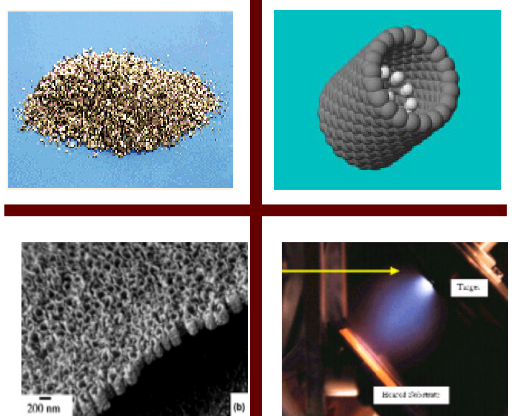

We Put Science To Work

Evaluation of Natural Gas Pipeline Materials for Hydrogen Service

Dr. Thad M. Adams
Materials Technology Section
Savannah River National Laboratory

DOE Hydrogen Pipeline R&D Project Review Meeting

January 5-6, 2005

Hydrogen Technology at the Savannah River Site

- Tritium Production/Storage/Handling and Hydrogen Storage/Handling since 1955
  - Designed, built and currently operate world's largest metal hydride based processing facility (RTF)
  - DOE lead site for tritium extraction/handling/separation/storage operations
- Applied R&D provided by Savannah River National Laboratory
  - Largest hydrogen R&D staff in country
- Recent Focus on Related National Energy Needs
  - Current major effort on hydrogen energy technology (storage, production and infrastructure development)
  - Developing strategic university, industrial and other partnerships in hydrogen energy R&D and demonstrations.

Advanced Hydride Laboratory

Fuel Cell Vehicle w/MH Storage

Tritium Storage and Separation Technology

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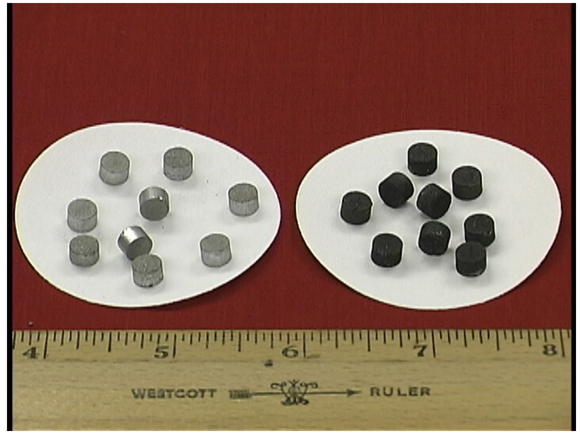
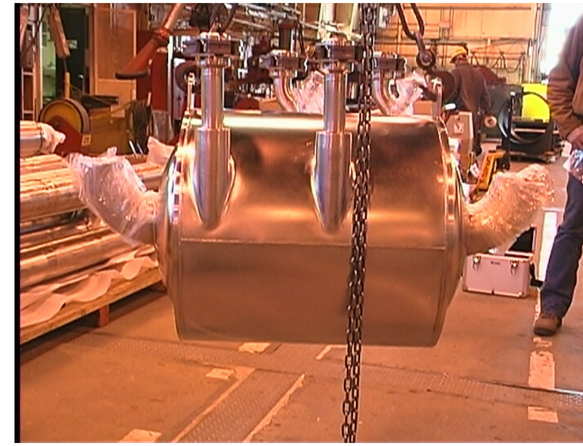
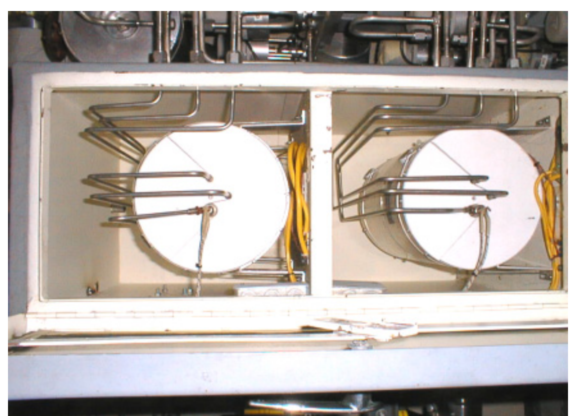




