructure Technologies Program—has established three hydrogen storage research Centers of Excellence, one on metal hydride (i.e., rechargeable) and one on chemical hydride (i.e., non-rechargeable) materials and systems.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing metal hydride vessel design in a code case to Section VIII-1.

Recommendations

Currently rechargeable metal hydride hydrogen storage systems can be transported upon review and approval by the OHMS of the packaging using NA 9279 and UN 3468 identifiers and descriptions. It is recommended that the OHMS develop a minimum set of design and test criteria for packaging of systems that meet the UN 3468 and NA 9279 hazard descriptions and that meet the rechargeable system definition used in this report. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. It is preferred that these criteria be performance-based. Ideally they would be based on ISO 16111, underdevelopment by an international committee of experts.

For non-rechargeable or chemical hydride-based systems, there has been little work on developing system standards. This is partly due to the broad range of materials and system designs and the fact that most are currently proprietary and not commercially available. It is recommended that the DOT review current proposed chemical hydride systems against current regulations to start developing requirements and guidelines for potential special permits to regulations that would prohibit the systems. Experience from this effort could be used for possible new entries to the Hazardous Materials table (§172.101) and packaging specifications. The review should include persons from industry, the DOE Centers of Excellence, and DOT.

To help ensure that the standards being developed for hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on applicable standards development committees.

From experience obtained from systems approved under these guidelines, they could, at an appropriate future time, be refined and used as a basis for a New Rule Making Proposal for conversion into regulations and incorporated into 49 CFR 173.

Emergency Response Information: High Pressure Gas, Steel (19.1)

Criticality: High
Score: 10
Progress: Addressed, Monitoring
DOT Relevance: §172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving hydrogen stored and transported as a compressed gas in steel cylinders. The emergency response information must be applicable to tube trailers and/or any other compressed hydrogen steel cylinder packaging. In particular, the emergency response information resources must apply to operations such as the transfer of hydrogen from tube trailers to stationary pressure vessels at vehicle fueling stations, temporary parking of tube trailers to provide the hydrogen source at a fueling station, delivery of hydrogen-filled steel cylinders to fueling stations, and the use of hydrogen “mobile fuelers” with steel pressure vessels.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures evolve that utilize hydrogen transported as a compressed gas in steel cylinders. Examples include hydrogen transported in tube trailers from central production plants to fueling stations (with the gas transferred to permanently installed high-pressure vessels at the fueling station, or, as is more common, parking of the tube trailer at the fueling station to serve as a temporary gas supply) and “mobile fuelers” (some of which utilize compressed hydrogen stored in steel cylinders). Both of these examples are in common use at this time to support hydrogen-fueled vehicle demonstration projects. However, neither of these infrastructure scenarios are economically viable, nor are they likely to be part of a widespread hydrogen-fueled vehicle deployment scenario. They are not economically viable because, for example, a truck-transported tube trailer (which can hold up to 350 kg (772 lb) of hydrogen at up to 21.4 MPa (3100 psi)) consumes more energy than it delivers for distances greater than roughly 1610 km (1000 miles).

As discussed below, emergency response resources applicable to accidents involving compressed hydrogen steel pressure vessels (e.g., as used in tube trailers) are well developed for current applications, which are generally limited to restricted-access industrial sites and trained personnel. These same resources are probably appropriate and adequate for supporting current tests and demonstrations of hydrogen vehicles, which are few in number, have limited access, and are closely managed by trained personnel. A possible exception may be associated with current and future use of mobile fueling stations that store hydrogen in steel vessels. These units involve a relatively unusual combination of components (e.g., unlike tube trailers, they are not addressed specifically in the DOT ERG2004) and their application straddles two jurisdictions (i.e., DOT when they are transported on highways and OSHA/local AHJs when they are parked and operated as vehicle fueling stations).

If hydrogen-fueled vehicles commercialize with a fueling infrastructure that involves tube trailers and/or the use of any other steel pressure vessels in DOT-jurisdiction applications (which is judged to be unlikely), then new and specifically focused emergency response resources will be needed to enable first responders to deal effectively with potential accidents in environments such as public-access fueling stations.

Discussion of Progress

Progress toward providing the technical basis to support development of emergency response information applicable to a potential hydrogen fuel infrastructure involving compressed hydrogen stored in steel vessels is rated as “Addressed, monitoring.” This is because considerable resources are already available, and although these resources were not developed to apply specifically to environments like public-access fueling stations, it is unlikely that steel pressure vessels will be a significant element of the fuel-delivery infrastructure supporting commercialized hydrogen vehicles.

For example, in the DOT ERG2004, compressed hydrogen is assigned ID Number 1049 and covered by Guide Number 115 (Gasses—Flammable, Including Refrigerated Liquids). Emergency response guidance pertaining to tube trailers (which are designed, manufactured, tested, and marked consistent with DOT-3A or -33A specifications in 49 CFR 178.36 and §178.37, respectively) that might transport hydrogen is also contained in literature produced by industrial gas companies (e.g., “Safetygrams”) and other sources. Emergency response resources are also readily available for compressed hydrogen in individual steel cylinders.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing high pressure gas storage in metal and composite tanks. The work plan includes a proposed new article KD-10 to Section VIII-3, a code case on composite tanks for Section VIII-3, and a revision to code case 2390 on metal lined composite reinforced circumferentially wrapped pressure vessels under Section VIII-3. Transport tanks may also be included in Section XII.

Recommendations

Currently available emergency response information resources are adequate for current low-vehicle-number and controlled-access hydrogen vehicle demonstration projects that sometimes utilize compressed hydrogen delivered in tube-trailers or individual cylinders. More research is needed to develop emergency response resources applicable to mobile hydrogen fueling stations with steel pressure vessels, especially if the use of such mobile fueling stations increases.

Comprehensive emergency response resources applicable to compressed hydrogen steel pressure vessels employed as part of a commercialized hydrogen vehicle fueling infrastructure will probably not be needed, because steel pressure vessels are not anticipated to be a significant part of the fuel-transport aspects of such an infrastructure. However, hydrogen fueling infrastructure evolution should be monitored, and work to develop appropriate emergency response resources should be initiated if it appears that steel pressure vessels will in fact be part of this infrastructure.

Emergency Response Information: High Pressure Gas, Composite (19.2)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving hydrogen stored and transported as a compressed gas in composite cylinders, which may be part of a hydrogen fueling infrastructure. “Composite cylinders” as used here refers to a broad range of pressure vessel types that include metallic or polymer shells (liners) that are reinforced by being hoop- wrapped or full-wrapped with high-strength carbon, fiberglass, or other fibers, which are generally resin impregnated. DOT special permits currently allow compressed hydrogen to be transported in certain specific types of composite packagings, as specified in the special permit language.

The emergency response information must be applicable to tube trailers and/or any other compressed hydrogen composite cylinder packaging. In particular, the emergency response information resources must apply to operations such as the transfer of hydrogen from tube trailers to stationary pressure vessels at vehicle fueling stations, temporary parking of tube trailers to provide the hydrogen source at a fueling station, delivery of hydrogen-filled composite cylinders to fueling stations, and the use of hydrogen “mobile fuelers” with composite pressure vessels.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures evolve that utilize hydrogen transported as a compressed gas in composite cylinders. Examples include hydrogen transported in tube trailers from central production plants to fueling stations (with the gas transferred to permanently installed high-pressure vessels at the fueling station, or, as is more common, parking of the tube trailer at the fueling station to serve as a temporary gas supply) and “mobile fuelers” (some of which utilize compressed hydrogen stored in composite cylinders). However, the economic viability of these infrastructure scenarios appears to be poor at this time, and so they are unlikely to be part of potential future hydrogen-fueled vehicle commercialization. The economic problems derive from the fact that, even with composite cylinders, the total quantity of hydrogen that can be transported in a tube trailer (or a mobile fueler) is such that the cost per unit mass or energy of hydrogen delivered to a fueling station would require the dispensed hydrogen cost to substantially exceed established goals.

As discussed below, emergency response resources applicable to accidents involving compressed hydrogen in steel pressure vessels (e.g., as used in tube trailers) are well developed for current applications, which are generally limited to restricted-access industrial sites and trained personnel. These same resources are probably appropriate and adequate for supporting current tests and demonstrations of hydrogen vehicles, which are few in number, have limited access, and are closely managed by trained personnel. A possible exception may be associated with current and future use of mobile fueling stations that store hydrogen in composite vessels. These units involve a relatively unusual combination of components (e.g., unlike tube trailers, they are not addressed specifically in the DOT ERG2004) and their application straddles two jurisdictions (i.e., DOT when they are transported on highways and OSHA/local AHJs when they are parked and operated as vehicle fueling stations).

Another issue may derive from the fact that current experience and emergency response information resources pertain primarily to applications such as tube trailers equipped with steel pressure vessels, which are designed, manufactured, tested, and marked consistent with DOT-3A or -33A specifications in 49 CFR 178.36 and §178.37, respectively. An accident involving a composite tube trailer in a fire situation, for example, may include special issues associated with the flammability or combustion product toxicity of the fiber materials or resins used in composite pressure vessel construction.

If hydrogen-fueled vehicles commercialize with a fueling infrastructure that involves tube trailers and/or the use of any other composite pressure vessels in DOT-jurisdiction applications, then new and specifically focused emergency response resources will be needed to enable first responders to deal effectively with potential accidents in environments such as public-access fueling stations. Moreover, these emergency response information resources will need to address any special emergency response requirements associated with the fact that the pressure vessels are of composite construction rather than steel construction.

Discussion of Progress

Progress toward providing the technical basis to support development of emergency response information applicable to a potential hydrogen fuel infrastructure involving compressed hydrogen stored in composite cylinders is rated as “Addressed, Not Adequately.” This is because, although resources are currently available to guide emergency response to accidents involving compressed hydrogen packaging and transportation systems using steel pressure vessels, these were not developed with the anticipation that they would apply to public access situations such as fueling stations, and they do not include any special considerations that may be associated with composite materials (e.g., the previously mentioned potential flammability or combustion product issues).

The above-referenced currently available emergency response information resources include the DOT ERG2004. Compressed hydrogen is assigned ID Number 1049 and covered by Guide Number 115 (Gasses—Flammable, Including Refrigerated Liquids). Emergency response guidance pertaining to tube trailers that might transport hydrogen is also contained in literature produced by industrial gas companies (e.g., “Safetygrams”) and other sources.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing high pressure gas storage in metal and composite tanks. The work plan includes a proposed new article KD-10 to Section VIII-3, a code case on composite tanks for Section VIII-3, and a revision to code case 2390 on metal lined composite reinforced circumferentially wrapped pressure vessels under Section VIII-3. Transport tanks may also be included in Section XII.

Recommendations

It is recommended that progress toward hydrogen-fueled vehicle commercialization should be monitored, and if there are indications that composite pressure vessels may be used as part of the fueling infrastructure beyond the pre-commercial demonstration phase (e.g., for tube trailer delivery of hydrogen to fueling stations), then work to develop appropriate emergency response information resources should be initiated. These resources should address any particular requirements associated with compressed hydrogen delivery and unloading at public-access fueling stations and any special issues associated with the use of composite rather than steel pressure vessels.

