2005 DOE-EE Hydrogen Pipeline Delivery Program

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

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May 25, 2005

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Project PDP52

This presentation does not contain any proprietary or confidential information.

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Overview

Timeline

- Start Date: November, 2004
- End Date: September, 2005
- 50% Complete
- Initiation of 3-year program in FY05

Barriers

- Retrofitting Existing NG Pipelines fro Hydrogen/Hythane Service
- New Pipeline Installation and ROW Lower Capital Cost
- Hydrogen Effects on Materials
- Leakage/Seals
- Compressor/Valves/Inspection

Budget

- Total funding (to date) - $50 K
- FY05 Funding - $50 K—Program De-scoped from $150K
- FY06 thru FY08 – Implement De-scoped task from FY05 and Follow Initial 3-year plan for FY06-08

Collaborators

- South Carolina Electric and Gas
- University of South Carolina

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Objectives

- **To assist DOE-EE in evaluating the feasibility of using the existing natural gas transmission and distribution piping network for hydrogen/hythane delivery**
  - Develop and Perform the Requisite Hydrogen/Hythane Testing Methods and Data Regression to Provide the Technical Basis for Qualification of Existing NG Pipelines for Hydrogen/Hythane Service
  - Develop and Apply Advanced Fracture and Failure Methodologies to Allow for Data Transference from Laboratory Testing to Real-World System and Components
  - Identify Key Technical Challenges and Risks to Successfully Using the Existing NG Pipeline Network for Hydrogen/Hythane Distribution and Develop Mitigating Strategies for These Risks

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Technical Approach

- **Establish A Testing Protocols for Assessing Materials and Components for Hydrogen/Hythane Service**
  - Baseline Testing Methodologies by Evaluating Existing NG Transmission and Distribution Pipeline Materials
  - Apply Advanced Fracture Methodologies to Allow for Laboratory data to be Transferred to Real-World Systems and Components
- **Test Existing NG Transmission and Distribution Pipeline Materials and Components in Hydrogen/Hythane Environments**
  - Focused Data Generation Coupled to Advanced Fracture Modeling
  - Testing Focused on Data Generation to provide Technical Basis for Qualification via National Consensus Codes and Standards
  - Characterize Materials and Components Performance, Materials Integrity, and Effects of Operating Conditions (Temperature and Pressure)

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Accomplishments

- Established Suite of High Pressure Hydrogen Testing Capabilities (3/05)
  - Mechanical Testing
    - Charging Station Capability: 10,000psi/350°C
    - In-Situ Testing: 3000psi/350°C
  - Fracture Testing-- C-shaped Fracture Specimens
    - Charging Station Capability: 10,000psi/350°C
    - In-Situ Testing: 3000psi/350°C
  - Fracture Energy—Small Sample Punch Test
    - In-Situ Testing: 3000psi/350°C
  - Pressure Cycle Fatigue
    - Cycling Capability:0-2000psi/RT
    - Sample Size up to4” Diameter
  - Disc Rupture/ Burst Test
    - Pressures up to 3000psi in Hydrogen
    - Hydraulic Burst of Hydrogen Charged Components: 30,000psi

- Harvested Archival NG Piping From Local Utility (1/05)
  - 2” and 4.5” API 5L-X42 Piping Sections from SCEG

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SRNL Hydrogen Pipeline Delivery Focus

