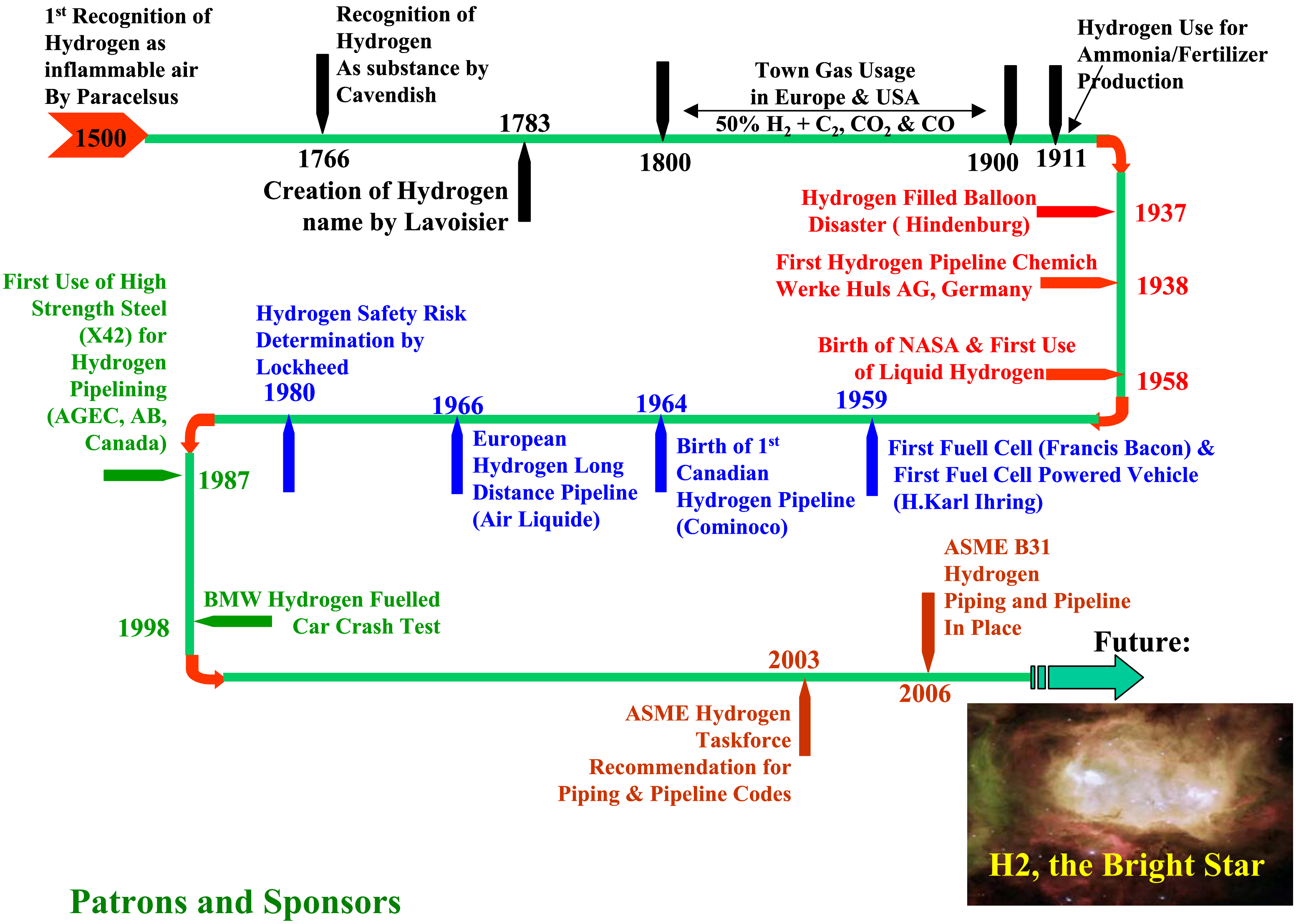
ASME 6th International Pipeline Conference

SECOND PANEL FORUM

HYDROGEN PIPELINE TRANSMISSION: UPDATES & OPPORTUNITIES

Program, Abstracts, and Speakers

September 25th, 2006, Telus Convention Centre, Rooms 104-105-106



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ASME 6th International Pipeline Conference
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SECOND PANEL FORUM

HYDROGEN PIPELINE TRANSMISSION: UPDATES & OPPORTUNITIES

Monday, 25th September 2006

Keynote Address: "The DOE Hydrogen Program and the Challenges for Hydrogen Delivery Infrastructure" ***Mark Paster & Matt Ringer, United States Department of Energy, Hydrogen and Fuel Cells Program***

Chairman and Moderator: Louis E. Hayden, ASME Chairman H2 Code Committee

Cochairmen:

Bill Leighty, *Director, The Leighty Foundation*
Gerry M. Eisenberg, *Director, Pressure Technology Codes and Standards & Secretary, B31.12 Project Team*
Dr. Mo Mohitpour, *President, Tempsys Pipeline Solutions Inc.*

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Forum Program Schdeule: (25th September 2006, 7.00 AM - 5.00 PM)

07.00 : 08.30 **FORUM REGISTRATION (Conference Registration Desk)**

08.15 : 08.30 **WELCOME & OPENING REMARKS,** Forum Chairman: **Louis E. Hayden &** Forum Co-Chairs: **Bill Leighty, Gerry M. Eisenberg, Dr. Mo Mohitpour**

08.30 : 08.45 **"ASME B31.12 Hydrogen Piping and Pipeline Code", Louis E. Hayden Jr., PE,** Louis E. Hayden Associates, Bethlehem, PA, USA

08.45 : 09.00 **"Safety and Risk Aspects of Hydrogen Transmission Pipelines", Jim Campbell, PE,** Manager, Pipeline Construction, Air Liquide Process & Construction, Houston, TX, USA

09. 00 : 09.15 **"Design Guidelines for Hydrogen Piping and Pipelines", Prof. Erol Ulucakli,** Mechanical Engineering Department, Lafayette College, Easton, PA & **Louis E. Hayden Jr**., **PE**, Louis E. Hayden Associates, Bethlehem, PA, USA

09.15 : 09.30 **"High Pressure Hydrogen Piping for Storage, Compression and Dispensing Systems", Daniel J Rabun,** Future Energy Solutions Group, Air Products and Chemicals, Allentown, PA ,USA

09.30 : 09.45 **"Costs of Installing and Operating Hydrogen Pipelines", Matt Ringer,** National Renewable Energy Laboratory (NREL), Golden, CO, USA

09.45 : 10.00 **COFFEE BREAK**

10.00 : 10.15 **"Large-scale Stranded Renewables: The International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)", Bill Leighty**, Director, The Leighty Foundation & Principal, Alaska Applied Sciences, Inc., Juneau, AK, USA

10.15 : 10.30 **"The Need for New Compression and Storage Options for Hydrogen Pipelining", Jeff Holloway, P.Eng.,** Pipeline Technologies Inc., Calgary, AB, Canada

