

# Hydrogen Pipeline Working Group Workshop

## Workshop Proceedings



August 30-31, 2005

Augusta Towers Hotel and Convention Center  
Augusta, GA



Sponsored by  
U.S. Department of Energy  
Office of Energy Efficiency and Renewable Energy  
Hydrogen, Fuel Cells, and Infrastructure Technologies Program

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# 1. Introduction

On August 30-31, 2005, more than 45 researchers and industry experts representing industrial gas and energy companies, national laboratories, consulting/engineering firms, academia, and federal agencies met at the U.S. Department of Energy (DOE) Hydrogen Pipeline Working Group Workshop. The purpose of the workshop was to:

- ◆ Provide a brief overview of DOE-funded hydrogen pipeline research and development (R&D) projects, including the most recent results, and
- ◆ Hear from industry experts about field experience with current in-service hydrogen pipelines (both new construction and converted) and what research or other activities are needed to reduce costs and improve operability.

The Workshop included a question-and-answer session with a panel of industry experts, the results of which are provided in Appendix B. Also, two facilitated breakout groups convened to identify R&D needs for steel pipelines and composite (non-steel) material pipelines. The results of the Workshop summarized in this report will be used to help structure DOE's hydrogen delivery R&D priorities and strategic directions. The agenda is shown in Appendix A and a complete list of workshop participants is provided in Appendix E.

# 2. Background

## DOE Hydrogen Fuel Initiative

In the 2003 State of the Union address, President Bush announced a \$1.2 billion Hydrogen Fuel Initiative to support the development of commercially viable, hydrogen-powered fuel cells. The Initiative recognizes hydrogen's potential to play a major role in America's future energy system and calls for increased federal funding for R&D. The goal is to enable industry to reach a commercialization decision by 2015 so that Americans will have the opportunity to purchase hydrogen-powered fuel cell vehicles in auto showrooms by 2020. The Initiative features parallel R&D tracks to develop (1) reliable, cost-effective, fuel cell vehicle and stationary power technologies and (2) the hydrogen production and delivery

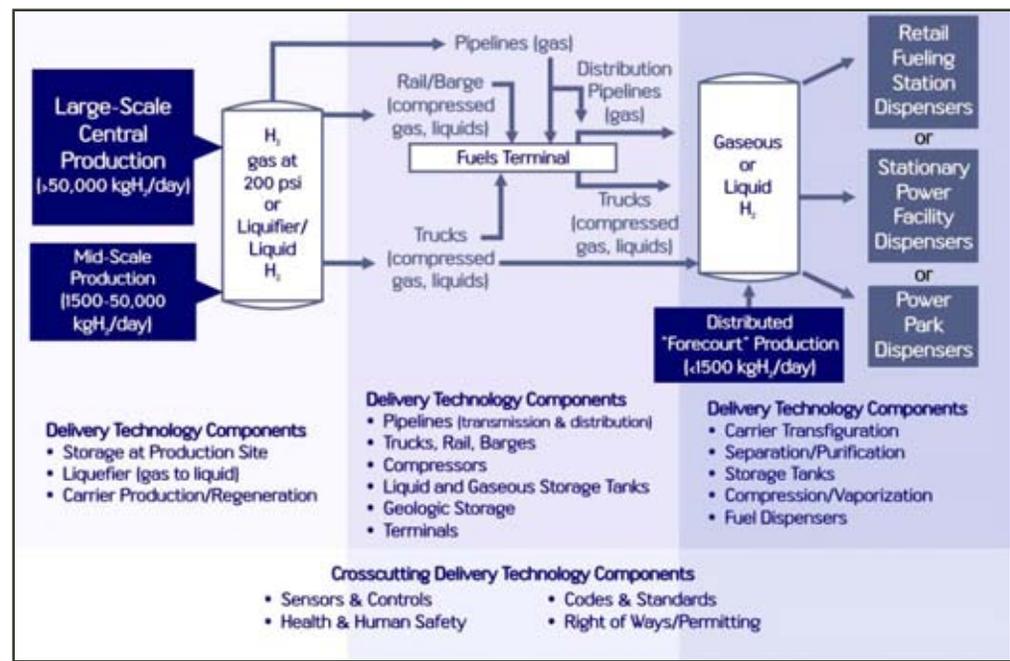


FIGURE 1. HYDROGEN DELIVERY INFRASTRUCTURE

infrastructure. The DOE Office of Energy Efficiency and Renewable Energy (EERE) is the lead organization for the President's Hydrogen Fuel Initiative. Within EERE, the Hydrogen, Fuel Cells, and Infrastructure Technologies Program (HFCIT) is conducting a research, development and demonstration (RD&D) program to overcome critical barriers to making hydrogen and fuel cell technologies competitive with alternative technology. The HFCIT program includes subprograms focused on Hydrogen Production, Hydrogen Delivery, Storage, Fuel Cells, Technology Validation, Safety, Codes and Standards, Systems Analysis, and Education. HFCIT coordinates its efforts with related and supporting activities conducted within DOE and the Department of Transportation.