SRS Tritium Defense Program has a > $200 M budget with > $25 M allocated to SRNL

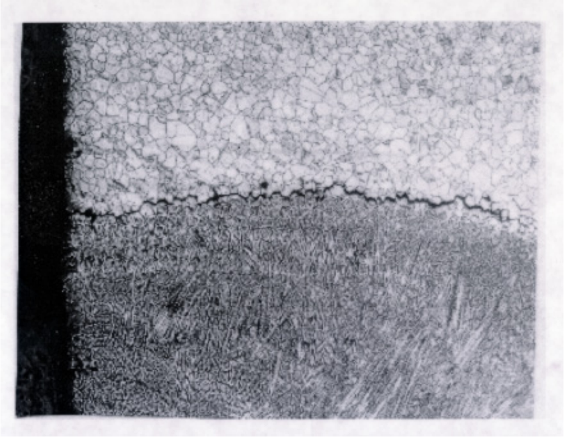


Hydrogen Technologies

- Metal & Complex Hydride
  - storage
  - compressors/pumps
  - purifiers/separators
  - heat pumps/refrigeration
- Battery / Fuel Cells
  - Ni metal hydride
  - Fuel Cells
- Sensors
  - fiber optic
  - composite (ceramic)
- Hydrogen Production
  - membranes
  - electrolysis
  - thermochemical water splitting
  - biohydrogen
- Materials Compatibility
  - H2 embrittlement
  - failure analyses
- Safety
  - H2 safety analyses
  - codes and standards

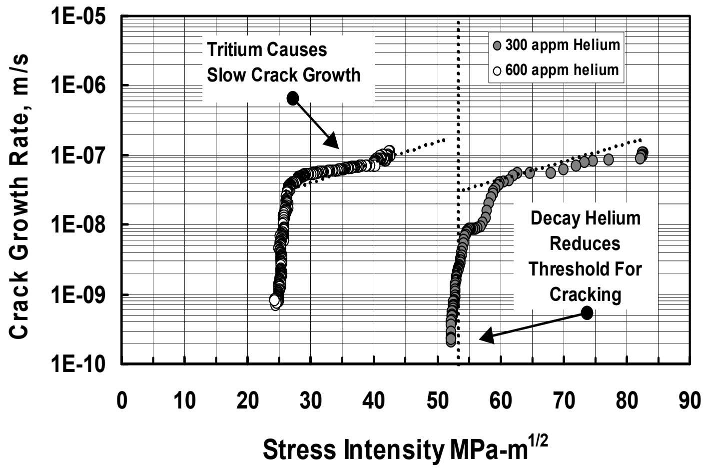
Hydrogen Isotope Compatibility

Understanding & Mitigation of Effects on Metals & Polymers

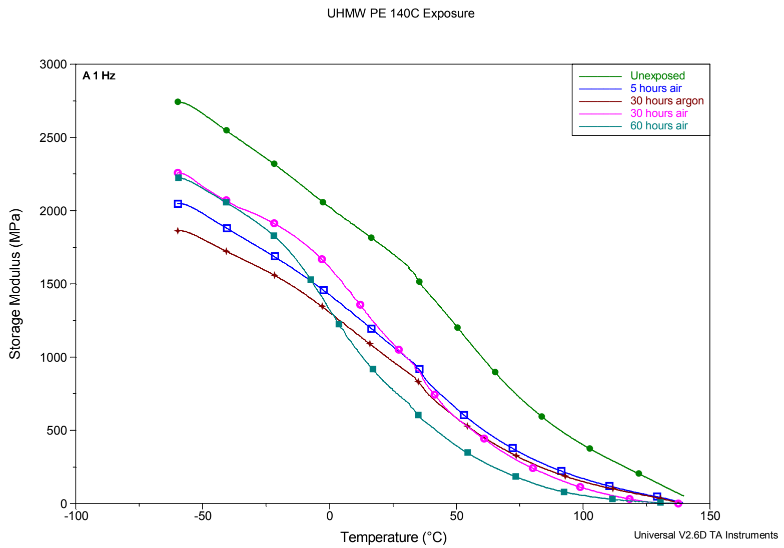


- **Tritium and Decay Helium Embrittlement of Stainless Steel Weld Heat Affected Zone**