10.30 : 10: 45 **"Hydrogen Cavern Operation", George D. Parks, Research Fellow,** ConocoPhillips, Bartlesville, OK, USA

10.40 : 11.00 **"NATURALHY-project: first step of the determination of the potential of the existing natural gas network for hydrogen delivery", Onno Florisson,** Gasunie Engineering & Technology, N.V. Nederlandse Gasunie, The Netherlands & **Isabelle Alliat**, Gaz de France - Research Division, France

11.00 : 11.45 **PANEL DISCUSSION**

12.00 : 13.15 **LUNCHEON**

INTRODUCTION: **Mr Jim Campbell**: Manager, Pipeline Construction, Air Liquide Process & Construction, Houston, TX, USA

KEYNOTE ADDRESS: "The DOE Hydrogen Program and the Challenges for Hydrogen Delivery Infrastructure", Mark Paster & Matt Ringer, United States Department of Energy (USDOE), Hydrogen and Fuel Cells Program
TO BE PRESENTED BY MATT RINGER

13.30 : 13.45 **"A Process to Separate Hydrogen Transported in Natural Gas Pipelines", Dr. Michael G. McKellar,** Fossil Fuels Department, Idaho National Laboratory (INL), USA

13.45 : 14.00 **"Delivery of Hydrogen Energy By Anhydrous Ammonia", Dr. John H. Holbrook,** AmmPower LLC, USA

14.00 : 14.15 **"Hydrogen Infrastructure Program – Hydrogen Delivery Scenarios, Pipeline Material/Composite Tank Testing, Hydrogen-Specific Sensor Research", Linda Eslin,** Concurrent Technologies Corporation (CTC), Johnstown, PA, USA

14.15 : 14.30 **"Assessment of Fracture Control of Pipes In Various Piping Codes", Mahendra Rana, PE**, Praxair, Inc., Tonawanda, NY, USA

14.30 : 14.45 **"Micromechanics of Embrittlement of Materials for Hydrogen Delivery", Prof. Petros Sofronis & I.M. Robertson,** University of Illinois at Urbana-Champaign, **B. Somerday,** Sandia National Laboratories (SNL), Livermore, CA, **G. Muralidharan,** Oak Ridge National Laboratory (ORNL), **D. G. Stalheim,** DGS Metallurgical Solutions, Inc., Vancouver, WA, USA

14.45 : 15.00 **"Material Challenges in the Use of High Strength Steel Pipelines for High Pressure Hydrogen Gas Transmission", Doug Stalheim,** DGS Metallurgical Solutions, Inc. Vancouver, WA, USA

15.00 : 15.15 **COFFEE BREAK**

15.15 : 15.30 **"High Strength Linepipe and Welding Requirements for High Pressure Transmission Pipelines", Dr Yong-Yi Wang,** VP, Engineering Mechanics Corporation, Columbus, OH, USA

15.30 : 15. 45 **"High-Pressure Hydrogen Permeation in Pipeline Steels and Issues Related to Welding of Hydrogen Pipeline Transportation", Dr. Zhili Feng,** Oak Ridge National Laboratory (ORNL), **Dr. Suresh Babu,** Edison Welding Institute, Oak Ridge, TN, USA

15.45 : 16. 00 **"Nondestructive Monitoring of the Effects of Hydrogen Pressure on the Tensile and Fracture Toughness Properties of Steel Pipelines and their Girth Welds", Dr. Fahmy M. Haggag,** Advanced Technology Corporation (ATC), Oak Ridge, TN, USA

16.00 : 16.15 **"Hydrogen Measurement in Steels", Dr. W.J.D. (Bill) Shaw & Thushanthi Senadheera**, Pipeline Engineering Center, Schulich School of Engineering University of Calgary, AB, Canada

16.15 : 17.00 **PANEL DISCUSSION**

17.00 : 17.15 **CLOSURE**

18.00 – 20.00 **CONFERENCE RECEPTION**

ASME SETTING THE STANDARD — PIPELINE SYSTEMS — CAPP CANADIAN ASSOCIATION OF PETROLEUM PRODUCERS — CEPA Canadian Energy Pipeline Association / Association canadienne de pipelines d'énergie — Alberta

EUB — Natural Resources Canada / Ressources naturelles Canada — National Energy Board / Office national de l'énergie

PRESENTATION ABSTRACTS

Louis E. Hayden, PE., Louis Hayden Consultants, Bethlehem, PA, USA **"ASME B31.12 Hydrogen Piping and Pipeline Code"** Two years ago, ASME authorized the creation of a new B31 code to address the unique needs of hydrogen piping and pipeline systems. This new code, B31.12, was scoped to cover industrial piping, transmission pipelines and distribution and commercial/residential piping. This new hydrogen-focused code contains information specific to the safe design of hydrogen pipeline and piping systems. The pipeline section of this code contains requirements for pressure design of pipelines in hydrogen service up to 3,000 psi. Modified operation and maintenance requirements and mandatory requirements for operational and maintenance or integrity management programs are included. Guidelines and requirements for conversion of existing petroleum or gas pipelines to hydrogen service are provided. Pipeline material MSYS (minimum specified yield strength) values are specified in view of system design pressure and material yield strength.

Jim Campbell P. Eng., Manager, Pipeline Construction, Air Liquide Process & Construction, Houston, TX, USA **"Safety and Risk Aspects of Hydrogen Transmission Pipelines"** Hydrogen has been transported by pipeline for over 50 years. There are now over 1,300 miles of operating hydrogen pipelines in Europe and the U.S.A., and although there have been occasional leaks and ruptures, there has never been an injury or significant property damage caused by a hydrogen pipeline. Hydrogen has many "safe" properties. It is non-toxic, it dissipates rapidly in open spaces, it burns rapidly with low radiant heat, and the explosive power of an air-gas mixture is much lower than natural gas. On the other hand, hydrogen poses some safety challenges which cannot be ignored. It is completely odorless, and it is proving difficult to find an odorant which will stay mixed with such a light gas. It has very low ignition energy, and a leak will often catch fire "spontaneously". The industry is responding by developing stringent standards for the construction and operation of hydrogen pipelines. In areas where a hydrogen pipeline is planned to be built near populated areas, a quantitative risk analysis is proposed. A computer simulation of a hydrogen pipeline leak is used to calculate radiant energy emission from a fire or explosion. If the simulation shows that there is an unacceptable level of risk, then the route must be changed.

Professor M. Erol Ulucakli, Mechanical Engineering Department, Lafayette College, Easton, Pennsylvania and **Louis E. Hayden, Jr. P.E,** Louis E. Hayden Associates, Bethlehem, Pennsylvania, USA **"Design Guidelines for Hydrogen Piping and Pipelines"** This presentation discusses design guidelines for hydrogen piping and pipeline systems. Motivated by the planned use of high pressures in hydrogen transmission systems and complications caused by hydrogen-induced embrittlement, we are interested in providing recommendations to the ASME Hydrogen Piping and Pipeline Project team for design margins for metallic and non-metallic pipe materials when used in a hydrogen environment.