### *HFCIT Hydrogen Delivery Program*

Delivery is an essential component of any future hydrogen energy infrastructure. As shown on the previous page in Figure 1, the hydrogen delivery scope encompasses all the technologies required to move hydrogen (e.g., pipelines, trucks, compressors, etc.) from the point of production to the point of end-use (e.g., light-duty vehicle). The hydrogen delivery program is focused on meeting the hydrogen delivery objectives outlined in the box by conducting R&D through industry, national laboratory, and university projects. Current hydrogen delivery R&D activities address challenges in cost and energy efficiency, purity requirements, leakage, and embrittlement.

The **goal** of DOE's hydrogen delivery program is to:

***Develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.***

Near-term research efforts are focused on infrastructure options cost and trade-off analysis, hydrogen compression, and storage technology improvements at the forefront. To support the long-term need for an expanded hydrogen delivery infrastructure, researchers are also investigating improved, lower cost materials for pipelines; breakthrough approaches to hydrogen liquefaction; lighter weight, stronger materials and structures for high pressure hydrogen storage and transport; and novel low pressure solid and liquid carrier systems for hydrogen delivery and storage.

### **HFCIT Delivery Program Objectives**

**Understand Infrastructure Trade-offs and Options:** By 2007, define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the transition and long-term use of hydrogen for transportation and stationary power.

#### **Cost Reduction:**

- *By 2010, reduce the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users to <\$0.90/gge of hydrogen.*
- *By 2010, reduce the cost of compression, storage and dispensing at refueling stations and stationary power facilities to <\$0.80/gge of hydrogen (independent of transport).*
- *By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <\$1.00/gge of hydrogen in total.*

### *Gaseous Hydrogen Delivery by Pipelines*

The gaseous hydrogen pipeline delivery path includes compression, bulk storage, transport by pipeline and/or tube trailer, and forecourt storage compression and dispensing. About 630 miles of transmission pipelines in the U.S. transport hydrogen today, most of which are located in the Gulf Coast region.

At very large volumes, an extensive pipeline infrastructure is currently the most cost-effective and energy efficient manner to transport hydrogen to much of the market as is done with natural gas today. Research is needed to resolve concerns about the possibility for hydrogen embrittlement of pipeline steels and/or to develop alternative (lower cost, durable) pipeline materials. If pipeline capital and labor costs could be substantially reduced, hydrogen pipeline transmission could be used sooner rather than later. Pipeline research requires a concerted and focused effort, including fundamental materials science. It will require strong government support.



Source: Air Liquide

The following sections of this report summarize the proceedings of the Hydrogen Pipeline Working Group Workshop, including the opening plenary session presentations, industry panel question-and-answer discussion session, and detailed breakout group results.

### 3. Opening Plenary Presentations

As shown in the agenda in Appendix A, the Workshop opened with an overview of the President's Hydrogen Fuel Initiative and the DOE/HFCIT Hydrogen Delivery Program. Eight presenters followed with summaries and recent results of their DOE-funded hydrogen pipeline R&D projects. On Day 2, six industry experts presented summaries of their experiences and issues with present in-service hydrogen pipeline within their respective companies. The presentations can be downloaded by visiting the Hydrogen Workshops section of the HFCIT's Workshop Proceedings Website at [http://www.eere.energy.gov/hydrogenandfuelcells/wkshp\\_proceedings.html](http://www.eere.energy.gov/hydrogenandfuelcells/wkshp_proceedings.html).

#### CURRENT DOE HYDROGEN DELIVERY R&D

**President's Hydrogen Fuel Initiative**



**Mark Paster**  
Technology Development Manager  
August 2005

**Hydrogen Permeability and Integrity of Hydrogen Delivery Pipelines**

Z. Feng\*, L.M. Anovitz\*, J.G. Blencoe\*, S. Babu\*, and P. S. Korinko\*\*

\* Oak Ridge National Laboratory  
\* Savannah River National Laboratory

August 30, 2005

OAK RIDGE NATIONAL LABORATORY  
U. S. DEPARTMENT OF ENERGY

**Evaluation of Natural Gas Pipeline Materials and Infrastructure for Hydrogen/Mixed Gas Service**

Thad Adams, George Rawls, Poh-Sang Lam and Robert Sindelar  
Savannah River National Laboratory  
August 30-31, 2005

SRNL

This presentation does not contain any proprietary or confidential information.

**New Materials for Hydrogen Pipelines**

Barton Smith, Barbara Frame, Cliff Eberle, Lamy Anovitz, James Blencoe and Tim Armstrong  
Oak Ridge National Laboratory

Jimmy Mays  
University of Tennessee, Knoxville

Hydrogen Pipeline Working Group Meeting  
August 30-31, 2005  
Augusta, Georgia

OAK RIDGE NATIONAL LABORATORY  
U. S. DEPARTMENT OF ENERGY



**Hydrogen Embrittlement of Pipeline Steels: Causes and Remediation**

P. Sofronis, I. M. Robertson, D. D. Johnson  
University of Illinois at Urbana-Champaign

Hydrogen Pipeline Working Group Workshop  
Augusta, GA, August 30, 2005



**Hydrogen-Assisted Fracture: Materials Testing and Variables Governing Fracture**

Brian Somerday, Chris San Marchi, and Dorian Balch  
Sandia National Laboratories  
Livermore, CA

Hydrogen Pipeline Working Group Workshop  
Augusta, GA  
August 30-31, 2005

**Materials Solutions for Hydrogen Delivery in Pipelines**

Dr. Subodh K. Das  
SECAT Inc.