More research is also needed to develop emergency response resources applicable to mobile hydrogen fueling stations with composite pressure vessels, especially if the use of such mobile fueling stations increases.

Emergency Response Information: Cryogenic (19.3)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the provision of appropriate information needed by first responders to potential emergencies (e.g., accidents) involving cryogenic liquid hydrogen, which may be part of a central-production hydrogen fueling infrastructure. The emergency response information must be applicable to liquid hydrogen tank truck transportation from the production plant to fueling stations, including liquid hydrogen loading and (especially) unloading operations.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures evolve that utilize hydrogen transported as a cryogenic liquid from central production plants to fueling stations. This key area is also obviously critical to infrastructures supporting vehicles that have liquid hydrogen fuel tanks. At the present time, during this pre-commercialization demonstration phase, a significant portion of hydrogen fueling stations do indeed receive and store liquid hydrogen. However, various DOE-sponsored “source-to-wheels” studies and the National Academies Review conclude that a fueling infrastructure involving hydrogen liquefaction is not viable, primarily because the liquefaction process is so energy intensive (requiring 30 to 40% of hydrogen’s heating value).

It is not possible to foresee how soon the goal of renewable-energy-based and low-greenhouse-gas-emissions hydrogen production, either distributed onsite at fueling stations or centralized with pipeline delivery, will be realized. If this infrastructure goal is reached at the same time as hydrogen-fueled vehicles become a commercial reality, then the need for enhanced cryogenic hydrogen emergency response information is less critical. This is because current emergency response resources, which support liquid hydrogen transportation for industrial applications, will probably suffice to support the needs of controlled-access technology demonstrations. If, however, hydrogen vehicle commercialization evolves with liquid hydrogen delivery, then the need to refine cryogenic hydrogen emergency response information is critical. This is because current emergency response resources are aimed at industrial applications with controlled access and trained personnel. Liquid hydrogen delivery to public-access fueling stations will involve a different set of circumstances and require different emergency response resources.

Discussion of Progress

Progress toward providing the technical basis needed for developing emergency response information applicable to cryogenic hydrogen transportation as part of a hydrogen vehicle fueling infrastructure is rated as “Addressed, Not Adequately.” This is because currently available resources (e.g., the DOT Emergency Responders Guidebook) are adequate to support the cryogenic hydrogen transportation required for delivery to controlled-access fueling stations supporting technology demonstration projects. In addition, new emergency response resources being developed specifically for hydrogen vehicle and infrastructure applications (e.g., CaFCP Emergency Responders Guide, DOT-FTA Hydrogen Bus Design Guidelines, etc.) usually have sections that address cryogenic hydrogen safety practice and/or emergency response.

However, if a fully commercialized hydrogen vehicle fueling infrastructure evolves that includes cryogenic hydrogen delivery and fuel storage, then new and different emergency response resources will be required to address the substantial increase in cryogenic hydrogen transportation (by highway truck and possibly also by railroad and/or marine vessel) and the substantial implications of unloading liquid hydrogen at public-access fueling stations.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

Recommendations

Work to update emergency response information resources supporting cryogenic hydrogen transportation should proceed in parallel with work to update other 49 CFR regulations pertaining to hydrogen vehicle cryogenic hydrogen packaging and transportation. Particular emphasis should be given to the implications of high-volume hydrogen delivery and unloading in an open public-access environment. If and when it appears that liquid hydrogen transportation may be an element of the hydrogen fueling infrastructure supporting fully commercialized hydrogen vehicle operations, then work to characterize the new requirements and develop appropriate emergency response resources should be substantially accelerated.

One reason for prioritizing cryogenic hydrogen transportation emergency response resource development is the fact that there has already been one noteworthy mishap involving cryogenic hydrogen truck delivery to a fuel cell test facility, and there have been more serious incidents involving analogous cryogenic tank trucks transporting LNG vehicle fuel.

Emergency Response Information: Metal Hydride (19.4)

Criticality: High
Score: 20
Progress: Addressed, Not Adequately
DOT Relevance: §172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving hydrogen transported in metal hydride storage systems used as part of a hydrogen vehicle fueling infrastructure.

“Metal hydrides,” as used here, refers to metals for which the hydriding reactions are reversible at convenient temperatures and pressures so that the recharging process is accomplished by simply applying hydrogen gas to the system over a brief time period with heat removed to a heat transfer fluid. DOE is sponsoring a large team headed by SNL to research and develop metal hydrides for low-cost on-vehicle hydrogen storage systems with high gravimetric and volumetric densities. Metal hydride hydrogen storage systems are also being developed by various industrial firms, some systems are being field demonstrated, and a few have been commercialized for specific applications.

Possible evolution of economical metal hydride storage systems with suitable density and convenient rechargeability brings up the possibility that such systems could be used to transport hydrogen from a central production plant to a fueling station. For example, metal hydride powder might be contained within a pressure vessel equipped with heat exchanger elements and connections, and the overall system might be trailer-mounted so that it resembles a tank truck trailer. At the hydrogen vehicle fueling station, hydrogen could be discharged from this trailer to charge permanently installed hydrogen storage equipment or the metal hydride tank truck trailer could be disconnected and parked to provide temporary hydrogen supply for the station (analogous to a tube trailer). If this type of hydrogen transportation system is used as part of a commercial hydrogen vehicle fueling infrastructure, then emergency response information resources specific to this technology will be needed.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures that utilize metal hydride hydrogen storage and transportation systems do in fact evolve. This is because, even though some partially applicable emergency response information resources current exist (e.g., the DOT ERG2004 lists hydrogen absorbed in metal hydride, as discussed below), these resources may not be applicable to new metal hydride technologies and storage/transportation systems, and they will probably not be applicable to operations in an open-public-access environment such as a public fueling station.

The important but unanswered question pertains to the likelihood that such a hydrogen vehicle fueling infrastructure will in fact develop. In this regard, it should be recognized vehicle fueling infrastructure will in fact develop but metal hydride based systems may not play a significant role relative to distributed production (i.e., at the fueling station) or delivery via pipeline.

Discussion of Progress

Progress toward providing emergency response information resources appropriate to metal hydride hydrogen storage packagings and transportation systems used as part of a hydrogen fueling infrastructure is rated as “Addressed, Not Adequately.” This is because, while some resources currently exist, they may not be applicable to evolving metal hydride technologies and packaging/transportation systems, and they may not be adequate to cover operations at public-access fueling stations.

The DOT ERG2004 lists both Hydrogen (ID Number 1049, with reference to Guide Number 115, “Gases—Flammable, Including Refrigerated Liquids) and Hydrogen Absorbed in Metal Hydride (ID Number 9279, which also refers to Guide Number 115). Other listings in the Guidebook address some of the solid material categories potentially applicable to uncharged (non-hydrided) metal powders that might be used in a hydrogen metal hydride storage system. Examples include various pyrophoric metals, self-heating solids, and water-reactive solids. However, there are serious uncertainties, which are discussed elsewhere, regarding the potential applicability of guidelines for non-hydrided materials to a metal hydride hydrogen storage package and transportation system delivering hydrogen to a hydrogen vehicle dueling station site.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing metal hydride vessel design in a code case to Section VIII-1.

Recommendations

It is recommended that research to develop metal hydride hydrogen storage technologies should be monitored. Analyses and perhaps testing should be carried out to identify any scenarios where accidents involving metal hydride hydrogen storage systems might involve exposure to non-hydrided materials that are pyrophoric, toxic, or otherwise hazardous. It is anticipated that these analyses and possible tests are being, or will be, carried out as part of current on-vehicle metal hydride hydrogen storage R&D efforts or current metal hydride commercialization activities, but this should be verified.

If R&D succeeds in developing practical and economical metal hydride hydrogen storage systems, and if it appears that this technology may be used as part of a commercialized hydrogen vehicle fueling infrastructure (e.g., tank trucks containing hydrogen absorbed in metal hydrides used to transport hydrogen from central production plants to fueling stations), then work to develop appropriate emergency response information resources should be initiated.

Emergency Response Information: Cryogas (19.5)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving hydrogen transported as a "cryogas" as part of a hydrogen vehicle fueling infrastructure.

"Cryogas" refers to a method of hydrogen storage being researched and developed at LLNL, which is also sometimes referred to as "cryogenic compressed hydrogen." This hydrogen storage strategy seeks to store hydrogen gas (but not usually liquid or liquid-gas mixtures) at cryogenic temperatures (e.g., 80°K) and moderately high pressures (e.g., 25 MPa). The claimed advantages of this storage strategy include: higher storage density than conventional compressed storage, less hold-time and boil-off issues than liquid storage, no energy consumption for ortho-to-para conversion, and flexibility to fill the tank to pressure-temperature conditions tailored to the specific mission.

DOE has sponsored LLNL to study potential applications of cryogas storage for hydrogen vehicle fuel tanks and also for the tube trailer delivery from centralized hydrogen production plants to fueling stations. If this type of tube trailer is in fact manufactured and used as part of a commercialized hydrogen fueling infrastructure (or if any other cryogas-type hydrogen packaging is used as part of such an infrastructure), then emergency response information resources specific to this technology will be needed.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures that utilize cryogas storage do in fact evolve. This is because the emergency response requirements may be different from currently available resources, and no known work is currently underway to develop cryogas packaging emergency response information resources. The important but unanswered question pertains to the likelihood that such a hydrogen vehicle fueling infrastructure will in fact develop. In this regard, it should be recognized vehicle fueling infrastructure will in fact develop but cryogas based systems may not play a significant role relative to distributed production (i.e., at the fueling station) or delivery via pipeline. Also, cryogas is in the R&D stage at this time. Small cryogas tanks have been fabricated and tested in the laboratory and in the field, but no large-capacity packaging or tube trailers have been built.

Discussion of Progress

Progress toward providing emergency response information resources appropriate to cryogas packagings and transportation used as part of a hydrogen fueling infrastructure is rated as “Addressed, Not Adequately.” This is because no specific resources exist at this time. The DOT ERG2004 Guide Number 115 (Gases—Flammable, Including Refrigerated Liquids) covers hydrogen that is either compressed or liquefied, but responding to a hypothetical cryogas tube trailer accident might involve some issues that are not covered in this guide.

LLNL and subcontractors have carried out some relevant tests of small cryogas “insulated pressure vessels” including burst tests and drop tests. They have also published claims that cryogas vessels would be safer than conventional high-pressure vessels because they contain less mechanical stored energy, the fatigue strength of reinforcement materials is higher at low temperatures, and other reasons.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

Recommendations

It is recommended that the development of cryogas storage technology for hydrogen should be monitored. If it appears likely that this technology may be used as part of a commercialized hydrogen vehicle fueling infrastructure (e.g., cryogas tube trailers), then work to develop appropriate emergency response information resources should be initiated.

Emergency Response Information: Physisorption (19.6)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving hydrogen transportation systems that may utilize physisorption hydrogen storage technology.