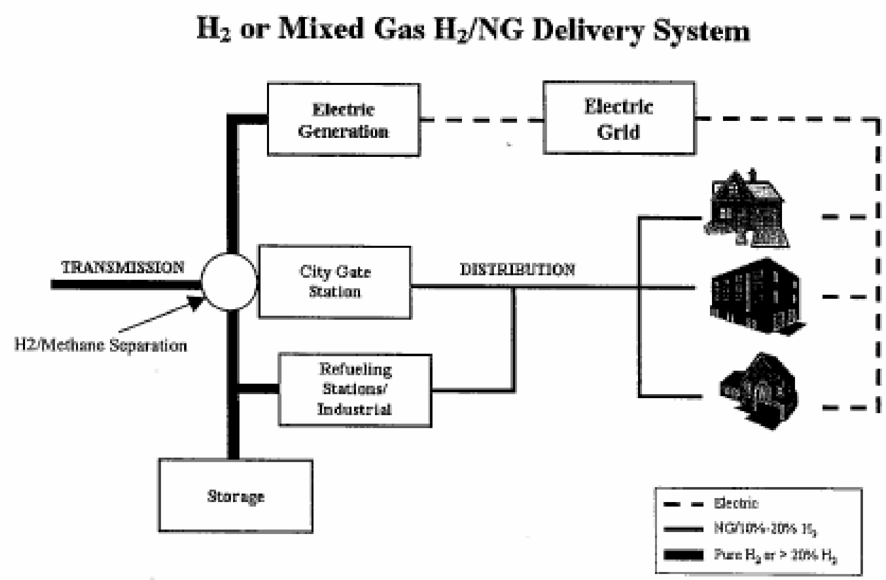
Use Existing NG Pipeline System for H2 or Hythane Transport

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

-DOE Hydrogen Delivery Goal

- **NG Transmission Pressure Range 500-1200 psig**
- **Few 100's Miles of Transmission Pipeline**

- **NG Distribution Pressure Range <100 psig**
- **Few Million Miles of Distribution Piping**



H2/NG Distribution Systems Materials Challenges

Materials of Construction

•Hydrogen Embrittlement
- • Presence of atomic hydrogen in carbon steel (permeability)

•Toughness or ductility of the metal is decreased
- •Results in Cracking or Fissuring of the Metal

Higher Strength Materials are Typically Perceived to Be More Susceptible to Hydrogen Embrittlement.

Examination in the scanning electron microscope reveals intergranular cleavage, characteristic of hydrogen embrittlement.

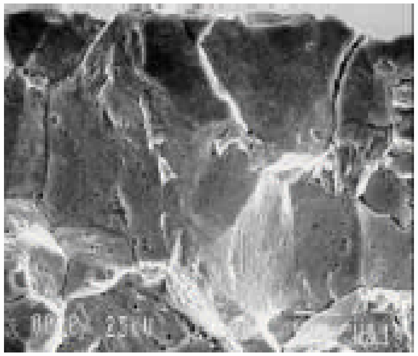


Photo Courtesy of NASA/Kennedy Space Center Materials Lab

Control of Hydrogen Embrittlement

The effect and level of hydrogen embrittlement on materials is dependent on a large number of variables such as:

- Environment temperature and pressure
- Hydrogen purity and concentration
- Hydrogen exposure time
- Stress state, secondary stresses, temperature range etc.
- Metal microstructure, physical, mechanical properties
- Metal surface finish and conditions
- Type of material crack front