This presentation does not contain any proprietary or confidential information.



OAK RIDGE NATIONAL LABORATORY  
U. S. DEPARTMENT OF ENERGY

**CTC** Concurrent Technologies Corporation

**HYDROGEN REGIONAL INFRASTRUCTURE PROGRAM IN PENNSYLVANIA**

Melissa Klingenberg, PhD



**Natural Gas Utilities Options Analysis for the Hydrogen Economy**

> **Hydrogen Pipeline R&D Project Review Meeting**  
30 August 2005  
Augusta, GA

Mark E. Richards  
Manager, Advanced Energy Systems

## INDUSTRY PRESENTATIONS



**Hydrogen Pipeline Experience**

**Presented By:**  
LeRoy H. Remp  
Lead Project Manager  
Pipeline Projects



**Questions and Issues on Hydrogen Pipelines**

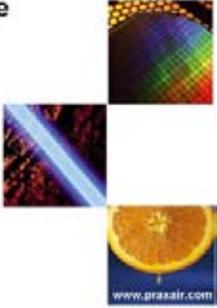
*Pipeline Transmission of Hydrogen*

DOE Hydrogen Pipeline Working Group Meeting ■ August 31, 2005



**Hydrogen Pipeline Discussion**

BY  
Robert Zawierucha, Kang Xu and Gary Koeppel  
PRAXAIR TECHNOLOGY CENTER  
TONAWANDA, NEW YORK



DOE Hydrogen Pipeline Workshop  
Augusta, GA  
August 2005

[www.praxair.com](http://www.praxair.com)



**Hydrogen Piping Experience in Chevron Refining**

**Ned Nicolls**  
Materials Engineer  
Chevron Energy Technology Company

**Hydrogen Pipeline Working Group Workshop**  
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**BP and Hydrogen Pipelines**

DOE Hydrogen Pipeline Working Group Workshop  
August 30-31, 2005  
Gary P. Yano, P.E.

**Code for Hydrogen Pipelines**

Hydrogen Pipeline Working Group Workshop

Augusta, Georgia  
August 31, 2005

Louis Hayden, PE  
Chair ASME B31.12



## 4. Hydrogen Pipeline Working Group

The Hydrogen Pipeline Working Group (PWG) was formed to facilitate collaboration and information sharing on hydrogen pipeline R&D to provide a synergy among projects and to eliminate duplication of efforts and facilities. The PWG includes a broad community of individuals associated with DOE-cost shared hydrogen pipeline R&D projects. Sub-teams were established within the PWG to coordinate specific areas in hydrogen pipeline R&D and related analytical efforts. Below is a brief description of the purpose of each sub-team.

### PIPELINE WORKING GROUP SUB-TEAMS

<b>New Materials and Related Computational Modeling</b>
<ul style="list-style-type: none"><li>◆ Develop synergies across materials technology research efforts to minimize hydrogen embrittlement associated with high-pressure transport</li><li>◆ Develop synergies across research efforts focused on identifying cost reduction methods for new pipeline construction and existing pipeline modification</li></ul>
<b>Natural Gas/Hydrogen Mixtures</b>
<ul style="list-style-type: none"><li>◆ Develop synergies across research efforts evaluating the viability of using existing natural gas transmission and distribution piping network for hydrogen/mixed hydrogen-natural gas delivery</li></ul>
<b>Hydrogen Pipeline Delivery Website/ Web-based Information Sharing</b>
<ul style="list-style-type: none"><li>◆ Develop password-protected website for information sharing among Pipeline Working Group members</li></ul>
<b>Testing, Standards, and Sample Standardization</b>
<ul style="list-style-type: none"><li>◆ Compare and share testing procedures, and help develop consistent methods, controls, and metrics across the Pipeline Working Group projects</li><li>◆ Coordinate cross-sharing of test specimens and testing methods (i.e., round-robin) to compare results across the Pipeline Working Group projects</li></ul>
<b>Cost Modeling Tools</b>
<ul style="list-style-type: none"><li>◆ Develop tools for consistent, comparable, transparent approach to hydrogen delivery cost analysis (H2A delivery effort)</li></ul>

## 5. Industry Panel on Hydrogen Pipelines

As shown in the agenda in Appendix A, the Workshop included an industry panel discussion and question-and-answer (Q&A) session among workshop participants and industry experts to discuss field experiences with current in-service hydrogen pipelines. A summary of the Q&A session is provided in Appendix B.