The scope of our study includes all common metallic piping and pipeline materials used in the construction of piping and pipeline systems, of seamless and welded construction; composite reinforced welded or seamless metallic-lined piping and pipelines that are currently commercially manufactured and for which technical design data is available; composite reinforced plastic-lined piping and pipelines that are currently commercially manufactured and for which technical design data is available.

Design margins were developed considering the operating conditions, internal hydrogen environment within the piping and pipeline systems and the effect of dry hydrogen gas on the material of construction. Composite piping and pipeline line pipe were considered as hoop wrapped construction with liners capable of withstanding longitudinal loads. We provide recommendations for further research in this area.

Daniel J. Rabun Air Products and Chemicals Inc. **,** Allentown, PA ,USA. **"High Pressure Hydrogen Piping for Storage, Compression and Dispensing Systems"** Compressed Gas Industry is facing new challenges as the hydrogen distribution pressure is increased from traditional 2,400 psig systems to 7,000 psig and even to 14,000 psig systems. ASME and CGA are leading efforts to develop standards and codes for addressing some of these challenges. The presentation will discuss safety critical elements of these standards and industry recommended practices.

PRESENTATION ABSTRACTS

Matt Ringer, National Renewable Energy Laboratory (NREL), Golden, CO, USA **"Costs of Installing and Operating Hydrogen Pipelines"** For the past three years, the US Department of Energy's Hydrogen, Fuel Cells and Infrastructure Technologies program has been working on the develop of clear and consistent analysis tools for determining cost contributions for various production and delivery technologies. On the delivery side, two models have been developed; one that determines the cost contributions for specific delivery components, and the other that integrates components results with market scenarios to determine a delivery pathway cost. In both of the models, pipelines are considered a potential critical element in the delivery of hydrogen from the production source to the end-use site. Therefore, the H2A delivery analysis team has had to develop a methodology for calculating the costs associated with pipeline delivery of hydrogen.

In this presentation, the modeling methodology will be presented. The H2A Delivery team, along with its industrial collaborators, has used costs from the Oil and Gas Pipeline journal as a basis for determining hydrogen pipeline costs. Additionally, a unique module for determining optimum pipeline layout, based on a two-ring design, for delivering to various markets has been developed. Both of these items (costs and optimum layout) will be presented, and preliminary results discussed.

Bill Leighty, Director, The Leighty Foundation and Principal, Alaska Applied Sciences, Inc., Juneau, AK, USA **"Large-scale Stranded Renewables: The International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)"** We assume humanity's goal is an equitable, affordable, accessible global energy system based on benign, renewable sources: "solar" in its many forms, including PV, wind, biomass, biological, thermal, geothermal -- and perhaps nuclear.

Earth's richest renewable resources are generally stranded, requiring costly new gathering and transmission systems to bring this energy to distant markets. Electricity transmission is costly, on towers vulnerable to acts of God and man, provides no storage for the time-varying output of renewable sources, and the public opposes large, new electric lines. Renewables can be converted to gaseous hydrogen (GH2) for gathering and transmission in pipelines, in a major new industrial process similar to that used by the natural gas (NG) industry for decades. Every new industrial process requires a pilot plant. We propose that the international hydrogen community starts immediately to design and build a pilot-scale GH2 pipeline system that would collect energy from diverse renewable sources, such as wind and biomass, and transport it ~30-100 km cross-country to a small community and / or a university campus where it would be used for vehicle and distributed-generation fuel.

This would be an international renewable-source hydrogen transmission demonstration facility (IRHTDF). International collaboration on preliminary design would lead to an RFP for final design, construction, and operation: an ideal project for the International Partnership for the Hydrogen Economy (IPHE). Designing and building the IRHTDF would require us to confront and solve a variety of technical, economic, and social challenges. Its successful operation will allow us to estimate the cost of GH2 fuel, delivered to major markets, from large-scale gathering and long-distance transmission of diverse, stranded, renewable sources.

Jeff Holloway, P.Eng. Pipeline Technologies Inc., Calgary, AB, Canada **"The Need for New Compression and Storage Options for Hydrogen Pipelining"** The need for new compression and storage options for hydrogen pipelining will cover:

- A discussion of what compression options presently exist for gaseous hydrogen in the large pipeline capacity range.
- What are the hurdles in the way of the development of these new compression designs?
- Looking for novel compression ideas – but are they here yet and who is looking?
- How better storage options for hydrogen can expedite the development of large cross country hydrogen pipelines.

PRESENTATION ABSTRACTS

Dr. George Parks, ConocoPhillips, Bartlesville, OK, USA **"Hydrogen Cavern Operation"** ConocoPhillips and its subsidiary, ChevronPhillips, have over 20 years of experience in operation of a hydrogen storage cavern. The cavern has a capacity of over 5,000 tons of hydrogen and is connected to a ConocoPhillips refinery by a 15 mile pipeline. The presentation will describe cavern construction, operation, maintenance. The refinery and pipeline operations and their relation to cavern operations will also be presented.

Onno Florisson, Gasunie Engineering & Technology, N.V. Nederlandse Gasunie, The Netherlands, and **Isabelle Alliat,** Gaz de France- Research Division **"NATURALHY-project[1]: first step of the determination of the potential of the existing natural gas network for hydrogen delivery"** Hydrogen is foreseen by many as an important energy carrier in the future sustainable energy society. The transition towards the situation in which hydrogen becomes an important energy carrier will be lengthy (decades), costly, and will need a significant R&D effort. In view of this, an examination of the potential of using the existing natural gas pipeline system for the widespread delivery of hydrogen is a logical step. The first step is defining the conditions under which hydrogen can be added to natural gas.

The chemical and physical properties of hydrogen and natural gas differ significantly, and this may have an impact on safety related to the delivery of gas, the use of gas and the integrity of the network.

The NATURALHY project investigates the conditions under which hydrogen can be added to natural gas with acceptable consequences for safety, durability of the system, gas quality management and performance of end-user appliances. Membranes will be developed to enable the selective extraction of hydrogen from the hydrogen/natural gas mixture. The work on safety aims to compare the safety risks presented by the transmission, distribution and use of a hydrogen/natural gas mixture to those of natural gas. The effects of hydrogen on the durability of materials and components used in the natural gas transmission and distribution networks and end user infrastructure will be determined experimentally. The socio-economic and Life Cycle Assessment aspects of the mixing option will be mapped out.

At the IPC2006 Hydrogen Forum, next to a general overview of the project results obtained concerning the work on pipeline integrity and safety will be presented.