- **Tritium (Beta Radiation) Degradation of UHMW-PE Valve Stem Tip**



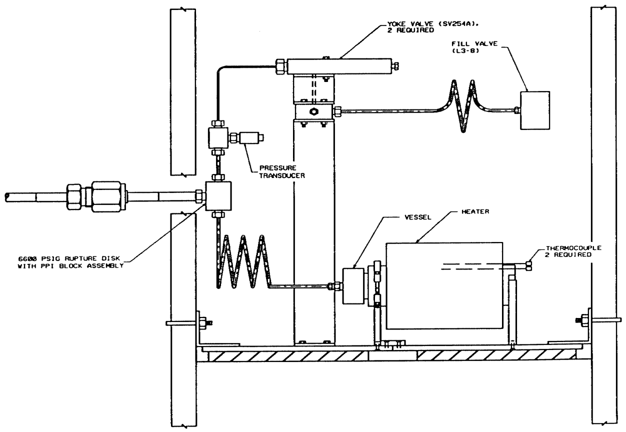
Cracking Thresholds for Structural Alloys

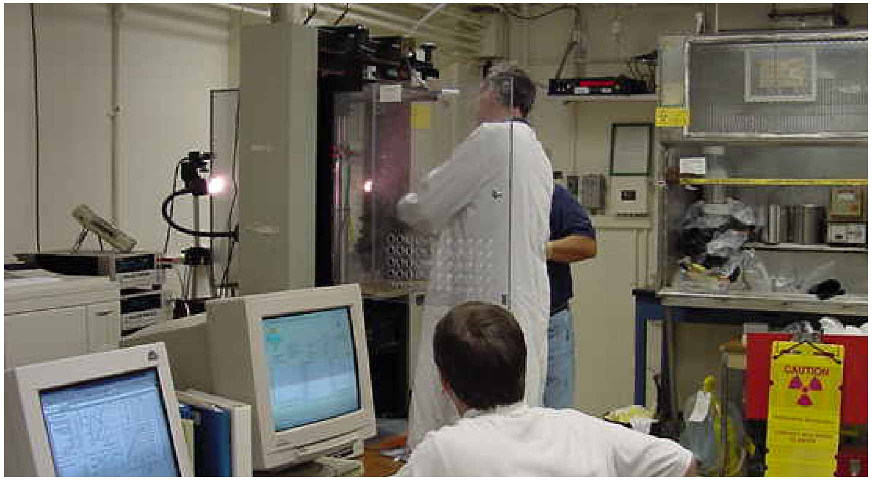


Dynamic Mechanical Analysis for Polymers

Hydrogen Isotope Compatibility

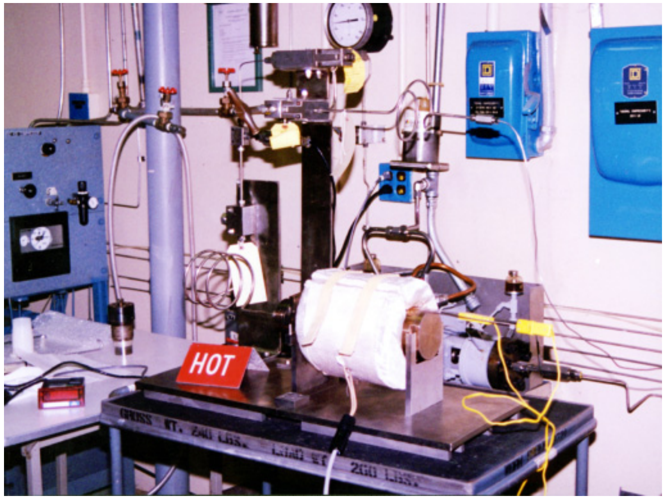
Hydrogen Isotope Charging and Mechanical Testing