### *Key Issues*

Hydrogen pipelines have operated safely for a long time using X42 or X52 steel to meet the present industrial hydrogen service needs when operated under current conditions (1,000 psi or less, constant pressure, low cycling). A pipeline system built to serve a much larger market for hydrogen as a transportation fuel might operate at different conditions, including increased load/pressure cycling, increased pressures, and higher requirements for end-of-pipe hydrogen purity. It is unclear today whether hydrogen embrittlement could pose a problem in an expanded hydrogen pipeline system built from existing steel pipelines. In particular, more data is needed relative to fatigue crack growth. Hydrogen purity issues (such as oil contamination from compressor lubricants) will also need to be addressed once minimum hydrogen purity specifications for hydrogen fuel cells have been defined.

While industry experts agree that current hydrogen pipeline costs no more to build today than natural gas pipeline, this cost is still above what would be required to meet DOE cost targets for hydrogen delivery. To achieve DOE cost targets, capital and labor costs will need to be reduced. Conversion of existing natural gas pipeline presents its own set of problems: 1) the pipeline is fully utilized for natural gas service in most areas, and 2) natural gas contains water, leading to corrosion and potential problems with hydrogen embrittlement if the pipe is converted to hydrogen service. Overall, further research for hydrogen pipelines is needed to have a successful transition to a hydrogen economy.

## 6. Facilitated Breakout Session Results

Participants met in facilitated breakout sessions to identify priority research and development (R&D) needs for hydrogen pipelines (see Appendix D for breakout group members). Two concurrent breakout sessions were convened in the following areas: **steel pipelines and composite material pipelines**. While X42 or X52 steel pipe joined by manual welding represents the current state-of-the-art for hydrogen pipeline construction, other materials or joining technologies may offer cost and/or performance advantages for a future hydrogen pipeline infrastructure. In addition, questions such as those posed above about hydrogen embrittlement, contamination prevention, effects of high pressures and other stresses, and other safety- and performance-related issues will need to be resolved before a widespread hydrogen pipeline infrastructure can be built.

Industry Panel Members	
NAME	ORGANIZATION
Leroy Remp	Air Products
James Campbell	Air Liquide
Robert Zawierucha	Praxair
Ned Niccolls	Chevron Corporation
Gary Yoho	BP
Louis Hayden	ASME

Table 1 lists the top-priority R&D needs for hydrogen pipelines identified in the breakout groups. The complete set of R&D needs identified by the groups are shown in Appendix C.

**TABLE 1. TOP-PRIORITY R&D NEEDS FOR HYDROGEN PIPELINES**

<b>Steel Pipeline</b>	<b>Composite Material Pipeline</b>
<ul style="list-style-type: none"> <li>◆ Round-robin testing to document fracture/hydrogen embrittlement properties in the heat affected zones (HAZ) of the weld, especially in new, higher strength steels</li> <li>◆ Research influence of high pressures and pressure cycling on new/existing materials and its effects on hydrogen embrittlement</li> <li>◆ Conduct thorough research (by two or three laboratories) focusing on key mechanical properties of X42 and X52 steel (base metal and welds) under hydrogen pressures of 1,000-2,000 psig</li> <li>◆ Conduct fracture mechanics research on new and existing materials with respect to hydrogen, especially in heat affected zones of the welds</li> <li>◆ Educate public on successes and safe use of hydrogen in existing pipeline service</li> </ul>	<ul style="list-style-type: none"> <li>◆ Define connection technology and how to successfully test and install it</li> <li>◆ Conduct field testing validation to prove availability to withstand mechanical damage</li> <li>◆ Develop simple analysis methods to design fiber reinforced polymer (FRP) systems to meet DOT 192 requirements</li> <li>◆ Determine hydrogen permeation rate of uncoated and coated FRP systems and evaluate the permeation range of polymers/composites in the hydrogen environment</li> <li>◆ Perform field evaluation of composite materials under a broad range of operating conditions (i.e., temperature, soil condition, rock impingement, bending, maintenance, joining, and pressure)</li> </ul>

### TUESDAY, AUGUST 30, 2005

1:00 pm	<b>Welcome and Overview Presentations</b> <b>DOE Hydrogen Program and Delivery</b> <i>Mark Paster, DOE/HFCIT</i>
1:30 pm	<b>Hydrogen Permeability and Integrity of Hydrogen Transfer Pipelines</b> <i>Zhili Feng, Oak Ridge National Laboratory</i>
2:00 pm	<b>Natural Gas Pipelines for Hydrogen Use</b> <i>Thad Adams, Savannah River Technology Center</i>
2:45 pm	<b>FRP Hydrogen Pipelines</b> <i>Barton Smith, Oak Ridge National Laboratory</i>
3:15 pm	<b>Break</b>
3:30 pm	<b>Hydrogen Embrittlement of Pipeline Steels: Causes &amp; Remediation</b> <i>Petros Sofronis, University of Illinois</i>
4:00 pm	<b>Hydrogen Material Research</b> <i>Brian Somerday, Sandia National Laboratory</i>
4:30 pm	<b>Materials Solutions for Hydrogen Delivery in Pipelines</b> <i>Subodh Das, SECAT (partners: ORNL, ASME, University of Illinois, Applied Thin Films, Columbia Gas, Chemical Composite Coatings, Advanced Tech Corp., Oregon Steel Mills, Schott North America)</i>
4:50 pm	<b>Pennsylvania Regional Infrastructure Project</b> <i>Melissa Klingenberg, Concurrent Technologies Corp. (partners: Air Products, Resource Dynamics Corp., EDO Fiber Science)</i>
5:20 pm	<b>Natural Gas Utilities Options Analysis for the Hydrogen Economy</b> <i>Mark Richards, Gas Technology Institute</i>
5:50 pm	<b>Adjourn</b>