LUNCHEON KEYNOTE ADDRESS

Mark Paster, Office of Hydrogen, Fuel Cells, and Infrastructure Technologies, USDOE, Energy Efficiency and Renewable Energy, and Matt Ringer, NREL **"The DOE Hydrogen Program and the Challenges for Hydrogen Delivery Infrastructure"** Two key goals of U.S. energy policy are energy security and reduced emissions including green house gas emissions. The use of hydrogen as an energy carrier, particularly in the transportation sector, is an approach that can help meet these goals. In 2003, President Bush announced the Hydrogen Fuel Initiative and pledged $1.2B over five years to hydrogen and fuel cell research and development. DOE has worked with public and private organizations to develop a *National Hydrogen Energy Technology Roadmap* and has developed the *DOE Hydrogen Posture plan*. These documents describe the research, development, and demonstration steps required to make a successful transition to a hydrogen economy. Key challenges include cost effective technology to store sufficient hydrogen on-board vehicles to provide at least 300 miles driving range, low cost and durable PEM fuel cells, lower cost hydrogen production technology, and a cost effective and energy efficient hydrogen delivery infrastructure. Progress is being made in all of these areas. Hydrogen delivery is an essential component of any future hydrogen energy infrastructure. Hydrogen must be transported from the point of production to the point of use, and handled within refueling stations or stationary power facilities.

[1] *The NATURALHY-project is financially supported by the European Commission within the sixth Framework Programme, and further information on the project is available on www.naturalhy.net*

PRESENTATION ABSTRACTS

The Department of Energy's Hydrogen Delivery Program element is a comprehensive effort to research and develop new technology to reduce the cost of hydrogen delivery for the transition and long term. It includes pipeline research, improved compression technology, breakthrough liquefaction technology, lower cost off-board storage and extensive analysis of the delivery options for both the transition and longer term. The results from the cost analysis tools and models that have been developed and the challenges and approaches to reduce hydrogen delivery costs will be discussed. **(The keynote address will be delivered by Matt Ringer on behalf of Mark Paster.)**

Dr. Michael G. McKellar, Dennis Bingham, Terry Turner, Kerry Klingler, Bruce Wilding, Fossil Fuels Department, Idaho National Laboratory (INL), USA **"A Process to Separate Hydrogen Transported in Natural Gas Pipelines"** Large-scale hydrogen production, i.e. from high temperature electrolysis using nuclear reactors, will require a transport system to distribute the hydrogen. Currently, hydrogen is transported primarily by way of railroad cars, tanker trucks, tanker ships and a limited amount of pipeline built specifically for hydrogen transport. With the goal from President Bush to develop a hydrogen economy, the demand for hydrogen will increase. Over the road transportation is very expensive due to the energy density of hydrogen. For long distance transportation, pipelines will be the most economical mode. Although a network of hydrogen pipelines may one day be developed, the current natural gas network could be utilized to transport hydrogen in the interim. The hydrogen molecule is small and can escape through the lattice of metals. The molecule can also interact with certain metals and cause them to become brittle. If the hydrogen is 20% or less of the total flow in the pipeline, embrittlement is not an issue. An obstacle to using the existing infrastructure is separating the hydrogen from the natural gas at the desired end destination. A cryogenic process has been developed at the Idaho National Laboratory that separates the hydrogen from the natural gas inexpensively and provides hydrogen purities > 95%.

Dr. John Holbrook, AmmPower LLC **"Delivery of Hydrogen Energy By Anhydrous Ammonia"** Ammonia (anhydrous, NH_3) represents an excellent, energy-efficient means for delivering hydrogen energy to the marketplace. Ammonia liquefies at 125 psi at room temperature and can be, and is, transported routinely in compact form in pipelines, barges, rail cars and trucks. Ammonia contains almost 18 weight percent hydrogen and in liquid form is over 20 times more energy dense by volume than 1,000psi gaseous hydrogen. At the point of delivery/use ammonia can be readily "cracked" to liberate the hydrogen gas, or as more and more studies are showing, the delivered ammonia can be used as a clean-burning direct fuel in internal combustion engines or fuel cells. Ammonia pipelines have been operating safely and reliably for decades in the United States delivering liquid ammonia for fertilizer use. Almost 3,000 miles of 6-8 inch diameter mild carbon steel pipeline are operated in the US, and have a delivery capacity of nearly 2 million tons of ammonia per year (~350,000 tons of hydrogen annually). These ammonia pipelines operate at ~250 psi, and with very few in-line compressors. They are generally underground, experience extremely few leaks or failures, and have essentially no internal corrosion issues, since anhydrous ammonia does not attack steels. The biggest issue for these ammonia pipelines is that the entire capacity of the existing lines is committed to transporting ammonia for agricultural purposes, and there is no current additional capacity for transporting ammonia/hydrogen for energy applications. The good news, of course, is that it is much less expensive to build additional 6-8 inch diameter, relatively thin-walled, low-pressure pipeline to transport liquid ammonia than it is to construct (or convert from NG use) large-diameter high-pressure hydrogen gas pipelines.

Linda Eslin, Concurrent Technologies Corporation (CTC), Johnstown, PA, **USA "Hydrogen Infrastructure Program – Hydrogen Delivery Scenarios, Pipeline Material/Composite Tank Testing, and Hydrogen-Specific Sensor Research"** Concurrent Technologies Corporation (CTC) is executing the Hydrogen Regional Infrastructure Program in Pennsylvania (PA) for the Department of Energy (DOE). In this program, CTC works with industry, a national laboratory, and reputable standards development organizations to perform research and development activities that will further the hydrogen economy under the DOE's Hydrogen, Fuel Cells, Infrastructure and Technologies Program (HFCITP).

PRESENTATION ABSTRACTS

The HFCITP Multi-Year Research, Development, and Demonstration Plan identifies goals, milestones and technical/cost barriers to overcome before the hydrogen economy will become a reality. Key activities performed by CTC include: hydrogen delivery scenarios, including hydrogen/natural gas separation technologies, material/composite testing, and sensor research. An overview of these activities is presented below.

Hydrogen Delivery Scenarios: CTC assessed the potential of co-transporting natural gas and hydrogen in the existing pipeline infrastructure by examining current natural gas and hydrogen pipeline transport parameters as well as applicable regulations. To further expand this assessment, CTC subcontracted to Resource Dynamics Corporation to develop hydrogen delivery (production and delivery) scenario options for Pennsylvania. Inputs to this evaluation are the H2A production and delivery models developed by the National Renewable Energy Laboratory, Geographical Information System data, and co-transport inputs such as feasible separation technologies as assessed in a joint effort between CTC and Air Products and Chemical Incorporated (APCI). Separation research has an added benefit in the potential reduction of hydrogen refueling cost by developing technologies for low cost hydrogen recovery from reformed natural gas streams.

Pipeline Material/Composite Tank Testing: CTC has subcontracted to Savannah River National Lab (SRNL) and Hypercomp Engineering to test pipeline and composite tanks, respectively with test data validation by ASME. An evaluation of pipeline material testing data was conducted to verify that existing low cost pipeline materials are adequate for long term hydrogen delivery and to predict the rate and intensity of material degradation. CTC has also developed statistical and finite element analysis models to assist in these determinations. SRNL is providing material test data performed in a high pressure hydrogen environment to be used in model validation. Composite tank research was conducted to determine if novel materials and/or configurations meet or exceed the 2010 DOE target of 0.03% H2 by volume and $500/kg.