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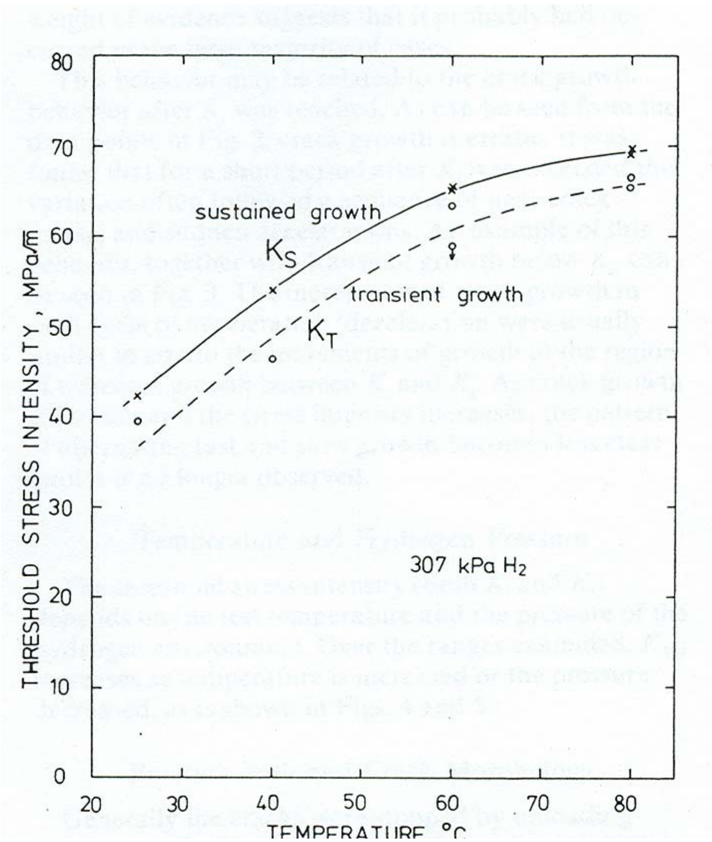
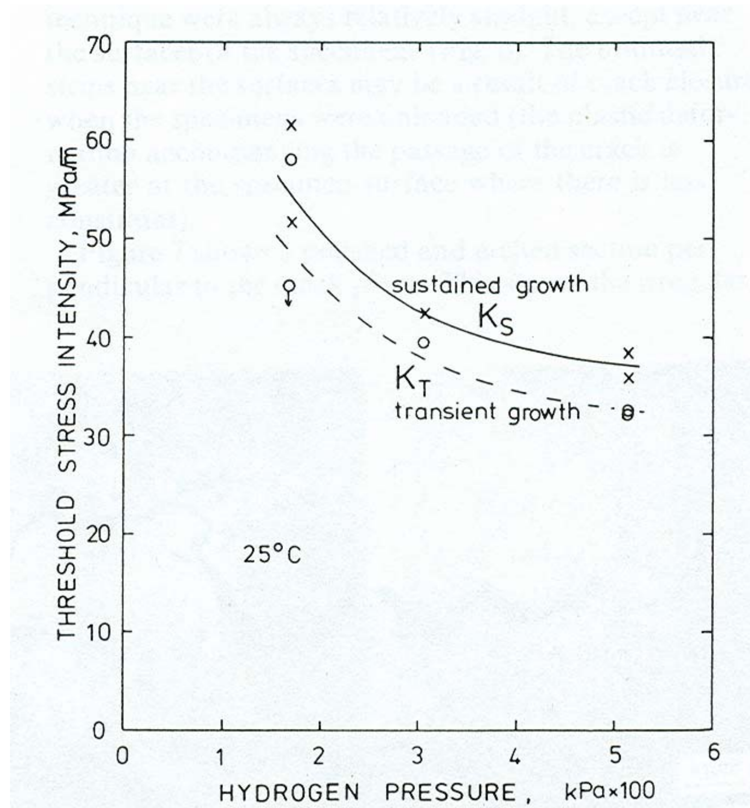
H2/NG Distribution Systems Materials Challenges