### WEDNESDAY, AUGUST 31, 2005

7:30 am	<b>Arrival and Breakfast</b>
8:00 am	<b>Reports from Pipeline Working Group "R&amp;D Collaboration Teams"</b>  <ul style="list-style-type: none"> <li>◆ Introduction: <i>Mark Paster</i></li> <li>◆ Natural Gas/Hydrogen Mixtures in Pipelines: <i>Eileen Schmura</i></li> <li>◆ Hydrogen Pipeline Delivery Website: <i>Steve Pawel</i></li> <li>◆ Testing, Standards, and Samples: <i>Thad Adams</i></li> <li>◆ H2A Delivery Cost Modeling Tools: <i>Mark Paster</i></li> </ul>
8:00 am	
8:10 am	
8:20 am	
8:30 am	
8:45 am	
9:00 am	<b>Hydrogen Pipeline Operating Experience and Issues</b>  <ul style="list-style-type: none"> <li>◆ Air Products: <i>Leroy Remp</i></li> <li>◆ Air Liquide: <i>James Campbell</i></li> <li>◆ Praxair: <i>Robert Zawierucha</i></li> </ul>
9:00 am	
9:30 am	
10:00 am	
10:30 am	<b>Break</b>
10:45 am	<b>Hydrogen Pipeline Operating Experience and Issues (Continued)</b>  <ul style="list-style-type: none"> <li>◆ Chevron: <i>Ned Niccolls</i></li> <li>◆ BP: <i>Gary Yoho</i></li> </ul>
10:45 am	
11:15 am	
11:45 pm	<b>Lunch</b> <ul style="list-style-type: none"> <li>◆ <b>Luncheon Speaker: Codes and Standards Issues for Pipelines</b> <i>Louis Hayden</i></li> </ul>
1:00 pm	<b>Industry Panel Session</b> <ul style="list-style-type: none"> <li>◆ <i>Discussion and Q&amp;A</i></li> </ul>
2:15 pm	<b>Break</b> <i>Informal Discussions and Move to Breakout Sessions</i>
2:45 pm	<b>Breakout Sessions (Concurrent)</b> <ul style="list-style-type: none"> <li>◆ Identify <i>Top-Priority R&amp;D Needs to Address Challenges for Hydrogen Pipeline Delivery with Respect to:</i> <ul style="list-style-type: none"> <li>● Group 1: Hydrogen Steel Pipelines</li> <li>● Group 2: Hydrogen Composite (or Non-Steel) Pipelines</li> </ul> </li> </ul>
4:00pm	<b>Report-Outs and Meeting Wrap-Up</b>
4:30 pm	<b>Adjourn</b>

## APPENDIX B

### Q&A from Panel Discussion

**Q:** Are odorants required for hydrogen pipelines in urban Class 3 locations?

**A:** The regulations state that odorants are not required if the gas is to be used in a manufacturing process or if it interferes with the use of the gas. The regulations state that odorants are required if the gas is for residential use or “fuel use.” DOT appears willing to consider some exemptions. There are currently hydrogen pipelines passing through Class 3 and Class 4 areas without an odorant for industrial use. Researchers in Japan are conducting some experiments on hydrogen odorants and the effects on fuel cells; tests so far are inconclusive.

**Q:** Are observed incidences of hydrogen pipeline corrosion all external, or have any been internal?

**A:** All have been external.

**Q:** Is the hydrogen pipe purchased for new pipeline construction/repair seam normalized or full-body normalized?

**A:** Most or all are only seam normalized.

**Q:** A paper by Robinson (SNL, 1970s) reported some hydrogen embrittlement (HE) problems in experimental pipelines. It appears that some minor flaws due to HE are tolerable (i.e., will not lead to failure of the pipeline). Would a flaw that is one-tenth the thickness of the pipeline be okay?

**A:** Praxair (Robert Zawierucha, Praxair) reported that they will be presenting a paper at The Pittsburgh Conference (PITTCON) in a few weeks with some data on tolerable flaws. The notion of “tolerable flaws” can be difficult for laymen to understand; the perception is that ANY flaws are intolerable. However, there are tolerable flaws from an engineering perspective. We will need to determine what kind of data is needed to effectively answer this question – is it stress dominated? Toughness dominated? etc.

**Q:** Since fatigue crack growth is accelerated by the presence of hydrogen, do we know the frequency of pipeline loading?