Hydrogen-Specific Sensor Research: Although current regulations cover the requirements for combustible gas pipeline surveys for leak detection and mitigation, more robust hydrogen-specific leak detection is needed to reduce the amount of combustible gas false alarms. Combustible gas sensors, although inexpensive cannot distinguish between hydrogen and other combustible gases, such as natural gas. CTC and APCI conducted a literature search of existing hydrogen-specific sensor technologies. After selecting the top three technologies, laboratory and field tests were conducted to verify performance, durability, and operation in the presence of contaminants. Recommendations for modifications to existing hydrogen-specific sensors were forwarded to the vendors to facilitate improved operation in field environments.

Mahendra Rana, PE, Praxair, Inc., Tonawanda, NY **"Assessment of Fracture Control of Pipes In Various Piping Codes"** Most pressure vessel and piping Codes provide rules on fracture resistance requirements to preclude in-service failures. In this presentation, fracture control rules specified in ASME B31.3 and B31.8 piping Codes will be discussed. Technical basis for these rules will also be presented. The presentation will also include preliminary thoughts on the fracture control plan for the upcoming ASME B12.12 Hydrogen Piping Code.

Prof. Petros Sofronis and I.M. Robertson, University of Illinois at Urbana-Champaign, **B. Somerday,** Sandia National Laboratories (SNL), Livermore, CA, **G. Muralidharan**, Oak Ridge National Laboratory (ORNL), and **D. G. Stalheim**, DGS Metallurgical Solutions, Inc., Vancouver, WA, USA **"Micromechanics of Embrittlement of Materials for Hydrogen Delivery"** The technology of large scale hydrogen transmission from central production facilities to refueling stations and stationary power sites is at present undeveloped. Among the problems which confront the implementation of this technology is the deleterious effect of hydrogen on structural material properties, in particular at gas pressure of 1,000 psi which is the desirable transmission pressure suggested by economic studies for efficient transport.

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To understand the mechanisms of hydrogen embrittlement our approach integrates mechanical property testing, TEM observations, and finite element modeling. In this work a hydrogen transport methodology for the calculation of hydrogen accumulation ahead of a crack tip in a pipeline steel is outlined. The approach accounts for stress-driven transient diffusion of hydrogen and trapping at microstructural defects whose density evolves dynamically with deformation. The transient and steady state hydrogen concentration profiles are used to assess the hydrogen effect on the mechanisms of fracture as they depend on material microstructure. Understanding this hydrogen effect is of paramount importance to the rapid assessment of using the natural-gas pipeline distribution system for hydrogen transport and of the susceptibility of new alloys tailored for use in the new hydrogen economy.

Doug Stalheim, DGS Metallurgical Solutions, Inc. Vancouver, WA, USA **"Material Challenges in the Use of High Strength Steel Pipelines for High Pressure Hydrogen Gas Transmission"** Steel has been historically the economical material of choice for the construction of high pressure oil and gas transmission pipelines. Steel transmission pipelines designed for oil and gas transmission have been used by current hydrogen producers, but at generally lower operating pressures. Over the years, hydrogen's ability to embrittle steel has been well documented. Residual stress, internal cleanliness, microstructure, and mechanical properties all play a role in steel's ability to resist hydrogen embrittlement. However, the long term effect of high pressure hydrogen transmission through commercial grade steel pipelines of various qualities and properties has not been thoroughly explored. This presentation will discuss material factors that need to be explored and addressed if current commercially available pipelines manufactured with steel are to be used for transmission of high pressure hydrogen gas.

Dr. Yong-Yi Wang, Engineering Mechanics Corporation, Columbus, OH, USA **"High Strength Linepipe and Welding Requirements for High Pressure Transmission Pipelines"** Modern high strength linepipes (pipe grades X80 and above) made from low carbon control-rolled TMCP steels usually have excellent weldability and high impact toughness. They may also possess some undesirable mechanical properties, such as low strain hardening (high yield to tensile ratio), low ductility, anisotropy, and heat-affected zone (HAZ) softening. The impact of these characteristic mechanical properties on the integrity of high pressure pipelines is examined in contrast to older and lower-grade linepipe steels. The need to update welding requirements from the viewpoint of weld integrity is explored. The material property requirements for arresting ductile fracture in gaseous hydrogen pipelines are investigated using existing fracture arrest models built primarily for natural gas pipelines.

Dr. Zhili Feng, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN and **Dr. Suresh Babu,** Edison Welding Institute, Oak Ridge, TN, USA **"High-Pressure Hydrogen Permeation in Pipeline Steels and Issues related to Welding of Hydrogen Pipeline Transportation"** Hydrogen, once produced, must be transported from the point of production to the point of use. Among a number of hydrogen delivery options, an extensive pipeline infrastructure would be the most cost-effective and energy-efficient means to transport very large amounts of hydrogen to much of the market as is done currently with natural gas. There are great concerns about hydrogen embrittlement of the steel pipelines under the high gaseous pressures environment expected for hydrogen transmission. As in the case of natural gas and other energy carrier transmission pipelines, the weld region in a steel pipeline for hydrogen delivery is expected to be most vulnerable to hydrogen embrittlement due to the formation of unfavorable microstructures and the high weld residual stresses. The presence of high-pressure hydrogen would bring up new challenges in welding construction and maintenance of pipelines to the pipeline industry and the regulatory body. This presentation will highlight some of the issues and on-going research to address these issues to ensure the safe, cost-effective operation and long-term reliability of the hydrogen delivery pipeline infrastructure.

Fahmy M. Haggag, Advanced Technology Corporation (ATC), Oak Ridge, TN, USA **"Nondestructive Monitoring of the Effects of Hydrogen Pressure on the Tensile and Fracture Toughness Properties of Steel Pipelines and Their Girth Welds"** The nondestructive Automated Ball Indentation (ABI) test technique developed by ATC was used to measure the tensile and fracture toughness properties from

PRESENTATION ABSTRACTS

each test on six samples of various pipeline steels while under hydrogen pressure in a sealed chamber. The chamber more accurately simulates real-world pipeline conditions where only the inside of the pipeline is exposed to hydrogen. The inner 12.5-mm (0.5-in) diameter of the bottom surface area of each sample (25-mm diameter by 9.5-mm thick) was exposed to 13.8 MPa (2,000 psi) hydrogen pressure. The innovative design of the hydrogen chamber allows six samples to be simultaneously exposed to hydrogen pressure for various lengths of time and performing up to 17 ABI tests on each sample using a 0.762-mm (0.030-in) diameter tungsten carbide indenter. Although the changes in tensile and hardness properties were very small, the fracture toughness of the X80 steel decreased by 15%, 26%, and 33% for the three exposure times of 5, 25, and 100 hours, respectively. The maximum increases in yield strength, ultimate strength, and hardness were 3%, 5%, and 5%, respectively. No changes in tensile and fracture toughness properties were detected in the steels of Grade B, X52, and X70 after exposures up to 100 hours. Additional work covering higher hydrogen pressure and exposure times and microstructure examinations will be continued next year. The in-situ Stress-Strain Microprobe® (SSM) system and its ABI technique provide a monitoring capability of the effects of pressurized hydrogen on the key mechanical properties of steel pipeline materials and their girth welds after increasing transmission service time in order to determine their fitness-for-service.