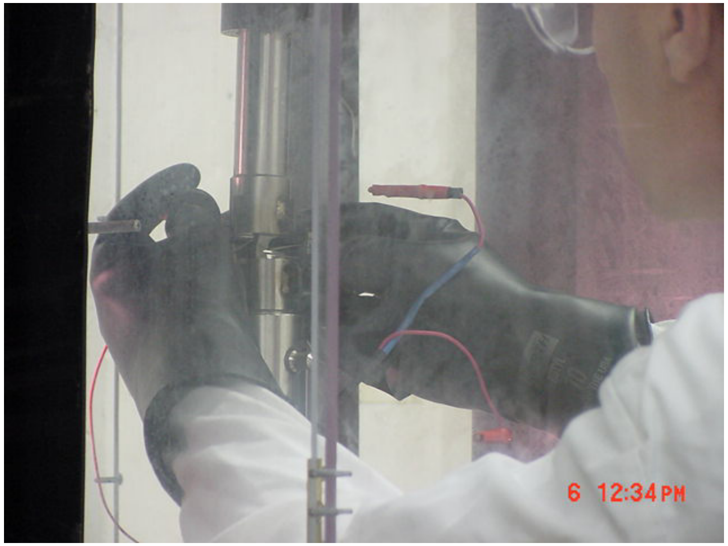




Tritium Charging Facility Schematic and Mock-up

Testing Tritium Exposed Samples





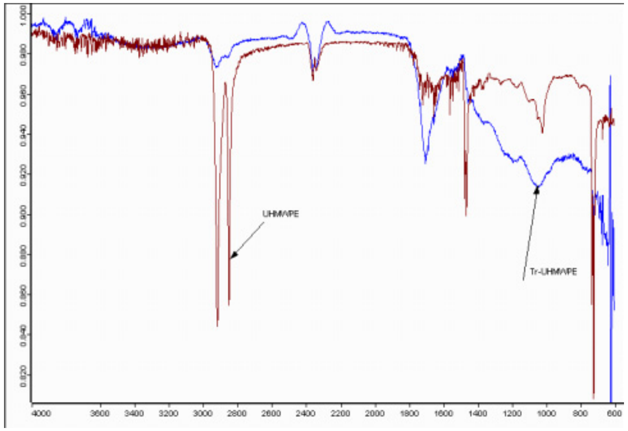
Hydrogen Isotope Compatibility

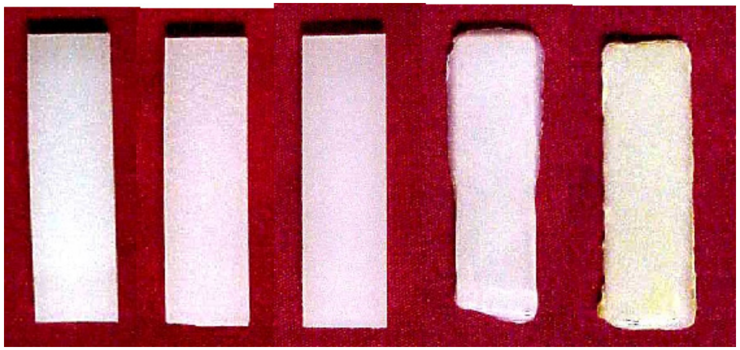
Hydrogen Isotope Effects on Polymers

Effects Charactized Using DMA, FT-IR, Color Measurements, Density, Offgas

DMA - Present Study of Ultrahigh Molecular Weight Polyethylene (UHMW-PE), Vespel™, Teflon™

FT-IR of Non-Exposed and T_2-Exposed UHMW-PE

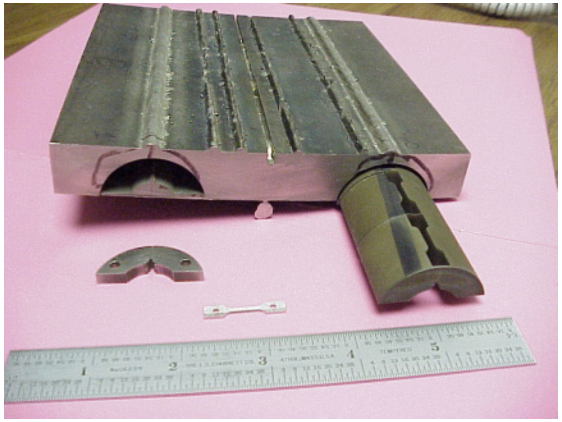




Colorimetry Used to Indicate Degree of Radiation Damage and Remaining Service Life