**Subquestion:** Today’s hydrogen service will look different from hydrogen service in a “hydrogen economy.” Should we look at natural gas cycling in pipelines and use that as our model?

**A:** The ASME B31 Hydrogen Service Committee will be looking at natural gas pipeline cycles as they develop new code for hydrogen piping and pipeline standards. Louis Hayden (ASME) will speak with a natural gas pipeline contact on September 19 and will forward Mark Paster (DOE/HFCIT) data on day-to-day pulsation and seasonal trends, if available. They will also look at demand cycling in today’s gasoline transportation market. This issue is important relative to future use of hydrogen in transportation.

**Q:** All the industrial gas producers seem to design more robustly than called for in the DOT 192 (CFR 49 Part 192) requirements. Do you keep your stress levels lower than required in ASME B31 (American Society of Mechanical Engineers)?

**A:** APCi reports that the majority of their pipelines have operating stresses limited to 30% of SYMS (Specified Minimum Yield Strength). All agreed that they keep stresses lower than required in the code to minimize crack formation.

**Q:** Do you back-purge the pipe or use backing rings during stick welding?

**A:** No. Do not use either back-purge or backing rings.

**Q:** Does the use of reciprocating compressors result in pressure cycling in the pipeline?

**A:** There are accumulators located near the exit of the compressors that dampen/eliminate this issue. We operate today’s hydrogen pipelines at a constant pressure without pressure cycles or swings.

- Q:** Can you publish results on the use of weld metal in high-pressure hydrogen service?
- A:** The Compressed Gas Association (CGA) will be doing this (follow up with Robert Zawierucha, Praxair). New data is expected to be published in October 2005.
- Q:** How do proximity distances for hydrogen pipelines compare to natural gas pipelines?
- A:** There is a much smaller radius of potential damage for hydrogen compared to natural gas because of the lower energy value of hydrogen and smaller concussion wave.
- Q:** When you find anomalies in hydrogen pipelines, what is the general technique for quick repairs?
- A:** We normally remove the pipe and replace it. But for temporary/quick repairs, clamps and club springs are used. It is common to conduct surface repairs for natural gas pipelines. More knowledge is needed on the relative impacts of dents, gouges, etc. for hydrogen pipelines.
- Q:** The DOE H2A Model uses “Panhandle-B” to calculate pipeline pressure drops – is this a reasonable approach?
- A:** Air Liquide uses the general flow equation modified for the particular pipeline design. Air Products uses “Pipeline Tool Box” software, which has a number of useful equations for calculating hydrogen flow and pressure drops in pipelines. Another source for hydrogen flow tools is the Southwest Research Institute.
- Subquestion:** What is Panhandle-B’s margin of error?
- A:** The Panhandle B equation is probably correct with about +/- 10%.
- Q:** If a research program develops an alternative, lower cost steel or composite material that shows promise for hydrogen pipelines, what kind of data or information would the industry need to adopt these new materials?
- A:** It must be accepted by DOT 192 requirements. In order for DOT to accept the new material, there must be an ASTM standard for it, which will require lab data, field testing, reproducible welding procedures, etc. There must also be a demonstrated advantage for the new material (e.g., lower cost; ability to handle hydrogen at higher pressure (>1,000 psi, etc.)).
- Q:** Do you have a design criteria/failure diagram for fatigue crack growth in X-52 steel?
- A:** There is a design criteria for fatigue crack growth in PSA vessels built from X-52 steel. (Also have equation for fraction analysis, but data is not in a useable format just yet (follow up with Louis Hayden).)
- Q:** How important is contamination control and should we study this?
- A:** In general, the hydrogen that is currently moved through pipelines meets the needs of the customers it currently serves. The electronics industry is the only customer that requires very high purity hydrogen, and this customer is served by electro-polished stainless steel pipelines. It is unclear exactly what the final purity requirements will be for fuel cells and whether this will cause a problem. The primary source of contamination in pipeline systems is lubricated compressors. Oil mist eliminators are used but some oil gets through. No other contamination has been observed although one panel member did say that some particulates have been observed on occasion.
- Q:** Can you provide us with samples of materials that have been used in the field – both good and bad?
- A:** Praxair can provide samples (follow up with Robert Zawierucha, Praxair).
- Q:** The DOE H2A model bases a lot of its cost data on the Oil and Gas Journal Report on Natural Gas Pipelines. In general, it takes reported costs for natural gas pipeline construction and adds 30% to get estimated hydrogen pipeline costs. This is to factor in the potential increase of material or other potentially higher cost. Is this a reasonable approach?
- A:** This is overly conservative. A hydrogen pipeline should cost no more to build than a natural gas pipeline (do not see material cost as a concern). Right-of-way costs and environmental permitting costs will be more of an issue in the future, but this will affect hydrogen and natural gas pipelines equally.

**Q:** Do you see a need for a compressor booster station every 200 miles?

**Subquestion:** How do you estimate compressor operation and maintenance costs?

**A:** No, not for 200 miles. One compressor is sufficient. In general, compressor maintenance cost is approximately 3% of the replacement value per year.