Dr. W.J.D. (Bill) Shaw and Ms. Thushanthi Senadheera, Pipeline Engineering Center, Schulich School of Engineering, University of Calgary, AB, Canada. **"Hydrogen Measurement in Steels"** The measurement of hydrogen in steels is not a simple matter, especially when trying to correlate the measurement of hydrogen with the mechanical damage that takes place. A key aspect in the development and use of the measurement techniques are reproducibility and accuracy of the measured values of hydrogen. There are various forms of hydrogen residing in steel, these being easy mobile, progressive mobile and trapped. When taken all together we obtain the total hydrogen. The methods of measurement are divided into two separate categories, direct measurements and indirect measurements. These in turn may be either non-destructive or destructive in nature. This presentation covers the various techniques of hydrogen measurement in steel along with the statistical behavior of hydrogen residing in steel and its variability from steel to steel.

INTRODUCING OUR SPEAKERS

Isabelle Alliat *is graduated in Materials & Physics from the engineer school of the National Institute of Applied Science in Lyon, France, and she holds a M.S. in Polymers and Composites Materials. She joint the Research Division of Gaz de France in 1993 as a research scientist. She became the project leader on ceramics materials and radiant burners for industrial applications. She is now involved in international R&D projects on hydrogen energy and natural gas. She is leading the Work Package on Durability of Materials in the NATURALHY project and she is coordinating a demonstration project on Hythane refueling stations in France.*

Jim Campbell, P. Eng. *is the Manager of Pipeline Construction for Air Liquide, an international supplier of industrial gases. Jim has been designing and building pipelines since 1971, and has been involved in hydrogen pipeline design for almost 15 years. He is a member of the ASME team working on a new Code for Hydrogen Piping and Pipelines.*

Linda Eslin *– Technical Lead Hydrogen Regional Infrastructure Program in Pennsylvania– Ms. Eslin is a Senior Process Engineer with over 12 years experience in process design, power plant commissioning, performance testing, research and development, safety, and chemical analysis. In addition to her leadership role in the Hydrogen Infrastructure Program, she currently also manages fuel cell related demonstration projects. Ms. Eslin holds a BS degree in Chemical Engineering and an MS in Engineering Management.*

INTRODUCING OUR SPEAKERS

Dr. Zhili Feng *is a Senior R&D Staff Member of the Materials Joining and NDE Group, Materials Science and Technology Division, Oak Ridge National Laboratory (ORNL). He received his Ph.D. degree in Welding Engineering from The Ohio State University. He specializes in the thermal-mechanical-metallurgical behaviors of materials during welding and joining. Dr. Feng has extensive experience in application of analysis results to solve industry problems, including hydrogen embrittlement issues in gas transmission pipelines and petrochemical refineries. Many of his R&D programs came from automotive, aerospace, petrochemical and power generation industries, as well as from government agencies such as DOE, DOD, NASA, NSF and NIST. He currently leads a DOE R&D program on Materials Joining Technology for Hydrogen Delivery Infrastructure.*

Onno Florisson *has a university degree in applied physics. He has been with N.V. Nederlandse Gasunie for 21 years, at which he has had several positions. The last 11 years he has been responsible for defining and coordinating international research projects, and he is currently the coordinator of the NATURALHY-project, which is the subject of the presentation he joins with Ms Isabelle Alliat of Gaz de France.*

Fahmy Haggag, *CEO and Founder of ATC received two M.S. degrees in Materials and Nuclear Engineering from The University of California, Santa Barbara, and the University of Alexandria, Egypt. He has 36 years of experience and more than 80 publications in various areas of fracture mechanics and nuclear engineering.*

Louis E. Hayden, PE, *President, Louis Hayden Consultants. Mr. Hayden has over 35 years of experience in the design of piping and pipeline systems. He has worked on refining, chemical, pipeline and power plant piping systems. As Vice President of Engineering at Tube Turns, Inc. he was responsible for the development of micro-alloyed plate specifications used in the manufacturer of high yield pipeline pipe fittings.*

Mr. Hayden is Chair of the ASME Task Group developing B31.12 Hydrogen Piping and Pipeline Code. He is Vice Chair of the ASME Board on Pressure Technology Codes and Standards and past Chair of the ASME B31 Piping Code Standards Committee. Mr. Hayden is currently providing consulting services to ASME as Project Manager of the ASME Section VIII, Division 2 Rewrite project. He is also co-author of "Design Factors for Hydrogen piping and Pipelines".

Mr. Hayden is an Adjunct Professor of Mechanical Engineering at Lafayette College, Easton, PA.

Dr. John H. Holbrook *has a BS in Metallurgical Engineering from the University of Cincinnati (1970) and a MS (1971) and PhD (1976) in Materials Science from Stanford University. Dr Holbrook's experience is extensive and covers:*

- *26 years with Battelle-- 14 in Columbus and 12 in Richland, WA at Battelle-PNNL*
- *Involved in a wide range of technical areas, including hydrogen embrittlement of structural materials and hydrogen storage and transfer*
- *In 2004, began studying anhydrous ammonia as a means for storage and delivery of hydrogen, and ammonia as a direct fuel*
- *Left PNNL in April to start AmmPower LLC to promote ammonia-fuel related technologies*

Jeff Holloway, P.Eng., *Started his career with Nova Corporation and has been consulting around the world through Pipeline Technologies Inc. since 1986. Prepared the feasibility report for the Alliance Pipeline and assembled a group which carried out the preliminary design of the Alliance Pipeline System.*

Mr.Holloway specializes in the application of compression to pipeline systems, equipment selection and station layout. Has been involved with multiple large pipeline and compression projects for pipeline companies in North, Central and South America, Europe and Australia.

INTRODUCING OUR SPEAKERS

Bill Leighty, *Director, The Leighty Foundation and Principal, Alaska Applied Sciences, Inc., Juneau, AK, USA. Mr. Leighty has BS Electrical Engineering and MBA degrees from Stanford. He has co-authored over 15 papers, in the last five years, on transmission and storage alternatives for diverse, large-scale, stranded, renewable energy resources, including as gaseous hydrogen in pipelines.*

Dr. Michael G. McKellar *is research and development engineer at the Idaho National Laboratory (INL) and has been there since 1991. He has worked in the areas of high temperature electrolysis, natural gas liquefaction, refrigeration systems, and carbon dioxide sequestration. His primary expertise is process modeling of thermal systems and testing of refrigeration and liquefaction systems. He currently has 8 patents and 25 publications in the areas of high temperature electrolysis, liquefaction, enhanced two-stroke engines, carbon dioxide sequestration, and other areas. He was also a member of a team that recently received the R&D 100 Award for small-scale liquefaction. Dr. McKellar graduated from Purdue University in 1992 and 1987 with a Ph.D. and a Masters Degree in Mechanical Engineering. He also received a B.S. in Mechanical Engineering from Brigham Young University in 1984. His Masters and Ph.D. work was in refrigeration system modeling, testing, and optimization.*