Hydrogen Threshold Stress Intensity

•Sub-Critical Flaw Stability

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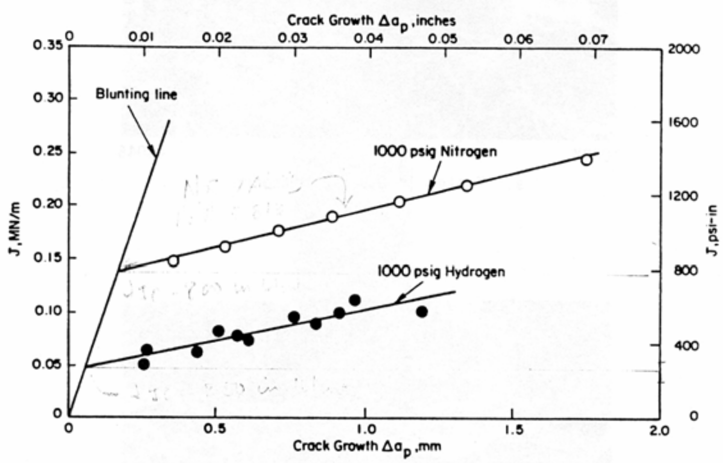
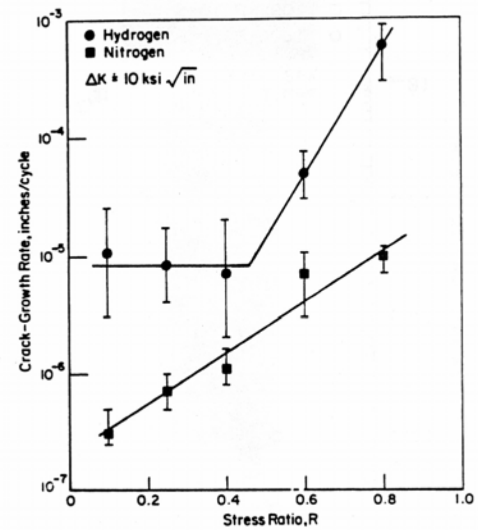
Adapted from Akhurst and Baker, Met Trans 12A, 1981

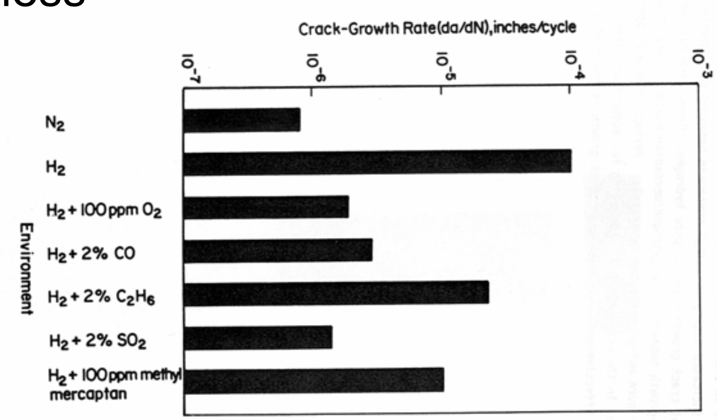
H2/NG Distribution Systems Materials Challenges



Fracture Toughness



Pressure Cycle Fatigue



Hydrogen Effects Minimized by Environmental Contaminants

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Adapted from J. H. Holbrook et al, Battelle Labs, 1988

H2/NG Distribution Systems Materials Challenges

Performance Criteria for Materials in Hydrogen Service

The following should be considered when choosing piping material for hydrogen systems:

- Hydrogen state (slush, liquid, or gas)
- Temperature, and/or temperature range
- Pressure
- Other secondary loading conditions
- Compatibility with operating environment (also include effects due to corrosion)
- Ease of fabrication and assembly
- Potential to minimize damage due to hydrogen fires.
- Cost

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H2/NG Distribution Systems Materials Challenges

Materials Data Needs for Hydrogen Service

- Minimum Specified Yield Strength
- Minimum Specified Tensile Strength
- Yield Strength to tensile Strength Ratio
- Steel Chemistry
- Weld-ability
- Minimum Design Temperature
- Fracture Initiation Toughness
- Burst/Rupture Strength
- Permeability
- Corrosion resistance, and corrosion prevention
- Failure prevention program including periodic inspection
- Resistance to environmentally caused degradation

"Coordinated research efforts is necessary to understand how line pipe steels are affected when exposed to hydrogen (particularly at high pressures), how to prevent or minimize the failure probability of a system, and finally to gather critical data that is essential for the development of codes and standards and government regulations"