**Q:** Are hydrogen sensors used on existing pipelines?

**A:** No – the industry does not use installed sensors. APCi does metering (scf in vs. scf out) to determine mass balance. Air Liquide checks their meters daily and conducts a detailed physical sensor sweep along the pipelines two times a year.

**Subquestion:** Would it be beneficial to install sensors in future hydrogen pipelines?

**A:** This is something that is being studied. Need to consider the best location on the pipeline to have sensors installed.

**Q:** Is it practical to envision a system of distribution pipelines to refueling stations in urban areas – what is the level of resistance to laying hydrogen pipeline in urban areas?

**A:** There will be SIGNIFICANT resistance. APCi has installed hydrogen pipelines in Class 4 areas, but these were permitted years ago. Getting the required environmental permits now will be the major hurdle.

**Subquestion:** Do you think it would be more difficult to site high pressure distribution lines (>500 psi) vs. low pressure lines (<200 psi)?

**A:** It seems that 100 psi is the “tipping point” for increased concern on the part of regulators and the public perspective. Less than 100 psi is very different than >100 psi in their perception. There appears to be little difference between 300 psi and 1,000 psi from their perspective. Regulators and regulations vary a great deal from area to area and state to state.

**Q:** Does a 0.5% leakage rate as a 2015 target for hydrogen pipelines seem realistic?

**A:** It is believed that hydrogen leakage is no different than natural gas leakage with today’s technology. The actual leakage rate in today’s hydrogen pipelines is unknown – but we do know it is relatively small.

**Q:** What might motivate an industrial gas company or energy company to install a hydrogen transmission pipeline on the east or west coast before a widespread consumer transportation market of a significant size is established?

**A:** 1) A guarantee of a major user in the region; and/or 2) incentives that lower the investment required to build the pipeline; and/or 3) joint venture between automobile companies and government to build the pipeline with contracts to gas companies to supply the hydrogen.

**Q:** Why is research being conducted on other materials if X42 and X52 steel works?

**A:** Still researching other material options that may be more economical to use other than current steels. The cost to construct hydrogen pipelines from steel is still too high to have a successful transition into a “hydrogen economy.” Welding and steel costs are large ticket items.

**Q:** Are any of the current hydrogen pipelines converted natural gas pipelines?

**A:** To the best of our knowledge very little if any. There might be some short sections but nothing significant. There are however some oil pipelines that have been converted to hydrogen use.

**Q:** What are your thoughts on hydrogen embrittlement if hydrogen and natural gas mixtures were put into existing natural gas pipelines?

**A:** Natural gas is not as dry as the hydrogen in hydrogen pipelines. It also contains some sulfur compounds. The presence of these materials creates internal pipe corrosion concerns. Hydrogen embrittlement may be much more of a concern if corrosion exists. More data is needed.

## APPENDIX C

### Table C-1. R&D Needs for Steel Pipelines

(Tasks are listed in order of priority and the tally of votes are indicated in red)

NEW/EXISTING MATERIALS RESEARCH	OPERATING PARAMETERS	FABRICATION AND INSPECTION
<ul style="list-style-type: none"> <li>• <b>Demonstrate influence of high pressures on hydrogen embrittlement (9)</b></li> <li>• <b>Generate data on X-42 and X-52 (base metal &amp; welds) under hydrogen pressures of 1,000-1,500 psig (by 2-3 labs focusing on key mechanical properties specified by industry) (8)</b> <ul style="list-style-type: none"> <li>– also for A106, A33, and new materials</li> <li>– under different scenarios of pressure and time</li> </ul> </li> <li>• <b>Fracture mechanics data in hydrogen, especially for weld heat-affected zones (7)</b></li> <li>• Old infrastructure: (5)           <ul style="list-style-type: none"> <li>– welding and repair</li> <li>– cracking susceptibility</li> </ul> </li> <li>• Fatigue data for new and existing pipeline alloys base metal and weld metal – pressure up to 3,000 psi (3)</li> <li>• Permissible hydrogen uptake/concentration in select steels/coatings (3)</li> <li>• Conduct materials-compatibility studies in hydrogen to determine application envelopes: (3)           <ul style="list-style-type: none"> <li>– for A333 pipe, for A-350 forgings, and for A-352 castings</li> </ul> </li> <li>• How do we leverage high strength pipelines developed for oil and gas transmission? (2)</li> <li>• Standardize testing terminology and loading conditions (1)</li> <li>• Conduct materials compatibility studies of stable austenitic stainless steels (316/316L) in other mill forms: (1)</li> <li>• Casting analogs and forgings</li> <li>• Existing natural gas network (1)           <ul style="list-style-type: none"> <li>– feasibility of low hydrogen mixtures for a "near" term transition</li> </ul> </li> <li>• Hydrogen materials/weld "re-qualification"</li> <li>• Confidential repository of hydrogen embrittlement failures (2)</li> </ul>	<ul style="list-style-type: none"> <li>• Compile current operating envelopes (1)           <ul style="list-style-type: none"> <li>– with respect to particular operating conditions</li> </ul> </li> <li>• Integrity management – material process and service</li> <li>• Zero in on steel that will meet requirements for hydrogen pipelines (X-42/X-52? Higher Y?) and zero in on P&amp; T range for investing</li> <li>• Current design based on plastic yielding is overly conservative; need to proceed with a fracture mechanics methodology</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Round-robin testing to document fracture/hydrogen embrittlement properties in the HAZ of the weld, especially in new, higher strength steels (9)</b></li> <li>• Develop in-line/in-situ techniques to monitor hydrogen embrittlement and mechanical property degradation (5)</li> <li>• Is weld the weakest link? (2)</li> <li>• Effect of hydrogen embrittlement on mechanical damage (third party) effects (1)</li> <li>• Develop methodology for evaluating suitability of girth welds in existing pipelines for hydrogen service (1)</li> <li>• Develop repair and hot tap techniques for hydrogen pipelines</li> <li>• Research on automatic welding for small diameter pipelines           <ul style="list-style-type: none"> <li>– or prefabricated assembly</li> </ul> </li> </ul>