Dr. George Parks, Ph.D. *is a research fellow with ConocoPhillips, Bartlesville, OK, USA. Dr. Parks joined Phillips Petroleum in 1976. He began his career as a researcher in fundamental materials science with a focus on heterogeneous catalysis. In subsequent years, he has carried out and supervised both experimental and computational research aimed at gaining fundamental understanding of commercially relevant products and processes. He currently serves as Research Fellow and is responsible for research in advanced fuels. Dr. Parks received his undergraduate education at David Lipscomb College. After graduation, he spent a year at the University of Heidelberg as a German Academic Exchange Fellow. He has a Ph.D. in physical chemistry from Rice University.*

Mark Paster *is the Hydrogen Delivery Lead and has additional responsibilities within Hydrogen Production in the Hydrogen, Fuel Cells and Infrastructure Technology Program at the US Department of Energy (USDOE). He has led the development of the DOE Hydrogen Delivery Program element and the H2A Delivery Analysis Tools. He worked in R&D at Monsanto for 27 years prior to joining USDOE six years ago.*

Daniel J. Rabun *- Business Development, Commercial Sales Engineer, Future Energy Solutions Group, Air Products and Chemicals, Inc. Dan leads Business Development and Commercial Sales for Hydrogen and Hydrogen Equipment related to all energy and fuel applications, in Western United States.*

He joined Air Products in 1976 as a Chemical Engineer from Villanova University. During his 30 years with Air Products he has worked in Process Engineering, Project Development, Project Engineering, and Construction for U.S. and worldwide projects.

For 15 years he was Engineering Manager for the Western United States, with responsibility for Safety, Engineering, and Installation of industrial gas and utility supply systems at customer sites. He joined the Future Energy Solutions Group in 2004, to find, develop, and guide the best new hydrogen and energy related technologies, to create viable commercial projects and signed contractual business arrangements. He is a strong advocate for clean energy and the environment. He is interested in all areas of engineering, science, technology, and policy.

Mahendra Rana, PE *has an MSME degree from Illinois Institute of Technology, Chicago, IL. He is an ASME Fellow. Mr. Rana is working for Praxair, Inc. and is involved in the areas of fracture mechanics, pressure vessel design and development and materials testing. He is a member of several ASME Boiler and Pressure vessel Code committees, including the Main Committee and the Board on Pressure Technology C&S. He is the Chairman of the ASME H2 Project Team on 15,000 PSI vessels and a member of B31.12 Hydrogen Piping Committee.*

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Matt Ringer *is a Senior Engineer at the National Renewable Energy Laboratory (NREL), and heads all hydrogen delivery analysis projects. With USDOE's guidance, Matt developed the H2A Delivery Components model, and helped with the creation of the H2A Delivery Scenario model. Matt has investigated hydrogen delivery options for more than 4 years. He is also aligned with NREL's biomass program, and jointly working in business development and analysis for biomass to fuels technologies. Matt received his BS in Chemical Engineering from the University of California at San Diego in 1995, and will receive his MBA from the University of Denver in March of 2007.*

Dr. W.J.D. (Bill) Shaw *is a Professor & Director of Pipeline Engineering Center, Schulich School of Engineering, University of Calgary, Alberta, CANADA. Dr. Shaw graduated in mechanical engineering, University of Saskatchewan. Dr. Shaw has been a - professor in Mechanical & Manufacturing Engineering for 25 years, a consulting engineer in Saskatoon, Saskatchewan, for 12 years and a mechanical engineer with Boeing Aircraft Company, Seattle Washington for 1.5 years. Dr. Shaw's area of research covers materials science, corrosion, hydrogen embrittlement, mechanical behavior of materials, failure analysis, stress corrosion cracking, mechanical alloying,creep, fatigue, fracture mechanics. Dr Shaw is fully familiar with metals, polymers and ceramics currently involved in hydrogen measurement techniques for determination of hydrogen in steel.*

Prof. Petros Sofronis' *education and research orientation are in the area of mechanics of materials. He is an expert in the theories of solid mechanics that includes the disciplines of elasticity, viscoelasticity, plasticity,and fracture mechanics. His research methodology involves analytical and computational techniques, and in particular linear and nonlinear finite element analysis.*
Petros Sofronis has been active in the field of hydrogen embrittlement for nearly 20 years. Since 1991, Sofronis has been a principal investigator in the interdisciplinary environment of the Materials Research Laboratory at the University of Illinois at Urbana-Champaign. In collaboration with Professor Ian Robertson of the Materials Science Department, Sofronis has been investigating the HELP and hydride mechanisms for hydrogen embrittlement by coupling solid mechanics techniques with experimental observations. His theory on the hydrogen induced shielding theory to explain the mechanism of hydrogen enhanced localized plasticity for embrittlement is the first proposed rational explanation of the hydrogen induced fracture. Recently, Prof. Sofronis has been working on materials for the new hydrogen economy in collaboration with Prof. Robertson. His research aims at developing and verifying a lifetime prediction methodology for failure of materials used in hydrogen gaseous environments. Development and validation of such predictive capability and strategies to avoid material degradation is of paramount importance to the rapid assessment of the suitability of using the current natural gas pipeline distribution system for hydrogen transport in the new hydrogen economy and of the susceptibility of new alloys tailored for use in hydrogen related applications.

Douglas G. Stalheim*, President, DGS Metallurgical Solutions, Inc. has a BS in Metallurgical Engineering and 25 years of industrial experience within the steel and aluminum industries. Recognized as one of the top experts in the world in API line pipe production including specification review, alloy design, rolling design, plate, coil and pipe production. Involvement in over 2.2 million tons representing in excess of 650 API line pipe projects in the world market, including hydrogen infrastructure research for USDOE. Experience in all aspects of steel and aluminum production. Extensive heat treat experience along with a specialty of high carbon abrasion resistant grinding media, practical experience with hydrogen effects on steel, and contacts around the world in these industries. DGS Metallurgical Solutions, Inc. 16110 NE 4th Street, Vancouver, WA 98684 USA., (360) 713-2407, Fax – (360) 882-1775, dgstalheim@comcast.net, www.dgsmet.com*

Professor M. Erol Ulucakli, *Ph.D. (University of Michigan, Ann Arbor) is a member of the faculty at the Mechanical Engineering Department of the Lafayette College in Easton, Pennsylvania. Professor Ulucakli teaches in the areas of heat transfer, fluid mechanics, thermodynamics, biomedical engineering, and engineering design process. His research interests include heat transfer, fluid mechanics, biomedical*

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engineering, and hydrogen-induced embrittlement of materials. He is a member of ASME and is actively involved in the Heat Transfer Division.