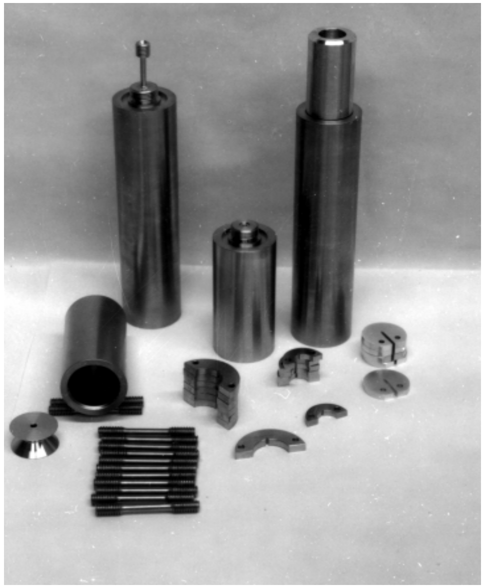
Hydrogen Isotope Compatibility

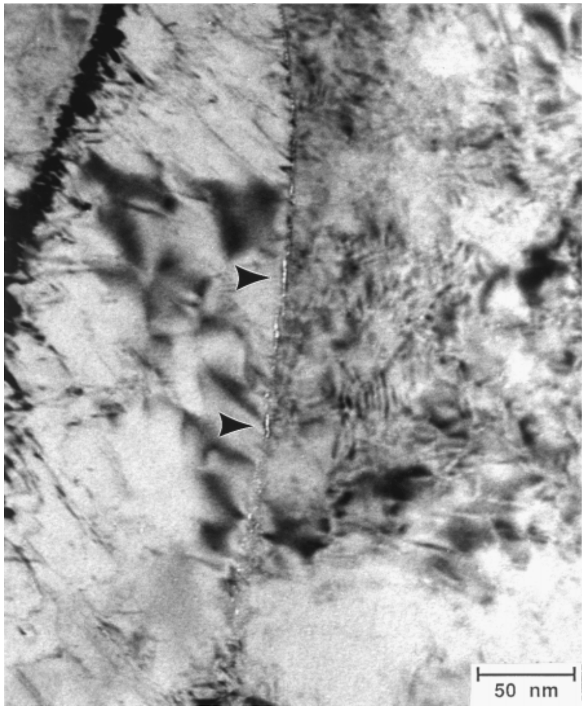
Hydrogen Isotope Effects on Containment Alloys



Fracture Toughness Samples Taken from Welds and Base Metal

- Samples Exposed to Tritium in Charging Facility
- Aging and Testing to Characterize Effects of Tritium and Decay to Helium





Investigate Material Processing Effects (Forging, Welding, HAZ) on Embrittlement from Tritium and Decay to Helium