ANCILLARY COMPONENTS	ECONOMICS	PUBLIC EDUCATION
<ul style="list-style-type: none"> <li>• Develop low cost compressor for the refueling station</li> <li>• Material selection for components that have high strength/heavy strained capacity (i.e., springs)</li> </ul>	<ul style="list-style-type: none"> <li>• Can we practically reach the targets set by DOE? "especially cost" (2)</li> <li>• Optimum pipeline transmission pressure vs. compressor costs (3)</li> <li>• Research a suitable business model for a hydrogen distribution system           <ul style="list-style-type: none"> <li>– private owned vs. other options</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <b>Prove to the community that there is no danger in using existing pipeline materials/welding (X-42/X52) for hydrogen service (define pressure) (5)</b></li> <li>• Demonstrate statewide pipeline in California up to 1,000 psi using current materials (California hydrogen highway) (1)</li> <li>• Public perception and pipeline safety; nimbly use existing right-away</li> <li>• DOT involvement in Codes &amp; Standards</li> </ul>

## APPENDIX C

### Table C-2. R&D Needs for Composite Material Pipelines

(Tasks are listed in order of priority and the tally of votes are indicated in red)

BACKGROUND	BASIC MATERIALS SCIENCE/RESEARCH	JOINING AND REPAIR	FIELD TESTING/ VALIDATION	DESIGN RULES/ CODES & STANDARDS	EDUCATION
<ul style="list-style-type: none"> <li>Research past produced pipes and reasons for lack of commercial success; identify past service experience with FRP piping in any gas service (1)</li> </ul>	<ul style="list-style-type: none"> <li><b>Determine hydrogen permeation rate of bare and coated FRP, and coating failure mode; evaluate range of polymers/composites for permeation/strength in hydrogen environments (6)</b></li> <li>Research high pressure composite pipelines (2)</li> <li>Develop smart structure capabilities (2)</li> <li>Basic R&amp;D on hydrogen compatible materials; cost effective (2)</li> <li>Environmental damage</li> </ul>	<ul style="list-style-type: none"> <li><b>Joining methods</b> <ul style="list-style-type: none"> <li>What is connection technology and how is it tested? How to qualify installation? (10)</li> </ul> </li> <li>Maintenance repairs/replacement of subsections (2)</li> <li>Connection of ancillaries</li> </ul>	<ul style="list-style-type: none"> <li><b>Prove ability to withstand mechanical damage (i.e., soil settlement, impact, cycling/fatigue) (8)</b></li> <li><b>Perform field evaluation of composite materials under a broad range of operating conditions (i.e., temperature, soil condition, rock impingement, bending, maintenance, joining, and pressure) (4)</b></li> <li>Need acceptance criteria for third party damage and repair methods for FRP piping (1)</li> <li>Conduct constant tests and field tests (1)</li> <li>Environmental damage</li> </ul>	<ul style="list-style-type: none"> <li><b>Develop simple analysis method to design FRP systems to 192/B31.8 requirements (8)</b></li> <li>Develop design/performance specifications to provide high confidence of life-cycle integrity (2)</li> <li>Develop design tools for composite/hybrid systems to optimize on cost (1)</li> <li>Qualify production of FRP (it has to be readily available, economically acceptable, and deliverable)</li> </ul>	<ul style="list-style-type: none"> <li>Improve perception of using polymer pipelines (2)</li> </ul>

## APPENDIX D

### Breakout Group Members

#### Steel Pipeline Breakout Group Participants

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Thad Adams	Savannah River National Laboratory
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Zhili Feng	Oak Ridge National Laboratory
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#### Composite Material Breakout Group Participants

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Barton Smith	Oak Ridge National Laboratory
Allen Spivey	Gas Technology Institute
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**FACILITATOR:** Mark Paster, DOE/HFCIT

# APPENDIX E

## Hydrogen Pipeline Working Group Workshop

*Augusta Towers Hotel & Convention Center  
Augusta, Georgia  
August 30-31, 2005*

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