Dr. Yong-Yi Wang *received his Ph.D. and M.S. in Mechanics and Materials from the Massachusetts Institute of Technology (MIT). He has been one of the primary contributors to the weld integrity programs in PRCI (Pipeline Research Council International). Some of his recent work involves strain-based design of high-strength pipelines, reliability-based defect assessment, girth weld ECA code revisions in North America, and integration of multi-scale mechanics with welding process simulation. His consulting activities cover both onshore and offshore pipeline constructions in the areas of weld defect tolerance levels, material test procedures, welding requirements, and material specifications.*

Dr. Wang is a member of ASME B31.8 Section Committee, ASME B31.12 Committee on Hydrogen Piping and Pipelines, and API 1104. He is an active contributing member to CSA Z662. Dr. Wang serves as the Vice President at the Engineering Mechanics Corporation of Columbus , Columbus, Ohio, USA

INTRODUCING OUR CO-CHAIRS

Gerry Eisenberg *is Director, Pressure Technology Codes and Standards at ASME. He has held several positions on the ASME staff over a period of 33 years, including project leader for the Boiler and Pressure Vessel Committee and Director of Nuclear Codes and Standards. His current responsibilities include standards development on a global scale for boilers, pressure vessels, piping, valves, flanges and fittings. He is a graduate of the US Merchant Marine Academy, Kings Point NY with a BS in Marine Engineering, and he is a Fellow of ASME.*

Bill Leighty: *Director, The Leighty Foundation: www.leightyfoundation.org Principal, Alaska Applied Sciences, Inc.: wind generation and R+D. BS Electrical Engineering, Stanford, 1966; MBA, Stanford, 1971. Small business owner and resident of Juneau, Alaska, for 34 years. 2000 – 2005: Co-author of twelve papers, presented at international conferences, exploring transmission and energy storage alternatives for diverse, large-scale, stranded renewable energy resources, especially as gaseous hydrogen via pipeline.*

Dr. Mo Mohitpour: *Professional Engineer with Thirty one years of experience in engineering, construction, inspection and management of pipeline systems and associated facilities for oil, gas, condensate, batched products, speciality fluids (hydrogen and carbon monoxide, bitumen etc) transmission, storage, tankage and distribution. Has worked with IMEG, Bechtel, Fluor, NOVA/TransCanada, Canauck Engineering and is currently President of Tempsys Pipeline* Solutions Inc.

Co-author of books "Pipeline Design & Construction - A Practical Approach" ASME Publication*, released Oct. 2000, 2nd edition Oct 2003* ***and "Pipeline Operation & Maintenance - A Practical Approach" ASME Press 2004****. Has Published 37 Technical Papers.*

Dr Mohitpour has a Ph.D in Mechanical Engineering from University of London, Imperial College of Science & Technology and Medicine, and is Fellow of the institute of Mechanical Engineers (UK), Fellow of American Society of Mechanical Engineers (ASME) and a Fellow of Engineering Institute of Canada (EIC). He hold professional engineering status in the State of Texas & the Provinces of Alberta and British Columbia. He is also a Chartered Engineer, UK

Pipeline Systems Division

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ASME 6th International Pipeline Conference, Second Panel Forum

HYDROGEN PIPELINE TRANSMISSION: UPDATES & OPPORTUNITIES

Air Liquide POX (Partial oxidation) unit at Longview Texas

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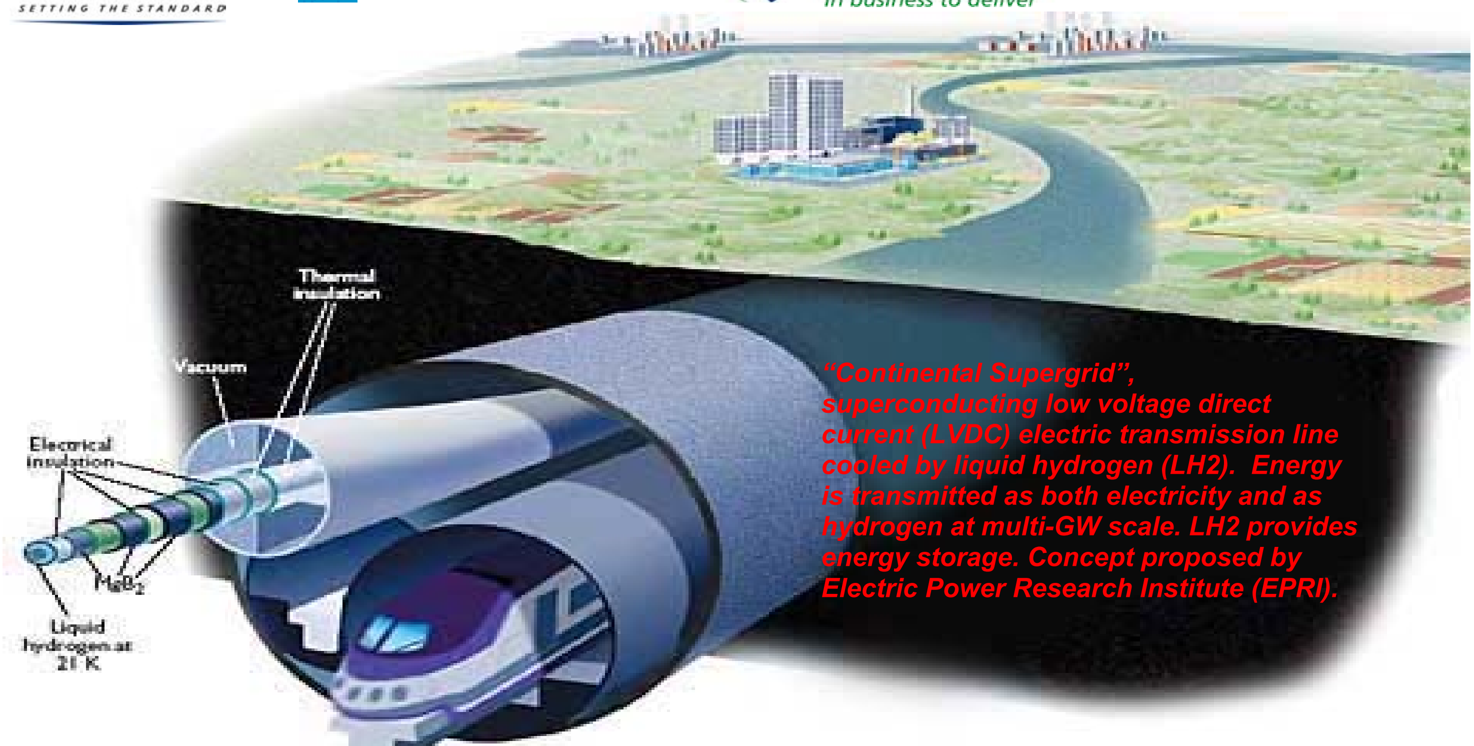

"Continental Supergrid", superconducting low voltage direct current (LVDC) electric transmission line cooled by liquid hydrogen (LH2). Energy is transmitted as both electricity and as hydrogen at multi-GW scale. LH2 provides energy storage. Concept proposed by Electric Power Research Institute (EPRI).