Physisorption refers to the process by which hydrogen molecules can be adsorbed into the surface of certain materials such as activated carbon. DOE is sponsoring a large team headed by NREL to research and develop high-physisorption-capacity carbon structures such as nanotubes, which may enable hydrogen storage systems with high gravimetric and volumetric energy densities. In general, hydrogen is adsorbed at low temperatures and desorbed (released) when the temperature is increased. Research is seeking materials with high surface-to-volume ratios that do not require cryogenic temperatures to achieve adequate hydrogen adsorption capacity.

The current DOE research is focused toward on-vehicle hydrogen, but if this R&D is successful, larger-scale adsorbed hydrogen storage systems may be developed (e.g., hydrogen tank truck trailers that transport hydrogen adsorbed on carbon nanostructures). If this type of hydrogen transportation system is used as part of a commercialized hydrogen fueling infrastructure, then emergency response information resources specific to this technology will be needed.

Discussion of Criticality

This key area will be critical if hydrogen fueling infrastructures that utilize physisorption hydrogen storage and transportation systems do in fact evolve. This is because the emergency response requirements may be different from those addressed by currently available information resources, and no known work is currently underway to develop emergency response information specific to hydrogen physisorption packagings (e.g., tank truck trailers containing hydrogen adsorbed in activated carbon nanostructures) or their transportation. The important but unanswered question pertains to the likelihood that such a hydrogen vehicle fueling infrastructure will in fact develop. In this regard, it should be recognized vehicle fueling infrastructure will in fact develop but physisorption based systems may not play a significant role relative to distributed production (i.e., at the fueling station) or delivery via pipeline

Discussion of Progress

Progress toward providing emergency response information resources appropriate to hydrogen physisorption storage packagings and transportation used as part of a hydrogen fueling infrastructure is rated as “Addressed, Not Adequately.” This is because, as discussed above, no specific resources exist at this time.

The DOT ERG2004 lists Activated Carbon, ID Number 1362, and refers to Guide Number 133 (Flammable Solids). The Guidebook also lists Hydrogen, ID Number 1049, and refers to Guide Number 115 (Gases—Flammable, Including Refrigerated Liquids). It might be supposed that the information resources in these two guides is applicable to a tank truck trailer containing a hydrogen physisorption storage system, but it remains to be determined if information resources specifically tailored to this evolving hydrogen storage technology will be needed.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

Recommendations

It is recommended that research to develop physisorption-based hydrogen storage technology should be monitored. If this R&D succeeds in developing practical and effective hydrogen storage systems and it appears that these systems may be used as part of a commercialized hydrogen vehicle fueling infrastructure (e.g., tank truck trailers containing hydrogen adsorbed in carbon nanostructure media used to transport hydrogen from central production plants to fueling stations), then work to develop appropriate emergency response information resources should be initiated.

Emergency Response Information: Complex Hydrides (19.7)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving the refueling material transportation infrastructure that might be used for hydrogen vehicles with complex hydride fuel storage systems.

“Complex hydrides,” as used here, refers to hydrides that are not readily reversible so that they are not regenerated while packaged in the vehicle fuel tank by being exposed to hydrogen gas. Instead, they are usually processed as a solution or slurry, which is often called a carrier. The hydrogen-releasing reaction usually involves mixing the carrier with water with the aid of a catalyst. The vehicle is refueled by removing the spent carrier and replacing it with freshly regenerated (hydrided) carrier. The spent carrier is then regenerated at a central processing plant, and the cycle repeats. Sodium borohydride is the most frequently cited example of this type.

DOE is sponsoring a large team jointly headed by LANL and PNNL to research and develop chemical hydrogen storage technologies of this type for low-cost on-vehicle systems with high gravimetric and volumetric energy density. Sodium borohydride systems have been field tested to a limited extent, e.g., in the Chrysler Natrium fuel cell vehicle.

Here we are concerned with the material packaging and transportation system that would be needed to support the refueling infrastructure for hydrogen vehicles with hydrogen storage systems that require defueling of a spent material, refueling with a regenerated material, and material regeneration at a central plant.

Discussion of Criticality

This key area will be critical if commercial hydrogen vehicles employ fuel storage systems containing hydrides such as sodium borohydride, which must be recharged at a central processing plant. This is because, even though some partially applicable emergency response information resources currently exist (e.g., the DOT ERG2004, as discussed below), these resources may not be ideally applicable to the specific chemicals and transportation systems that support the refueling infrastructure, and they will probably not be applicable to operations in an open-public-access environment such as a public fueling station.

The important but unanswered question pertains to the likelihood that hydrogen vehicles of this type will be commercialized, and the associated spent/regenerated slurry exchange type of refueling infrastructure will develop. In this regard, it should be recognized vehicle fueling infrastructure will in fact develop but complex hydride based systems may not play a significant role relative to distributed production (i.e., at the fueling station) or delivery via pipeline

Discussion of Progress

Progress toward providing emergency response information resources appropriate to the refueling transportation infrastructure that might be used to support hydrogen vehicles with chemical hydride slurry fuel storage systems is rated as “Addressed, Not Adequately.” This is because, while some resources currently exist, they may not be applicable to the specific hazardous materials that might be used in commercialized chemical hydride slurry fuel storage systems, and they may not be adequate to cover operations at public-access fueling stations.

For example, the DOT ERG2004 lists Sodium Borohydride (ID Number 1426, with reference to Guide Number 138). Guide Number 138 is for “Substances—Water Reactive (Emitting Flammable Gases).” Other listings in the Guidebook address other candidate chemical hydrides such as Magnesium Hydride (ID Number 2010, which also references Guide Number 138). It remains to be determined if all materials that might be used in a commercialized chemical hydride slurry refueling infrastructure are in fact covered in the Guidebook, and if these emergency response information resources are adequate for operations (i.e., tank truck loading of spent carriers, unloading of freshly regenerated carrier) at public-access fueling stations.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

Recommendations

It is recommended that research to develop chemical hydride hydrogen storage technologies (that are regenerated at a central plant and not in the vehicle fuel tank) should be monitored. Emphasis should be placed on characterizing the infrastructure required to "refuel" these systems—specifically, the processes envisioned for transporting spent carrier from fueling stations to central plants and for transporting regenerated (hydrided) carrier from central plants to fueling stations. Potential hazards associated with this transportation, including loading/unloading operations at public-access fueling stations, should be identified and the applicability of existing emergency response information resources should be assessed.

If R&D succeeds in developing this type of hydrogen storage and refueling infrastructure technology, and it appears that this technology may be used to support hydrogen vehicle commercialization, then work to develop appropriate emergency response information resources should be accelerated.

Emergency Response Information: Reactive (Including Methanol) (19.8)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart G

Description of Key Area

This key area pertains to the availability of appropriate information resources needed by first responders to potential emergencies (e.g., accidents) involving the infrastructure that might be used to support the refueling of hydrogen vehicles that have onboard reformers that produce hydrogen from liquid hydrocarbon feedstocks such as methanol.

“Reactive,” as used here, refers to the concept of fueling hydrogen vehicles with hydrogen-rich liquid hydrocarbon fuels, which are reacted in an onboard reformer to produce the hydrogen gas stream that fuels the fuel cell or internal combustion engine. Methanol (CH_3OH, which is often abbreviated as MeOH) is a frequently considered fuel for vehicles with onboard reformers. Methanol, of course, also fuels direct-methanol fuel cells, which are being developed to power small appliances (e.g., notebook computers) but are not likely candidates to power automobiles. Other fuels considered for onboard reforming include gasoline, diesel fuel, and ethanol.

Considerable R&D has been directed toward onboard reforming, vehicles with this technology have been tested, and some fuel cell vehicle fueling stations (e.g., the CaFCP station in West Sacramento) have methanol dispensers. However, this hydrogen vehicle fueling strategy has recently been deemphasized, and DOE has discontinued support of R&D in this area.

Here we are concerned with the packaging and transportation systems that would be needed to support the refueling infrastructure for hydrogen vehicles with onboard reformers.

Discussion of Criticality

This key area will be critical if commercialized hydrogen vehicles have onboard reformers so that they are refueled with a liquid hydrocarbon fuel such as methanol. The liquid hydrocarbon feedstock delivery infrastructure for these vehicles will be similar to the current gasoline and diesel fuel delivery infrastructure. While some applicable emergency response information resources currently exist (e.g., the DOT ERG2004, as discussed below), these resources may not be fully adequate for operations in an open-public-access environment such as a public fueling station.

The important but unanswered questions pertain to the likelihood that hydrogen vehicles with onboard reformers will be commercialized, and which liquid hydrocarbon feedstock delivery infrastructure will develop.

Discussion of Progress

Progress toward providing emergency response information resources appropriate to the refueling transportation infrastructure that might be used to support hydrogen vehicles with onboard reformers is rated as “Addressed, Not Adequately.” This is because, while some resources currently exist, they may not be fully applicable to delivery of the specific chemical feedstocks to public-access fueling stations.

For example, the DOT ERG2004 lists Methanol (ID Number 1230, with reference to Guide Number 131). Guide Number 131 is for “Flammable Liquids—Toxic” (methanol is poisonous; ingestion of a few ounces can be fatal to humans). The Guidebook also lists and provides some emergency response information for all other likely hydrocarbon feedstocks.

In 2005, the NASFM and DOT’s RITA established the Hydrogen Executive Leadership Panel (HELP). HELP’s mission is “…to bring together emergency responders, government regulators, scientists, consumers and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.” HELP will focus on issues involved in training, educating, and mobilizing emergency responders to work with government, industry, and community groups to facilitate and ensure hydrogen transport, storage and distribution, and the safety of vehicles and environs.

Recommendations

It is recommended that hydrogen vehicle research, development, and demonstration activities should be monitored to identify likely candidate fueling infrastructures that will support the commercialization phase. If it appears that hydrogen vehicles with onboard reformers will be commercialized, the candidate hydrocarbon feedstock to be delivered to fueling stations should be identified, and the adequacy of emergency response information resources for covering delivery of that feedstock to public-access fueling stations should be assessed. If this assessment indicates that more focused emergency response resources are needed, then development of the needed resources should be initiated.

Training (20)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§172 Subpart H

Description of Key Area

This key area involves training requirements, responsibilities, and resources for personnel involved in the infrastructure supporting commercialized hydrogen vehicle operations. The scope of this specific training area is limited to that which is or should be regulated by 49 CFR 172.700-172.704, which addresses hazardous materials training. This applies, for example, to training for personnel involved in transporting fuel to hydrogen vehicle fueling stations. It is assumed that the training referred to in this key area does not apply to other personnel working at hydrogen vehicle fueling stations and involved in tasks outside the scope addressed by DOT hazardous materials regulations (e.g., personnel involved in vehicle refueling or station maintenance).

Discussion of Criticality

This key area will be critical if hydrogen fuel cell vehicles are commercialized with a fuel-supply infrastructure that involves personnel delivering fuel to the stations in a fashion that is significantly different from current gasoline and diesel fuel deliveries to automotive fueling stations. The likelihood of this depends on the likelihood of future hydrogen vehicle commercialization and the type of fueling infrastructure that evolves to support the vehicles.