•*Mohitpour,* Tempsys Pipeline Solution Inc, CANADA, 2004

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SRNL H2 Pipeline Delivery Program

SRNL Program is Focused on Developing the Necessary Materials Data for Demonstrating the Use of Existing NG Pipeline Network for Hydrogen Service

- **Mechanical Property Studies on Archival and New NG Pipe—FY05**
- Fracture Mechanics Testing and Approaches for NG Pipeline Materials
- Component Fatigue Testing
- Burst Prediction and Modeling

The Initial Focus of this Program is Centered on Metallic Transmission NG Pipeline Materials; However, the approach and methodology developed under this program could be adapted to evaluating distribution piping materials which include both metallic and polymeric materials

SRNL is working to leverage its experience at developing and operating hydrogen production, storage, and delivery Technologies to develop the necessary technical data for qualification of the existing NG pipeline network for hydrogen service

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SRNL H2 Pipeline Delivery Program

- API 5L-Spec 2004
- X-42
  - C:0.22 max
  - Mn: 1.30max
  - P:0.025max
  - S:0.015max
  - Ti:0.04max
  - Other: <0.15%

- *API 5L-X-42; 4.5" ODx 0.188 wall thickness*
- *Yield Strength:42ksi (min)-72ksi(max)*
- *Tensile strength:60ksi(min)-110ksi(max)*
- *Elongation in 2"=1.944($A^{.2}/U^{.9}$)*

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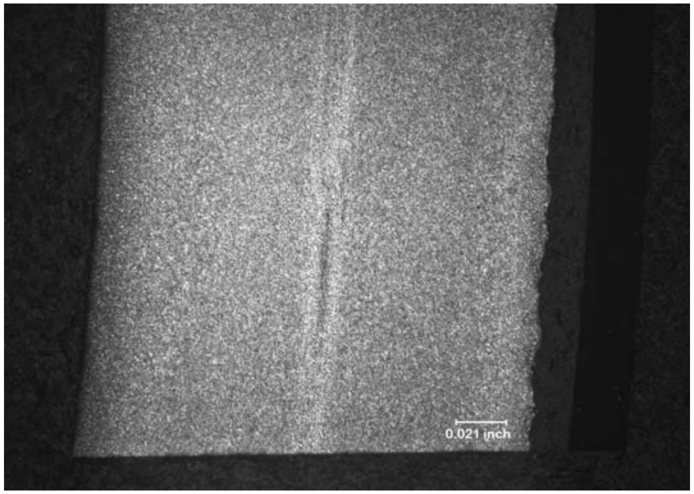
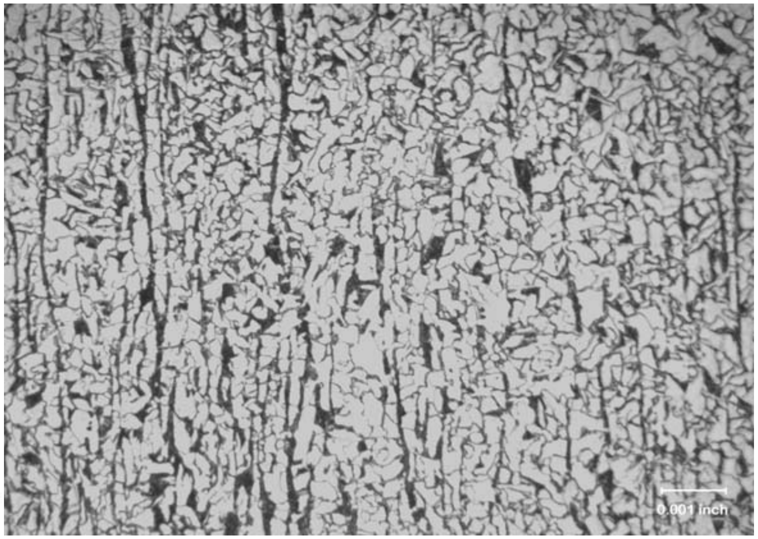
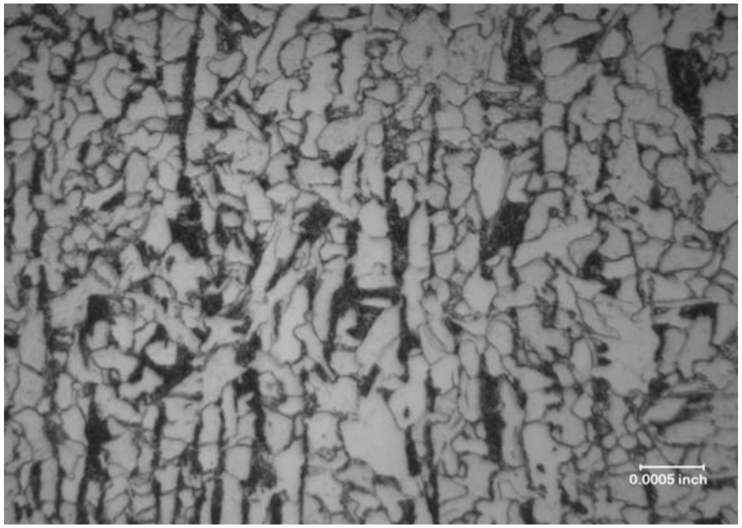
SRNL H2 Pipeline Delivery Program