Hydrogen Isotope Compatibility

Permeation Barrier Development and Testing

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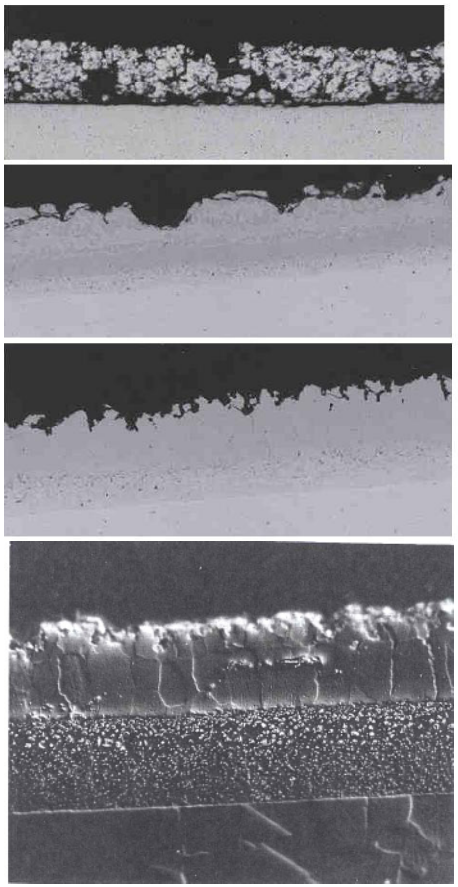
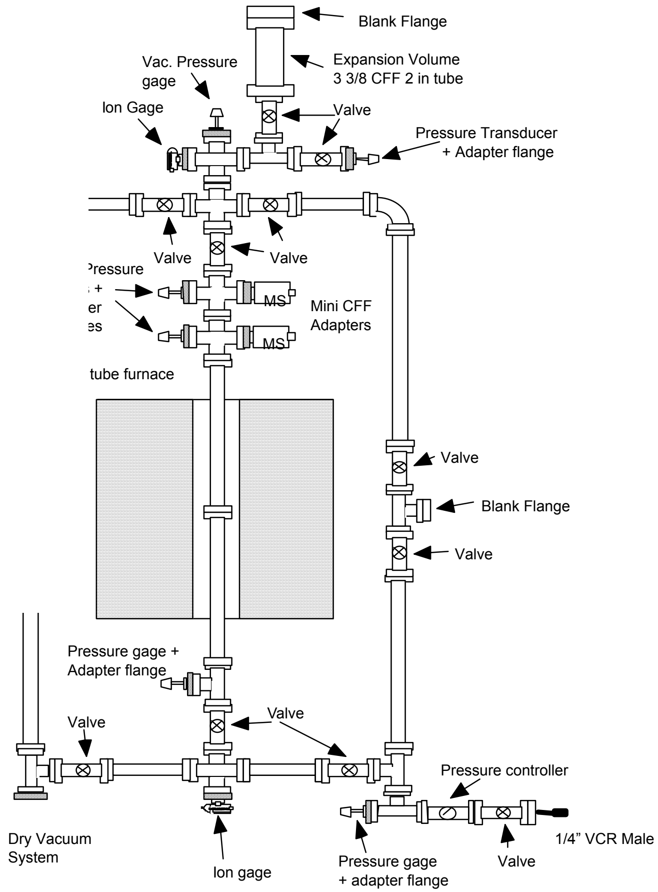


Al-rich Permeation Barriers



Schematic and Photograph of Permeation Test Rig

Major Needs per DOE Hydrogen Roadmap:

- **Hydrogen Storage** *(R&D w/major industrial partners)*
  - Develop lightweight, compact, low-cost systems
- **Supply & Infrastructure** *(w/automotive, energy and utility partners, including regional demonstrations)*
  - Create a national supply and delivery infrastructure
  - Develop low cost, efficient H2 production from non-fossil energy sources *(nuclear hydrogen production studies)*
- **Fuel Cells** *(w/university and industrial partners)*
  - Reduce costs and develop mass production
  - Increase lifetime and durability

New Hydrogen Research Laboratory

- 60,000 ft^2 Center for Hydrogen Research in Progress
  - Located at Savannah River Research Park
  - 30,000 ft^2 reserved for academic & industrial partners
- Construction Started, Operation Scheduled for October 2005
- Focus on Hydrogen Technology R&D
  - Advanced storage
  - Separation, production, sensors, safety and hydrogen effects on materials
  - User Center/Demonstration Facility (e.g. Pipeline Project)

Hydrogen Pipeline Demonstration Project

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•Purpose:

The project will provide a facility for the testing of safety codes and standards with emphasis on the development of components, materials, and repair techniques for piping in high pressure hydrogen service.