For example, if hydrogen vehicles are commercialized with fuel tanks that store hydrides (such as sodium borohydride) that must be recharged at a central processing plant, then this key area will be critical because new and specialized training regulations and resources will be required. In this fueling infrastructure scenario, personnel will have to transport and conduct operations with hazardous materials in a public-access environment in a fashion that is quite different from current gasoline or diesel fuel delivery.

Discussion of Progress

The language of 49 CFR 172.700-172.704 regulations pertaining to hazardous material training purpose and scope, federal-state relationship, applicability and responsibility for training and testing, and training requirements may adequately apply to potential future commercialized hydrogen vehicle fueling infrastructures. However, the specific training resources, programs, responsibilities, and testing procedures are very uncertain at this time. Therefore, progress in this key area is rated as “Addressed, Not Adequately.”

Some training materials and programs for hydrogen vehicle operations are being developed and do exist at this time. Examples include the CaFCP’s Emergency Response Guide. Other examples include various hazardous materials transportation and operations training programs provided by industrial gas and chemical companies. However, current hydrogen-vehicle-specific training does not include all possible fuel-supply infrastructures, and the industrial gas and chemical training does not generally address the special public-access-delivery issues that may apply to deliveries to public fueling stations.

Recommendations

It is recommended that progress toward commercialized hydrogen vehicle operations should be monitored with particular emphasis on potential hazardous materials transportation operations that may be part of the fuel supply infrastructure. The applicability and adequacy of the training regulations contained in 49 CFR 172.700-172.704 should be assessed, and the development of the required training programs and materials should be monitored. If these regulations and/or training programs are found to be inadequate, then the development of new specifically focused regulations and/or training programs should be initiated.

Security Plans (21)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§172 Subpart I

Description of Key Area

This key area pertains to security plans that are required for the transportation of hazardous materials such as would be required by the fuel supply infrastructure supporting hydrogen fueled vehicles under most scenarios. These requirements are specified in §172.800 (Purpose and Applicability), §172.802 (Components of a Security Plan), and §172.804 (Relationship to Other Federal Requirements). Review of the applicability provisions in §172.800 indicates that these DOT security plan regulations would apply to many of the fuel-supply infrastructure scenarios being considered as candidates for commercialized hydrogen fueled vehicle operations.

Discussion of Criticality

This key area is judged to be of medium criticality because the regulations contained in §172.800, §172.802, and §172.804 appear to be appropriate and directly applicable to potential hydrogen vehicle fuel-supply infrastructure requirements, and because it is anticipated that organizations that might transport hazardous materials as part of such an infrastructure will be experienced in this area and capable of addressing the security plan requirements.

Discussion of Progress

Progress toward developing security plans for hazardous material transportation as part of hydrogen vehicle fuel supply infrastructure is rated at "Addressed, Not Adequately." This is because, as mentioned above, it is anticipated that organizations responsible for hydrogen vehicle fueling infrastructure hazardous material transportation will be able to meet the security plan requirements. Moreover, it is anticipated that some existing hazardous materials transportation security plans are partially applicable, although this has not been verified.

ASME Innovative Technologies Institute, LLC is working on a new standard for Risk Analysis Methodology for Critical Asset Protection (RAMCAP). This new standard may be applicable to many of the security issues discussed. The standard is expected to be available by the end of 2006.

Recommendations

It is recommended that the development of hydrogen vehicle commercialization should be monitored with emphasis on the fuel supply infrastructure in general and any unique security planning requirements in particular. Any need to refine 49 CFR 172.800, §172.802, or §172.804 should be assessed, and potential programs to support security planning work should be considered. At a higher level, if and when it appears that hydrogen vehicles will be commercialized, DOT, the Department of Homeland Security, and perhaps responsible state agencies should cooperate to determine if there are any new or special security issues that should be addressed.

Filling and Purging Requirements for Advanced Media (22)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§173.302

Description of Key Area

Emerging hydrogen storage technologies (e.g., hydrides, cryogas, physisorption, and reactives) are being developed to address the low storage density—both gravimetric and volumetric—of gaseous hydrogen. Certain of these may require special handling when filling or purging. For example, heat transfer mechanisms are generally needed to remove heat generated during hydrogen charging for metal hydride containers. When purging (emptying) packagings containing hydrogen in advanced media, there could be a potential for a release of media or an inability to remove sufficient hydrogen (to remove any potential hazard) without removing the media.

Discussion of Criticality

It is anticipated that as these storage technologies develop, their proponents will determine any unique conditions or procedures for container filling and purging. It is also anticipated that as early products are brought to market, initial regulatory coverage will be via special permits which will likely require filling or purging to be performed by the manufacturer or their designated agents, providing a level of control over the filling or purging processes through manufacturers' developed practices.

Discussion of Progress

As most storage technologies based on advanced media are not widely deployed (if at all), progress was assessed as "Not Addressed".

Recommendations

As development and deployment activities increase, initially the special permit process could be used to incorporate any special handling requirements during filling. With sufficiently wider deployment, requirements could be considered for incorporation into regulatory structures.

Unless a particular filling or purging procedure could result in the development of a potentially hazardous situation, specific guidance may not be necessary.

Filling and Purging Requirements for High Pressure Containers (23)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§173.302

Description of Key Area

High pressure hydrogen storage technologies are being developed to address the low storage density—both gravimetric and volumetric—of gaseous hydrogen. Fast filling of high pressure gaseous hydrogen containers can result in significant gas temperature increases due to heat of compression. Plastic lined composite containers can have material temperature limits that can be exceeded if proper procedures and controls are not employed. Additionally, thermally-activated pressure relief devices could suffer thermal degradation from repeated exposure to high gas temperatures. Purging of plastic-lined containers Rapid depressurization of plastic lined containers can place potentially harmful thermal stresses on sealing/mating areas between the plastic liner and metal connecting hardware (bosses). Also, it also not generally recommended to bring the internal pressure of a plastic-lined container appreciably below atmospheric pressure as the vacuum pressure can lead to the separation of the liner from the structural composite overwrap, potentially damaging the liner.

Discussion of Criticality

It is anticipated that as these storage technologies develop, their proponents will determine any unique conditions or procedures for container filling. It is also anticipated that as early products are brought to market, initial regulatory coverage will be via special permits which will likely require filling to be performed by the manufacturer or their designated agents, providing a level of control over the filling process through manufacturers' developed practices.

Discussion of Progress

Most high pressure storage technologies are currently being developed for vehicular applications and are at the prototype stage. They are not yet in use for hydrogen transport. Progress was assessed as "Not Addressed".

Recommendations

As development and deployment activities increase, initially the special permit process could be used to incorporate any special handling requirements during filling. With sufficiently wider deployment, requirements could be considered for incorporation into regulatory structure.

Loading and Unloading Requirements for Composite Containers (24)

Criticality:	Medium	**Progress:**	Not Addressed
Score:	24	**DOT Relevance:**	§177.840

Description of Key Area

High pressure hydrogen storage technologies are being developed to address the low storage density—both gravimetric and volumetric—of gaseous hydrogen. Composite wrapped containers are susceptible to different types of external damage than all metal containers. For composite containers to be used for transportation applications, additional precautions may need to be specified. Additionally, composite containers are more susceptible to impact damage when empty as flexure of the composite fibers could cause fiber damage or breakage.

Discussion of Criticality

It is anticipated that as these storage technologies develop, their proponents will determine any unique conditions or procedures for container filling. It is also anticipated that as early products are brought to market, initial regulatory coverage will be via special permits which will likely require filling to be performed by the manufacturer or their designated agents, providing a level of control over the filling process through manufacturers' developed practices.

Discussion of Progress

Most high pressure storage technologies are currently being developed for vehicular applications and are at the prototype stage. They are not yet in use for hydrogen transport. Progress was assessed as "Not Addressed".

Recommendations

As development and deployment activities increase, initially the special permit process could be used to incorporate any special handling requirements during filling. With sufficiently wider deployment, requirements could be considered for incorporation into regulatory structure.

Container Specifications for Composite Storage (25.1)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§178

Description of Key Area

DOT requires in that non-liquefied compressed gases be shipped in specification containers. Composite cylinders are not included in DOT cylinder specifications. Therefore, composite cylinders are only allowed in service by obtaining a special permit in accordance with 49 CFR 107 Subpart B.

Discussion of Criticality

Compressed hydrogen gas is currently held in steel, aluminum, or composite cylinders for portable applications, typically at pressures from 16.5 to 41.4 MPa (2400 to 6000 psi). Volume for cylinders is up to 454 kg (1000 lb) of water capacity; larger cylinders are covered under tube specifications. Light weight is one consideration for cylinders, so that they can be carried more easily. Composite cylinders are lighter in weight than metallic cylinders. As pressure increases, this weight advantage of composite tanks will increase further.

Composite tanks can also be designed to higher operating pressures without introducing significant manufacturability issues. However, obtaining required special permits to use composite cylinders in portable applications may take from six months to several years.

Discussion of Progress

DOT currently has no composite cylinder standards. It is planning to recognize ISO 11119 as part of the cylinder standards adopted by the UN Committee of Experts in its “orange book”. However, there are additional cylinder standards in use in North America that may offer advantages if used for portable cylinder applications.

Composite cylinder standards have been developed or are in development by various groups, including CGA, CSA in Canada and in America, and ASME. Standards developed by these groups include FRP-1, FRP-2, FRP-3, CSA B51, CSA NGV2, and ASME Section X.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing high pressure gas storage in metal and composite tanks. The work plan includes a proposed new article KD-10 to Section VIII-3, a code case on composite tanks for Section VIII-3, and a revision to code case 2390 on metal lined composite reinforced circumferentially wrapped pressure vessels under Section VIII-3. Transport tanks may also be included in Section XII.

Recommendations

DOT should work with SDOs noted above that have developed, and are developing, standards that apply to composite cylinders that are capable of carrying hydrogen. These standards should be evaluated for ability to address cylinders that would carry compressed hydrogen in transportable applications. DOT should work with these SDOs to develop updates that can address the size and pressures needed by the hydrogen distribution industry. DOT should then adopt acceptable standards by reference.

Container Specifications for Metal Hydride Based Storage (25.2)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§178

Description of Key Area

Metal hydride-based hydrogen storage systems are presently being commercialized. While there are many different materials that may be used as hydrogen storage materials, they can be divided into two distinctive categories: rechargeable and non-rechargeable. The term rechargeable is used to describe a system which can be refilled by introducing hydrogen to the depleted system without the need to add or remove any other reactant or by-product and the system is designed to retain all material other than hydrogen. Non-rechargeable describes systems where to refill the system, the hydrogen-depleted material or by-products must be removed and fresh hydrogen-containing materials replenished. These systems are therefore designed to allow removal and addition of material other than just hydrogen. This part will discuss rechargeable systems; non-rechargeable systems are discussed in Item 25.3.