•X42 Archival NG Pipe Microstructure—Polioshed and Etched
•Ferrite/Pearlite Microstructure
•Single Weld Seam Pipe
•Evidence of banding







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SRNL Hydrogen /Hythane Testing Facility

SRNL High Pressure Hydrogen Facility

•Hydrogen Charging Station:10,000psi/350°C
•Mechanical Property Testing in Hydrogen:3,000psi/350°C
•Fracture Toughness Testing
  •C-Shaped Specimens:3,000psi/350°C
  •Fracture Energy—Small Sample Punch:3,000psi/RT
  •Disc Rupture Burst Testing: 3,000psi/RT
  •Hydrogen Charged Component Hydraulic Burst Testing:30,000psi

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SRNL H2 Pipeline Delivery Program—FY06 Focus

Advanced Fracture Modeling

- Traditional fracture mechanics uses K (linear elastic materials) or J (elastic-plastic materials) to characterize fracture processes and failure events.
- J_{IC} and J-R Curves show certain amount of specimen geometry dependence (data from 3PB, CT, CCP, SCP, SENB, SENT, DECP, etc.)
- Develop a three-term asymptotic solution (J- A_2) for a stationary crack.
- Identify A_2 as an additional fracture parameter.
- J-A_2 controlled crack growth.

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SRNL H2 Pipeline Delivery Program—FY06 Focus

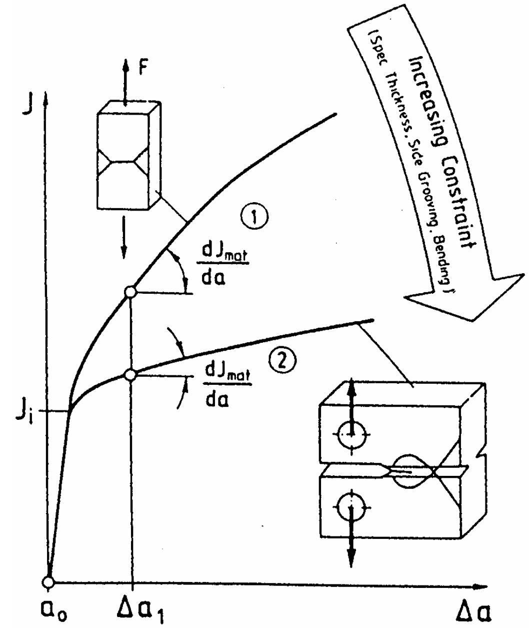
Advanced Fracture Modeling

Traditional ASTM J-R Curve:

$$J(Da) = C_1(Da)^{C_2}$$

Constraint Modified J-R Curve:

$$J(Da, A_2) = C_o(A_2)+C_1(A_2)(Da)^{C_2(A_2)}$$



The results can have full transferability from test specimen to large structure

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Technical Issues and Concerns