Rechargeable systems meet the description of entries UN 3468, *Hydrogen in a metal hydride storage system* and NA 9279, *Hydrogen absorbed in metal hydride* of 49 CFR 172.101, the Hazardous Materials table; this discussion will therefore apply to both. These entries have a hazard classification of 2.1 flammable gas with no listed subsidiary hazard. Neither table entry contains packaging instructions; therefore both require either approval of the Associate Administrator or issuance of a special permit before first shipment. Without any guidance on packaging, the OHMS must individually review and issue an approval or special permit for each system design and manufacturer/offeror for all metal hydride-based hydrogen storage systems.

The OHMS has issued several special permits for UN 3468 and NA 9279 systems. The special permits approved to date have included systems that utilize DOT specification 3AL (E 12650, E 13280, and E 13598), DOT specification 3E (E 13036) or ASME (E 13560) cylinders. It is anticipated that not all future applications for approval will utilize DOT specification cylinders.

Metal hydride-based hydrogen storage systems truly are systems. The cylinder or pressure container is only one part of the system that is needed for safe and proper operation and performance. For rechargeable systems, hydrogen gas reacts with another material, normally a solid phase material, to form a new hydrogen-containing compound, the “hydride” phase, in which hydrogen is chemically bonded. This reaction is normally exothermic or heat producing on hydride formation and endothermic or heat absorbing on hydrogen release. The systems will therefore typically contain a means of heat transfer between the contained material and an external heat sink. Means must also be provided to retain all material except for hydrogen gas. The hydride phase typically has a lower density than the non-hydride phase. The lower density means that the contained material literally swells on formation of the hydride phase. This could cause detrimental effects by overstressing the pressure container walls if a means is not provided to prevent non-uniform distribution of the material within. Most DOT specification cylinders require periodic requalification according to 49 CFR 180. Typically cylinders are requalified by visual inspection and the hydrostatic test method. The hydrostatic test method will most likely not be suitable for metal hydride systems. An ultrasonic method has been found to be suitable and was allowed by special permit E 13280. These are just a few examples of how metal hydride-based hydrogen storage systems differ from compressed gas and why there need to be requirements other than simply use of a specification cylinder.

Another way in which metal hydride-based systems differ from standard compressed gases is their response to pressure changes with changes in temperature. The change in pressure of a compressed gas due to a change in temperature is fairly linear and is approximated by the ideal gas law: $\Delta P = (nR/V)\Delta T$, where T is the absolute temperature and nR/V is constant for a closed cylinder. This is not the case for metal hydride-based systems. With these systems, the pressure and temperature are related through the van’t Hoff relationship: $\ln P = \Delta H/RT - \Delta S/R$, where ln P is the natural log of pressure and ΔH and ΔS the enthalpy and entropy of reaction, respectively. The result is that, for example, using a material with reaction enthalpies typical of intermetallic hydrides (20 to 40 kJ/mole H_2), within the ambient temperature range expected during transport, the system gas pressure will approximately double with every 15 to 20°C (27 to 36°F) temperature increase. In other words, a system with a pressure of 1.7 MPa (250 psi) at 15°C (59°F) could have a pressure of approximately 6.9 MPa (1000 psi) at 55°C (131°F), whereas for a simple compressed gas the pressure change would be from 1.7 to 2.0 MPa (250 to 285 psi) for the same temperature rise. This pressure-temperature relationship must be accounted for when consideration is given to the pressure container and pressure relief device (PRD) selection.

Currently there are a lot of development activities being carried out by various companies and organizations around the world on these technologies. Entry level products have started entering the marketplace. The number of products, choice of hydride material and system designs available is expected to increase dramatically over the next few years. Without container specifications or at least a template or set of guidelines for use by the manufacturer for design, testing and manufacture and the

OHMS for evaluating these systems, the effort required to review and approve or issue special permits for each may be burdensome.

Discussion of Criticality

This item has been assigned a criticality of high. Without system and testing specifications being developed for metal hydride-based hydrogen storage systems, there is no set of consistent minimum requirements to manufacturers and offerors follow. The absence of specifications or guidelines requires that OHMS personnel individually review and approve each system from each offeror and manufacturer. This could present a burdensome work load on the OHMS if this technology is found to be able to meet current expectations leading to many requests for approval.

While it is considered critical that system specifications or at least guidelines be developed for rechargeable metal hydride-based hydrogen storage systems, it is also recommended that the specifications or guidelines be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The specifications should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

The OHMS has performed system reviews and has issued several special permits for metal hydride-based hydrogen storage systems. The special permits include DOT-E 12650, E 13036, E 13280, E 13560 and E 13598. DOT-E 13036 is for a system that is not allowed to be recharged, i.e., for a single use only. The review for the other special permits, which allow recharging, have included consideration of stress on the cylinder walls and have therefore required either in-process testing (E 12650, E 13280 and E 13598) or periodic strain monitoring (E 13560). While in the initial stage of introducing these products, in-process testing is reasonable, as more systems are developed and the systems become more ubiquitous, it might become impractical.

Efforts are being carried out on developing consensus standards for metal hydride-based hydrogen storage systems. The efforts include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (ISO 16111). This document is currently in the approval stage as a committee draft (“CD”) for advancement to the

draft international standard stage ("DIS"). In parallel to the CD approval, the document is being considered for publication as a technical specification; with possible publication of the TS much earlier than possible for the International Standard. Once the international standard is approved, the technical specification will be withdrawn. This document only considers stand-alone containers.

2. CGA has also considered developing a standard for portable metal hydride hydrogen storage systems. This effort is early in development and the expected publication date is unknown.

IEC TC 105 on fuel cell technology and UL's STP 2265 have considered some additional requirements and testing for "Micro" systems that might be used with low-power portable fuel cell products.

The CGA pamphlet S-1.1-2001, referenced in 49 CFR 171.7, does not contain any guidance for PRD selection for metal hydride systems. More recent versions of pamphlet S-1.1 do contain guidance, however it is based on what has been approved by the OHMS in special permits and not on what experts of metal hydride systems consider to be the most appropriate PRDs for use.

Recommendations

It is recommended that the OHMS develop a minimum set of design and test criteria for rechargeable metal hydride-based hydrogen storage systems. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. Following guidance in current versions of CGA pamphlet S-1.1 for PRD selection is not recommend. It is preferred that these criteria be performance-based. Ideally they would be based on ISO 16111, underdevelopment by an international committee of experts.

Current cylinder markings will not be appropriate for metal hydride-based hydrogen storage systems. This is partly due to fact the pressure container design must account for stress from factors other than just gas pressure and that gas pressure does not vary according to the gas law with changes in temperature. Current cylinder testing and markings relate to cylinder service pressure, test pressure and PRD settings. Metal hydride systems will not have the same relationship between these pressures. A new standard for relating markings with service pressure, test pressure and PRD settings of metal hydride-based systems will need to be developed. Guidance on marking is given in ISO 16111.

To help ensure that the standards being developed for metal hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on the applicable development committees. These would include ISO TC 197 working group 10 and the Compressed Gas Association’s Hydrogen Fuel Technology committee.

From experience obtained from systems approved under these guidelines, they could, at an appropriate future time, be refined and used as a basis for a New Rule Making Proposal for conversion into regulations and incorporated into 49 CFR 173.

Container Specifications for Reactive Type Storage (25.3)

Criticality: Medium **Progress:** Not Addressed
Score: 24 **DOT Relevance:** §178

Description of Key Area

Metal hydride-based hydrogen storage systems are presently being commercialized. While there are many different materials that may be used as hydrogen storage materials, they can be divided into two distinctive categories: rechargeable and non-rechargeable. The term rechargeable is used to describe a system which can be refilled by introducing hydrogen to the depleted system without the need to add or remove any other reactant or by-product and the systems are designed to retain all material other than hydrogen. Non-rechargeable describes systems where to refill the system, the hydrogen-depleted material or by-products must be removed and fresh hydrogen-containing materials replenished. These systems are therefore designed to allow removal and addition of material other than just hydrogen. This part will discuss non-rechargeable systems; rechargeable systems are discussed in Item 25.2.

Non-rechargeable systems may contain a mixture of hazardous materials that are selected such that they combine or react to produce hydrogen gas. These systems may contain mixed solids, mixed liquid and solid phases, liquids with dissolved solids, gaseous and liquid or solid phases, etc. They may also contain gaseous hydrogen during part of the time or at all times in at least part of the packaging.

A number of different types of non-rechargeable systems have been developed and/or proposed. Three examples include:

1. Reacting alkali (e.g., sodium and potassium) or alkaline earth metals (e.g., calcium) or their hydrides with water to produce hydrogen gas. For example with sodium metal the reaction would be:

   $$Na_{(s)} + H_2O_{(l)} \rightarrow \frac{1}{2} H_{2(g)} + NaOH_{(aq)}$$

   Various method of containing reactants and controlling the reaction have been proposed, such as making a slurry of the metals in an organic or inorganic oil and controlling the addition of water and encapsulating the solids in with a non-reactive coating and placing them in a container with water—the encapsulating coating is then mechanically breached as required to allow reaction and liberate gaseous hydrogen.

2. Reacting ammonia with an aluminum hydride, such as $LiAlH_4$, to produce hydrogen gas and various amines and amides as by-products. In one system developed for and tested by the military, the ammonia, which is contained in one pressurized compartment, passes through a one-way valve into a second compartment that contains the solid hydride phase. In the second compartment the reaction occurs, producing gaseous hydrogen. The hydrogen gas pressure is used to control the rate of ammonia passing into the second compartment and thus the rate of reaction.

3. Reacting sodium borohydride catalytically with water to produce hydrogen and sodium borate. The reaction is:

$$NaBH_{4(aq)} + 2\,H_2O_{(l)} \text{ –(cat.)}\rightarrow 4\,H_{2(g)} + NaBO_{2(aq)}$$

   If not taken to completion, the reaction by-product could be $NaB(OH)_4$. In one version of this type of system, the aqueous solution of sodium borohydride is stabilized by buffering the solution to a high pH, typically in the 12 to 14 range. The stabilized solution is then passed through a second chamber containing the catalyst where the reaction rapidly occurs, liberating gaseous hydrogen. The spent solution is collected in a third chamber.

For safety and proper operation, non-rechargeable hydride systems will need to be able to contain both the reactive phases and the produced by-products, while “idle” and while producing hydrogen. There must be a means to remove the by-products and replenish the reactive species. These systems may therefore contain multiple compartments, one-way flow valves, multiple PRDs, manifolds, etc. Since the materials are selected to react to produce hydrogen, a flammable gas, current regulations might prohibit containing these materials in a single package. The hazardous materials regulations contain packaging requirements and packaging specifications for the various hazard classifications, however the current requirements and specifications may not be suitable for non-rechargeable or “reactive” hydride-based hydrogen storage systems.

Due to the variety of non-rechargeable hydride systems being investigated and the early stage of most of their development, it is not likely that a single set of packaging specifications could be developed to appropriately cover them all. A more appropriate approach would be to treat them as articles and develop general guidelines as found in Subpart E- Non-bulk Packaging for Hazardous Materials Other Than Class 1 and Class 7 of 49 CFR 173. Consideration will also need to be given to allowing exceptions to current restrictions on mix content hazards, as discussed in Item 18.4 of this report.