- Potential for Degradation of Material Properties from NG Service
- Acceptance of Possibility for "De-Rating" Ng Piping for Hydrogen/Hythane Service
- Better Understanding of Potential User-End Energy Density requirements and Subsequent Operating Pressure Requirements
- Better definition of Operating Service Conditions
- Definition of "Data Needs" for Qualification of Pipeline Materials for Hydrogen/Hythane Service
- Upper-Bound for Hythane Mixture Concentrations
- Definition of Options to Reduce/Retard Hydrogen/Hythane Interaction with Pipeline Materials and Potential Materials Issues with Proposed Approaches
- Definition of Potential "First" Use Strategies—Local/Regional Distribution or Cross-Country Distribution as They Impact Materials Issues

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Response to Previous Year Reviewers' Comments

- Not Applicable
- This is the first year of this project

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Milestone Status and Project Issues

Milestones

- High Pressure Hydrogen/Hythane Test Facilities Established (Completed 3/05)
- Safety—Conduct of R&D Acceptance of Test Facility -5/30/05 (On Schedule)
- Mechanical Testing of NG Piping Materials Harvested from Archival Pipe – 8/1/05 (On Schedule)
- Project Report on Mechanical Testing Data—9/15/05 (On Schedule)

Issues

- FY05 funding was significantly cut—initial proposal of $250K , DOE-EE offered $150K in Fall ’04—Program Cut to $50K in January 05
- Severe Descope of project due to Budget Cut—To Stay on a 3-year plan Requires Full Funding in FY06 to Include De-scoped funding from FY05(=$100K +$375K)

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Future Plans

- FY05 Second Half
  - Mechanical Testing of Hydrogen Charged Archival NG Piping Samples
  - K_{th} Testing of Self-Loaded C-ring Piping Specimens
  - Characterization of Failure Surfaces
  - Project Report
- FY06 Proposed
  - Descoped FY05 Fracture Testing and Advanced Fracture Modeling
  - Original FY06 Scope of Constraint Modified J-R Curve Fracture Testing and Transference of Laboratory Data to Real-World Systems and Components
  - Original FY06 Scope of Burst Modeling and Transference from Disk Rupture Testing J-R Curve Fracture Testing

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Publications and Presentations

1. T.M. Adams, “Evaluation of Natural Gas Pipeline Materials for Hydrogen Service”, DOE-EE Hydrogen Pipeline Delivery, Pipeline Delivery Workshop, Oak Ridge, TN January5-6, 2005.

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Hydrogen Safety

- **The most significant hydrogen hazard associated with this project is:**

The wide range of flammability limits for hydrogen in air, from 4% by volume to 74.5% by volume. Hydrogen leaks from a poorly designed experiment could cause an invisible flame, deflagration or even detonation, potentially resulting in personnel burns or equipment damage.

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Hydrogen Safety –
Our approach to deal with this hazard is:

- **SRNL requires that all laboratory work be reviewed using the copyrighted SRNL Conduct of R&D Manual. This process includes performing hazard assessments and mitigation analyses prior to the start of any laboratory work.**
- **Specific procedures for this project include:**
  1. **Operate in a well ventilated specifically designed facilities that will maintain the hydrogen concentration well below the lower flammability limit, even with an equipment failure.**
  2. **Use components and piping rated for the pressure.**
  3. **Operate using a detailed and peer reviewed Work Instruction.**
  5. **Always have at least two people present in the laboratory when work is being performed that has the potential to release hydrogen.**
  6. **Restrict access to the laboratory during high pressure hydrogen work**

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