Discussion of Criticality

This item is considered to be of medium criticality. Non-rechargeable hydride-based hydrogen storage systems are likely to contain a mixture of hazardous materials. Due to the variety of potential materials and system designs, specific packaging specifications will need to be general, emphasizing demonstration of safety through testing and material compatibility. Considerations will need to be given for compatibility of packaging to the reactive species and the produced by-products. The ability of the packaging to contain all of the material (solid, liquid and gas as appropriate) while “idle” and while producing hydrogen must both be considered. The packaging must also be able to safely prevent and/or control any potential “run-away” reaction. At this time, there are few systems in commercialization. Over the next few years, more are expected to become commercial, however at this time which technologies and system designs likely to reach that stage is uncertain.

In the near-term it is expected that special permits may need to be granted to allow exceptions to regulatory prohibitions to combining certain reactive hazards within a single package, see Item 18.4 of this report. Review of these special permits could include system design for material of construction compatibility, reaction containment, etc. When the scope of technologies that are likely to be commercialized becomes apparent, it would be appropriate for exceptions to prohibitions of certain mixed hazards to be included into the 49 CFR. At that time, it would also be appropriate to include a general packaging section into Subpart E of §173, similar to that for wet batteries (§173.159).

Discussion of Progress

In the last several years, the US DOT has included in the hazardous materials table listing NA 9279, *Hydrogen absorbed in metal hydride* and UN 3468, *Hydrogen in a metal hydride storage system*. Both of these listing assign a hazard classification to the systems of 2.1 flammable gas. Currently these identifications can only be used with approval from the OHMS after review and approval of the packaging. No packaging instructions have been adopted in either the US regulations or the international Model Regulations. The OHMS has issued several special permits for metal hydride hydrogen storage systems, essentially approving the packaging and exempting them from §173.301(d).

Currently there are no known special permits issued for non-reversible hydride-based hydrogen storage systems. However there are numerous companies and organizations that are developing various types of systems. Systems of this type have been tested by the military, government laboratories and corporations over a number of years. Commercially available products are expected to become available within the next few years. DOE—through its Hydrogen, Fuel Cells and Infrastructure Technologies Program—has established three hydrogen storage research Centers of Excellence, one on metal hydride (i.e., rechargeable) and one on chemical hydride (i.e., non-rechargeable) materials and systems.

Recommendations

For non-rechargeable or chemical hydride-based systems, there has been little work on developing system standards. This is partly due to the broad range of materials and system designs and the fact that most are currently proprietary and not commercially available. It is recommended that the DOT review current proposed chemical hydride systems against current regulations to start developing requirements and guidelines for potential special permits to regulations that would prohibit the systems. Experience from this effort could be used for eventual inclusion of possible new entries to the Hazardous Materials table (§172.101) and/or development of packaging specifications, specifically for Subpart E of §173. The review should include persons from industry, the DOE Centers of Excellence and the DOT.

To help ensure that any standards being developed for hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on applicable standards development committees. These might include ISO, IEC, CGA, and UL committees.

Composite/Novel Media Tube Trailer Specifications (26)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	§178

Description of Key Area

DOT requires that non-liquefied compressed gases be shipped in specification containers. Composite cylinders are not included in DOT cylinder specifications. Therefore, composite cylinders are only allowed in service by obtaining a special permit in accordance with 49 CFR 107 Subpart B.

Discussion of Criticality

Compressed hydrogen gas is currently transported in steel tube trailers, typically at pressures from 16.5 to 27.6 MPa (2400 to 4000 psi). Volume for tubes is a minimum of 454 kg (1000 lb) water capacity. Diameters are typically from 0.23 to 0.56 m (9 to 22 in). The weight efficiency of steel tanks is not high. The weight of hydrogen stored on a trailer with steel tubes is approximately one percent. As pressure increases, this weight efficiency will decrease further. A trailer with steel tubes is limited by gross vehicle weight, not by size of the trailer. As the need for hydrogen grows the need for transporting by tube trailers increases, particularly for distribution within major cities where it is not practical to build hydrogen pipelines.

Trailers with composite tubes would be able to carry about three percent hydrogen by weight, allowing a greater volume of gas to be carried. Composite tanks can also be designed to higher operating pressures without introducing significant manufacturability issues. However, obtaining required special permits to use composite cylinders in transportation may take from six months to several years.

Discussion of Progress

DOT currently has no composite cylinder standards. It is planning to recognize ISO 11119 as part of the cylinder standards adopted by the UN Committee of Experts in its “orange book”. However, ISO 11119 and other industry standards have not, to date, addressed larger cylinders such as would be used in tube trailers. The lack of coverage for large cylinders is not due to specific technical issues, it is more a reflection that no one has asked for this coverage in the past.

Composite cylinder standards have been developed or are in development by various groups, including CGA, CSA in Canada and America, and ASME. Standards developed by these groups include FRP-1, FRP-2, FRP-3, CSA B51, CSA NGV2, and ASME Section X.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing high pressure gas storage in metal and composite tanks. The work plan includes a proposed new article KD-10 to Section VIII-3, a code case on composite tanks for Section VIII-3, and a revision to code case 2390 on metal lined composite reinforced circumferentially wrapped pressure vessels under Section VIII-3. Transport tanks may also be included in Section XII.

Recommendations

DOT should work with SDOs noted above that have developed, and are developing, standards that apply to composite cylinders that are capable of carrying hydrogen. These standards should be evaluated for ability to address larger cylinders that would carry compressed hydrogen. DOT should work with these SDOs to develop updates that can address the size and pressures needed by the hydrogen distribution industry. DOT should then adopt acceptable standards by reference.

Composite/Novel Media Portable Tank Specifications (27)

Criticality:	Medium	**Progress:**	Addressed, Not Adequately
Score:	12	**DOT Relevance:**	§178

Description of Key Area

DOT requires that non-liquefied compressed gases be shipped in specification containers. Composite cylinders are not included in DOT cylinder specifications. Therefore, composite cylinders are only allowed in service by obtaining a special permit in accordance with 49 CFR 107 Subpart B. Section 178 Subpart H deals specifically with portable tank specifications, which contain liquefiable gases with a liquid/gas interface.

Discussion of Criticality

Fluids held in §178 Subpart H portable tanks must currently be made of steel with welded construction in accordance with ASME Section VIII. Portable tanks are held at relatively low pressures, which would imply storage of hydrogen would be cryogenic or in the form of a solution or chemical hydride. Light weight is one consideration for portable tanks, so that they can be transported more easily. Composite tanks are lighter in weight than steel tanks, although this would be less significant with liquefied contents at lower pressures. Consideration must be given to temperature compatibility of composite materials, to thermal stresses in the composite tank, and dynamic loads.

Composite tanks have been used in cryogenic applications, but their use in transportation is insignificant. Composite tanks have been used to transport liquids, but these have generally been at low internal pressure.

Discussion of Progress

DOT currently has no composite portable tank standards. Composite tanks have been developed for containing pressurized liquid hydrogen, but their use in transportation has been limited. Composite tanks for liquids are generally not at high pressure. There is likely insufficient transportation experience with portable composite tanks to deal with standards development at this time.

ASME's Boiler and Pressure Vessel project team on hydrogen tanks is addressing high pressure gas storage in metal and composite tanks. The work plan includes a proposed new article KD-10 to Section VIII-3, a code case on composite tanks for Section VIII-3, and a revision to code case 2390 on metal lined composite reinforced circumferentially wrapped pressure vessels under Section VIII-3. Transport tanks may also be included in Section XII.

Recommendations

The industry and DOT should monitor the need for composite portable tanks. Design studies may be required to assess the practicality of using composite portable tanks to transport hydrogen or hydrogen compounds. DOT should address any applications with special permits until a sufficient data base of use exists and a larger market need exists.

Continuing Qualification and Maintenance (28)

Criticality:	Low	**Progress:**	Addressed, Not Adequately
Score:	4	**DOT Relevance:**	§180

Description of Key Area

DOT addresses continuing qualification and maintenance in 49 CRF 180. This section applies primarily to specification cylinders, which are metallic. This section also addresses special permit cylinders, which would include composite cylinders. Inspection intervals for specification cylinders range from three to twenty years. Inspection intervals for composite cylinders have generally been three years, but DOT has recently been allowing five year inspection intervals. The industry, particularly CGA, has standards that are used for visual inspection. CGA standards include C-6, C-6.1, C-6.2, C-6.3, and C-6.4. Continuing qualification generally involves a hydrostatic pressure test. DOT has issued special permits to allow alternate non-destructive evaluation (NDE). Cylinders in transportation service have generally been at pressures of 41.4 MPa (6000 psi) or lower.

Discussion of Criticality

Appropriate inspection intervals and qualification methods are important, particularly as service pressure increases with hydrogen gas contents. The current experience with specification and special permit cylinders offers assurance of safety within the current limits of pressure and design constraints. As pressures increase, and as design requirements may change, the inspection intervals and qualification methods must be evaluated. This is especially true if any of the materials of construction are adversely affected by exposure to high pressure hydrogen.

Discussion of Progress

Hydrogen cylinders with service pressures from 48.3 to 89.6 MPa (7000 to 13000 psi) are now entering service. These cylinders will be subject to periodic inspection and qualification in accordance with current guidelines. This will give some indication of adequacy of current guidelines.

Recommendations

The industry and DOT should monitor safety of high pressure hydrogen cylinders as they enter service. Adjustments in continuing maintenance and qualification guidelines should be made as data is gathered. The industry and DOT should continue to investigate the effects of high pressure hydrogen on materials of construction and alternate NDE methods that could be used to identify potential damage in cylinders made from materials that are subject to hydrogen embrittlement.

Mobile Fuelers, Treatment of Gas Storage Containers (29)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	

Description of Key Area

Typical fuel cell vehicle demonstration projects generally involve only a handful of vehicles per location, making the installation of hydrogen fueling infrastructure a costly proposition. Also, as initial demonstrations grow and new ones are initiated, mobile fuelers represent fueling infrastructure that can be readily redeployed and therefore has significant advantages.

To address the need for small, mobile fueling infrastructure, several organizations have developed or are developing mobile fuelers, incorporating hydrogen storage and dispensing equipment and sometimes hydrogen generation and compression equipment. The most pressing obstacle in the design of mobile fuelers is the selection of hydrogen storage containers.

Discussion of Criticality

At its point of use, the mobile fueler is treated (in some jurisdictions) as stationary equipment. This treatment typically entails that gas storage meet ASME requirements. As this designation would not allow the mobile fueler to be transported over the road with any appreciable amount of flammable gas on board, purging would be required before transport. Purging would greatly reduce the utility of a mobile fueler lacking a means to generate hydrogen. DOT approved storage containers would allow the mobile fueler to be moved with gas on board, but once located for fueling operations, local authorities could refuse to allow its use. Additionally, the weight of high-pressure containers meeting either DOT or ASME requirements (i.e., all steel) makes their use on a mobile fueler impractical to impossible.

Discussion of Progress

There is no specific code or standard coverage for mobile fuelers at this time.

Recommendations

In the near term, designers and users of mobile fuelers need to consider their anticipated areas of operations with respect to local code restrictions and consider operational issues such as the availability of purge gas. DOT approved composite cylinders (either via specification or special permit) would address most issues but local code approval would still be required. ASME is also developing standards for composite pressure vessels for compressed hydrogen used in portable, transportable, and stationary applications under Section VIII Division 3, which could help address mobile fueler storage issues.

Aircraft Carriage, Hydride Systems (30.1)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§175

Description of Key Area

The carriage by aircraft of hydride-based hydrogen storage systems is considered critical for commercial success by many potential manufacturers of the hydrogen storage systems and fuel cell appliances and devices powered by them. This area covers both rechargeable and non-rechargeable type hydrogen storage systems, micro and portable systems and stand-alone systems and systems coupled to appliances. This section will discuss stand-alone systems that are being transported when not coupled to an appliance; Item 30.2 discusses aircraft carriage of systems coupled to an appliance.

As has been previously discussed, hydride-based hydrogen storage systems can be divided into two broad categories, rechargeable systems and non-rechargeable systems. The rechargeable systems contain a reversible hydride-forming material and are refilled by applying hydrogen; they will most likely be identified by UN 3468 or NA 9279 with a 2.1 flammable gas hazard classification. Non-rechargeable systems will likely contain a mixture of hazardous materials that are not normally allowed within a single package since they are capable of reacting together to produce a flammable gas. These systems will require exceptions to a number of clauses in current regulations and may require either new hazardous materials table entries or ORM-D exceptions. Each of these two categories can be further divided into “micro” and “portable” systems, with the difference being the intended use of the appliance they fuel. Micro systems are primarily intended for use with low-power fuel cell appliances for use in consumer electronics, such as cellular phones and laptop computers. It is considered essential that these systems be able to be carried and used by travelers in the passenger cabin of aircraft and upper size limitations will likely be imposed. Portable systems are not intended to be used in fixed, stationary locations but it is not expected that they need to be carried or used in the passenger cabin of aircraft.

Hydride-based hydrogen storage systems may be transported onboard aircraft as either cargo or in passenger baggage, especially with micro systems. When transported by individuals within baggage, the systems may or may not include any original overpacking supplied by the manufacturer. For allowance onboard cargo-only aircraft, modifications to appropriate entries of the hazardous materials table, §172.101, will need to be made. Exceptions or packaging instructions may need to be included in 49

CFR 173. Packaging instructions and container specifications were discussed in Items 18 and 27 of this report.

For allowance onboard passenger aircraft, in addition to what is required for cargo-only aircraft, further consideration needs to be given to the potential hazards and risks. As cargo onboard passenger aircraft, the hazards are essentially the same as for cargo-only, however with greater potential risk of loss of life if an accident was to occur. When carried onboard passenger aircraft by passengers there is even more risk due to lesser control over packaging. Here it may be appropriate to apply limitations on individual system size or capacity and limits on amounts that can be carried by individual passengers. This allowance may require modification to the language that is required to be posted by commercial airlines, §175.25(a)(1). The language currently forbids carrying onboard aircraft of hazardous materials with several cited exceptions, such as “certain smoking materials,” fuel cartridges for use with micro fuel cell systems may need to be included. Section 175.75 lists quantity limitations aboard aircraft, the appropriateness of these limitations with respect to hydride-based hydrogen storage systems need to be reviewed.

Paragraph 175.75(a)(2) allows up to 25 kg (55 lb) net weight of an allowed hazardous material to be carried aboard an aircraft; for a UN 3468 material, does net weight refer to hydrogen or the hydride material? The weight of hydrogen may only be a few percent of the total hydride weight, thus 25 kg (55 lb) of hydrogen could translate into several hundred kilograms of hydride material. In addition §175.75(b) places no quantity limitation on ORM-D materials, limitations may be appropriate if non-rechargeable hydride-based systems are shipped under ORM-D exceptions.

Discussion of Criticality

This item has been assigned a criticality of high. It is expected that many manufacturers will seek allowance of hydride-based hydrogen storage systems aboard aircraft. DOT-E 13598 currently allows up to 90.7 kg (200 lb) of UN 3468 material aboard cargo-only aircraft. Allowance will be sought to allow micro systems to be carried in carry-on baggage within the passenger cabin of aircraft.

Consideration must be given to size and quantity limitations to systems to be allowed within passenger baggage, carry-on and checked, and that allowed as cargo on passenger and cargo-only aircraft. Packaging instructions and container specification must include appropriate testing to ensure safety of the systems allowed aboard aircraft.

While it is considered critical that appropriate packaging instructions be developed, it is also recommended that the packaging instructions be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The packaging instructions should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

Hydrogen as a compressed gas, UN 1049, is allowed on cargo-only aircraft with a 150 kg (331 lb) net limit. UN 3468, *Hydrogen in a metal hydride storage system* has been included in ICAO's dangerous goods list and forbidden from carriage on either cargo-only or passenger aircraft. At the recent ICAO Dangerous Goods Panel meeting in Oct/Nov of 2005, the panel accepted a proposal from the US panel member to allow cargo-only carriage, with a 100 kg (220 lb) limit. This new ruling is to become effective in January of 2007. Carriage aboard passenger aircraft has not been allowed. US DOT special permit E 13598 allows up to 90.7 kg (200 lb) of UN 3468/NA 9279 material be carried aboard cargo-only aircraft.

An informal and then a formal proposal were made to the UN SCETDG by the representative from Japan, to allow micro fuel cell systems and the fuel cartridges to be carried aboard aircraft. The original informal proposal requested a new entry in the Dangerous Goods List (DGL), with a hazard class 9. The formal proposal submitted for consideration at the July 2005 meeting of the UN SCETDG was revised and instead requested a new DGL entry with a flammable gas hazard, class 2.1. This proposal was withdrawn without consideration. It is anticipated that a new proposal will be submitted requesting modification of UN 3468 to include systems coupled with fuel cell units as well as the stand-alone systems.

Progress on developing consensus standards that might be used as a basis for packaging instructions include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (ISO 16111). This document is currently in the approval stage as a committee draft ("CD") for advancement to the draft international standard stage ("DIS"). In parallel to the CD approval, the document is being considered for publication as a technical specification; with possible publication of the TS much earlier than possible for the International Standard. Once the international standard is approved,

the technical specification will be withdrawn. This document only considers stand-alone containers.

2. IEC TC 105 has drafted and is currently reviewing a draft publicly available standard for Micro Fuel Cell Systems (IEC PAS 62282-6-1). This document includes sections on fuel storage containers and complete integrated fuel cell appliances with fuel containers. This standard is expected to reference ISO 16111 for metal hydride-based hydrogen storage container design and testing.

3. UL is developing a consensus standard (UL 2265) on micro fuel cell systems. An effort is being made to keep UL 2265 consistent with IEC 62282-6 and its development is therefore trailing that of IEC 62282-6.

Recommendations

It is recommended that the OHMS develop a minimum set of design and test criteria for packaging of hydride-based hydrogen storage systems as previously recommended in Items 18 and 25 of this report. Consideration should be given to the impact of onboard aircraft carriage. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. Size and quantity limitations need to be considered for allowance aboard passenger aircraft, particularly for inclusion in passenger baggage, checked as well as carry-on. It is preferred that these criteria be performance-based. Ideally they would be based on the ISO and IEC standards underdevelopment by international expert committees (ISO 16111 and IEC 62282-6-1).

The language required to be posted by commercial airlines, §175.25(a)(1) needs to be reviewed for any appropriate changes if hydride-based hydrogen storage systems are allowed to be carried aboard aircraft by passengers. The quantity limitations of §175.25(a) and (b) need to be reviewed for appropriateness and possible revision if hydride-based hydrogen storage systems are allowed aboard aircraft.

To help ensure that the standards being developed for hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on the applicable development committees. These would include ISO TC 197 working group 10, IEC TC 105 working group 8, and UL’s STP 2265.

Aircraft Carriage, Hydride Systems in Appliances (30.2)

Criticality:	High	**Progress:**	Not Addressed
Score:	40	**DOT Relevance:**	§175

Description of Key Area

The carriage by aircraft of hydride-based hydrogen storage systems is considered critical for commercial success by many potential manufacturers of the hydrogen storage systems and fuel cell appliances and devices powered by them. This area covers both rechargeable and non-rechargeable type hydrogen storage systems, micro and portable systems, stand-alone systems, and systems coupled to appliances. This section will discuss systems transported while coupled to an appliance. Stand-alone systems, not coupled to an appliance, are discussed in Item 30.1 of this report. The discussion of Item 30.1 is applicable to systems coupled to an appliance as well as for stand-alone systems.

As has been previously discussed, hydride-based hydrogen storage systems can be divided into two broad categories, rechargeable systems and non-rechargeable systems. The rechargeable systems contain a reversible hydride-forming material and are refilled by applying hydrogen; they will most likely be identified by UN 3468 or NA 9279 with a 2.1 flammable gas hazard classification. Non-rechargeable systems will likely contain a mixture of hazardous materials that are not normally allowed within a single package since they are capable of reacting together to produce a flammable gas. These systems will require exceptions to a number of clauses in current regulations and may require either new hazardous materials table entries or ORM-D exceptions. Each of these two categories can be further divided into “micro” and “portable” systems, with the difference being the intended use of the appliance they fuel. Micro systems are primarily intended for use with low-power fuel cell appliances for use in consumer electronics, such as cellular phones and laptop computers. It is considered essential that these systems be able to be carried and used by travelers in the passenger cabin of aircraft and upper size limitations will likely be imposed. Portable systems are not intended to be used in fixed, stationary locations but it is not expected that they need to be carried or used in the passenger cabin of aircraft.

For micro systems, it is considered critical for commercial success that they be able to be carried and used in the passenger cabin of aircraft. For portable systems, it is not deemed critical that they be carried and used in the passenger cabin of aircraft; however there are situations where it may be important to be able to have them transported by passenger carrying aircraft while coupled to an appliance. An example would be for systems used with a fuel cell that powers a mobility device such as a wheelchair.

Standards being developed for hydride-based hydrogen storage systems, such as ISO 16111, consider the systems up to a shut-off valve. The standards are written to ensure that systems will not pose a hazard: by leaking hydrogen at a rate that could create a flammable fuel-air mixture; from overpressurization in fire conditions, etc. Either through the standards or regulations, overpacking and requirements for restraining the systems during transport may be imposed. When the systems are coupled into an appliance, the testing found in the standards may not be sufficient. When coupled to an appliance, the shut-off valve will likely be open and thus hydrogen will be able to pass out of the storage container into the appliance. In this situation, hydrogen leakage and overpressurization testing to ensure safety must include the coupling and fuel cell appliance. The robustness of the coupling between the storage system and appliance must also be tested against potential abuse the combined unit may experience in transport and use.

In addition to modifications that might be required discussed in Item 30.1 of this report, other modifications might be appropriate in §175.10(a) which is written specifically for battery power mobility devices. It might be appropriate to either modify them to include fuel cell powered devices or to include new paragraph(s) under §175.10(a) for fuel cell powered appliances.

Discussion of Criticality

This item has been assigned a criticality of high. It is expected that many manufacturers will seek allowance of hydride-based hydrogen storage systems aboard aircraft. DOT-E 13598 currently allows up to 90.7 kg (200 lb) of UN 3468 material aboard cargo-only aircraft. Allowance will be sought to allow micro systems to be carried in carry-on baggage within the passenger cabin of aircraft. There is currently no allowance for systems to be carried into or used within the passenger cabin of aircraft.

Consideration must be given to size and quantity limitations to systems to be allowed within passenger baggage, carry-on and checked, and that allowed as cargo on passenger and cargo-only aircraft. Packaging instructions and container specification must include appropriate testing to ensure safety of the systems allowed aboard aircraft. The testing for systems to be allowed to be transported while coupled to an appliance must include the coupling and appliance to ensure safety of the complete unit.

While it is considered critical that appropriate packaging instructions be developed, it is also recommended that the packaging instructions be designed so as to not prohibit new and innovative designs. This technology is relatively new and is evolving. New advanced materials and designs are expected. The packaging instructions should therefore be performance-based and avoid being too prescriptive, while ensuring a minimum level of safety.

Discussion of Progress

Hydrogen as a compressed gas, UN 1049, is allowed on cargo-only aircraft with a 150 kg (331 lb) net limit. UN 3468, *Hydrogen in a metal hydride storage system* has been included in ICAO's dangerous goods list and forbidden from carriage on either cargo-only or passenger aircraft. At the recent ICAO Dangerous Goods Panel meeting in Oct/Nov of 2005, the panel accepted a proposal from the US panel member to allow cargo-only carriage, with a 100 kg (220 lb) limit. This new ruling is to become effective in January of 2007. Carriage aboard passenger aircraft has not been allowed. US DOT special permit E 13598 allows up to 90.7 kg (200 lb) of UN 3468/NA 9279 material be carried aboard cargo-only aircraft.

An informal and then a formal proposal were made to the UN SCETDG by the representative from Japan, to allow micro fuel cell systems and the fuel cartridges to be carried aboard aircraft. The original informal proposal requested a new entry in the Dangerous Goods List (DGL), with a hazard class 9. The formal proposal submitted for consideration at the July 2005 meeting of the UN SCETDG was revised and instead requested a new DGL entry with a flammable gas hazard, class 2.1. This proposal was withdrawn without consideration. It is anticipated that a new proposal will be submitted requesting modification of UN 3468 to include systems coupled with fuel cell units as well as the stand-alone systems.

Progress on developing consensus standards that might be used as a basis for packaging instructions include:

1. The ISO technical committee for hydrogen technologies (TC 197) has a working group drafting a standard for transportable reversible metal hydride hydrogen storage systems (ISO 16111). This document is currently in the approval stage as a committee draft ("CD") for advancement to the draft international standard stage ("DIS"). In parallel to the CD approval, the document is being considered for publication as a technical specification; with possible publication of the TS much earlier than possible for the International Standard. Once the international standard is approved, the technical specification will be withdrawn. This document only considers stand-alone containers.

2. IEC TC 105 has drafted and is currently reviewing a draft publicly available standard for Micro Fuel Cell Systems (IEC PAS 62282-6-1). This document includes sections on fuel storage containers and complete integrated fuel cell appliances with fuel containers. This standard is expected to reference ISO 16111 for metal hydride-based hydrogen storage container design and testing. IEC document 62282-5 for Portable fuel cell appliances may also be appropriate for considerations for fuel cell appliances that do not qualify as micro, such as might be used on mobility devices.

3. UL is developing a consensus standard (UL 2265) on micro fuel cell systems. An effort is being made to keep UL 2265 consistent with IEC 62282-6 and its development is therefore trailing that of IEC 62282-6.

Recommendations

It is recommended that the OHMS develop a minimum set of design and test criteria for packaging of hydride-based hydrogen storage systems as previously recommended in Items 18 and 25 of this report. Consideration should be given to the impact of onboard aircraft carriage. These criteria should be provided to potential manufacturers and offerors for use in their design and testing of the storage systems and would help ensure consistency in application of rigor in determining the minimum level of safety. Size and quantity limitations need to be considered for allowance aboard passenger aircraft, particularly for inclusion in passenger baggage, checked as well as carry-on. It is preferred that these criteria be performance-based. Ideally they would be based on the ISO and IEC standards underdevelopment by international expert committees (ISO 16111, IEC 62282-6-1 and IEC 62282-5). Systems coupled to appliances must include the appliance standard, and may therefore have further restrictions imposed.

New exceptions or modifications of existing exceptions in §175.10(a) may need to be developed for hydride-based hydrogen storage systems coupled to an appliance allowed aboard aircraft.

To help ensure that the standards being developed for hydride-based hydrogen storage systems meet the need of OHMS, it is recommended that the OHMS assign personnel or contractors to actively participate on the applicable development committees. These would include ISO TC 197 working group 10, IEC TC 105 working groups 7 and 8, and UL’s STP 2265.

Pressure Relief Devices: High Pressure (31)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	

Description of Key Area

DOT has previously required that cylinders use pressure relief devices that conform to CGA S-1.1 (1994 release). There has been discussion within the industry as to whether pressure relief devices, which are non-reseatable, should be required or prohibited. Many of the problems with pressure relief devices have been related to adequacy of the standards that have been referenced. Pressure ratings of S-1.1 devices have generally been limited to 41.4 MPa (6000 psi).

Discussion of Criticality

Pressure relief devices for steel cylinders are often pressure activated, such as a rupture disk. The increased pressure due to exposure to high temperatures or a fire will generally cause the rupture disk to activate before the cylinder loses strength due to high temperature exposure. However, pressure activated devices may not work if the cylinder is not at service pressure when high temperature exposure occurs.

Composite reinforcement tends to insulate the contents of a cylinder, preventing buildup of internal pressure. In addition, composite reinforcement is degraded when exposed to fire. Therefore, composite cylinders are more likely to use thermally activated pressure relief devices.

Thermally activated pressure relief devices have been used to protect cylinders up to 70 MPa (10150 psi), but there are a limited number of applications. Pressure relief devices for higher pressures are being developed.

If a cylinder does not have protection from a thermally activated relief device, there is a significant risk of rupture in a fire. This would create an explosive release of energy initially, and the possibility of a second high rate energy release if the escaping hydrogen burns or detonates.

Discussion of Progress

The industry has developed the PRD1 standard for compressed natural gas, which was ANSI approved in 1998. PRDs qualified to this standard have demonstrated high reliability. The requirements of PRD1 were incorporated into a later revision of S-1.1 as a CG-10 device and into similar ISO standards. PRD1 is the de facto standard for high pressure hydrogen applications in North America. Efforts are currently underway to update PRD1 coverage to address use in hydrogen applications and use at higher pressures.

Recommendations

The industry should continue to develop standards for use with high pressure hydrogen cylinders. The industry and DOT should review field experience using PRDs built to standards that are current or in development. A determination should be made as to whether the industry has sufficiently addressed PRD safety, if special permits should be required that address the use of PRDs, or if reference to industry standards should be incorporated into the federal code.

Pressure Relief Valves: High Pressure (32)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	

Description of Key Area

Pressure relief valves are used on some DOT tanks and on stationary pressure vessels. These relief valves are reseatable, and protect against overpressure that may result from overfilling or from pressure increase due to temperature increase when the tank is not rated to accept the higher pressure.

Discussion of Criticality

Pressure relief valves will provide protection against overpressure, but will not protect against rupture in a fire. There are trade offs with the use of pressure relief valves, balancing the risk of a tank failure due to overpressure versus the risk of released hydrogen igniting.

Discussion of Progress

Standards exist for pressure relief devices for transportable and stationary tanks. The pressures intended for hydrogen storage are higher than typical current use.

Recommendations

A study should be conducted that evaluates potential for an event that would cause an increase in pressure above the rated pressure, the likelihood that overpressure could result in a tank rupture, the likelihood that a release of hydrogen due to overpressure would ignite and cause further problems, and the likelihood that an inadvertent release of hydrogen would ignite and cause further problems. A determination should be made as to what applications would benefit from use of pressure relief valves, and what applications would be safer without the use of pressure relief valves.

Valves: High Pressure (33)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	

Description of Key Area

High pressure hydrogen cylinders will require the use of high pressure valves. Because of problems dealing with high pressures in tubing and fittings, some of these valves may incorporate regulators.

Discussion of Criticality

Valves are generally required for portable and transportable applications, as the cylinders valves should be closed during transportation. High pressures induce high loads on threads and on internal valve and regulator components. Reliability of valves, regulators, and their components is critical to safety.

Discussion of Progress

High pressure hydrogen valves, particularly with integrated regulators, have limited availability and limited field experience.

Recommendations

Field service with these new, high pressure hydrogen valves, with integrated regulators, needs to be monitored for reliability and safety. Industry and DOT will need to determine if new or revised standards or regulations will be required.

Key/Sub Area Assessment Summaries

Welding (34)

Criticality: High
Score: 20
Progress: Addressed, Not Adequately
DOT Relevance:

Description of Key Area

Some metallic components, including cylinders, cylinder liners, valve components, and tubing may incorporate welded construction.

Discussion of Criticality

Welding of metals can introduce stress concentrations, and reduce strength and elongation of welded materials. Welding of some austenitic stainless steels that are resistant to hydrogen embrittlement can produce martensitic structures that are subject to hydrogen embrittlement.

Discussion of Progress

Welded metallic components are currently being used in hydrogen storage. However, the use of welded components becomes more of an issue as hydrogen gas pressure increases.

Recommendations

Industry and DOT should be developing performance based requirements in standards and regulations that demonstrate capability of any welds in components for hydrogen storage are of sufficiently strong and resistant to hydrogen embrittlement. It may be required to limit the use of welds in hydrogen storage components, to specify that only certain metals can be welded, or that higher safety factors will be required for welded components.

Tubing and Fittings: High Pressure (35)

Criticality:	High	**Progress:**	Addressed, Not Adequately
Score:	20	**DOT Relevance:**	

Description of Key Area

High pressure tubing and fittings will be required to fill and vent cylinders and to connect cylinders.

Discussion of Criticality

As pressure increases, making the connection of the tubing and fittings becomes more difficult. Connections are often made by plastically yielding portions of the tubing so that the fittings will not leak or fail to hold. As contained pressure increases, the tube walls thicken, making plastic deformation difficult and possibly inducing stress concentrations. This may compromise the integrity of the joint between the tubing and the fittings. If the joint fails, hydrogen can leak and ignite.

Discussion of Progress

Industry is working on new methods of connecting tubing and fittings.

Recommendations

Industry and DOT should monitor field experience with high pressure tubing and fittings to ensure that safe, reliable components are being developed. As experience progresses, standards should be developed for the qualification of high pressure tubing and fittings.