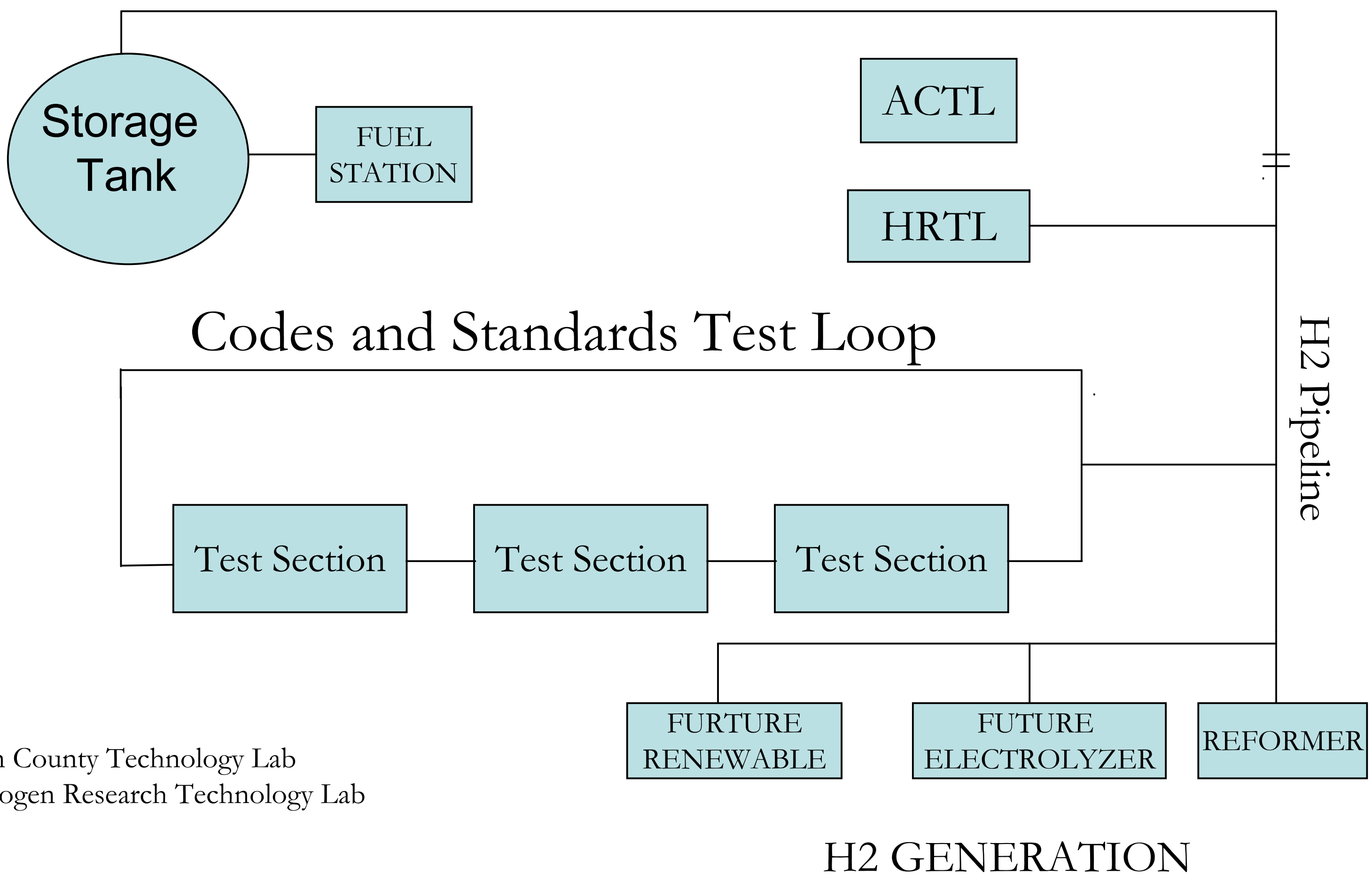
• Partners:

ASME and **SRNL** will partner with industry and government to provide a demonstration project relevant to the needs for a new hydrogen economy.

Key Issue for the Demonstration Project

- Design
  - Leakage of mechanical joints
  - Fracture prevention and mitigation
  - Fatigue at high pressure
  - Repair technology
  - Compression technology
- Fabrication
  - Joint quality
  - Liner technology
- Materials
  - Hydrogen embrittlement
  - New materials technology and testing
  - Heat to heat variation of ASTM specifications
  - Coating development
- Inspection
  - Internal inspection
  - Sensor development

Hydrogen Pipeline Demonstration Project



ACTL – Aiken County Technology Lab
HRTL – Hydrogen Research Technology Lab

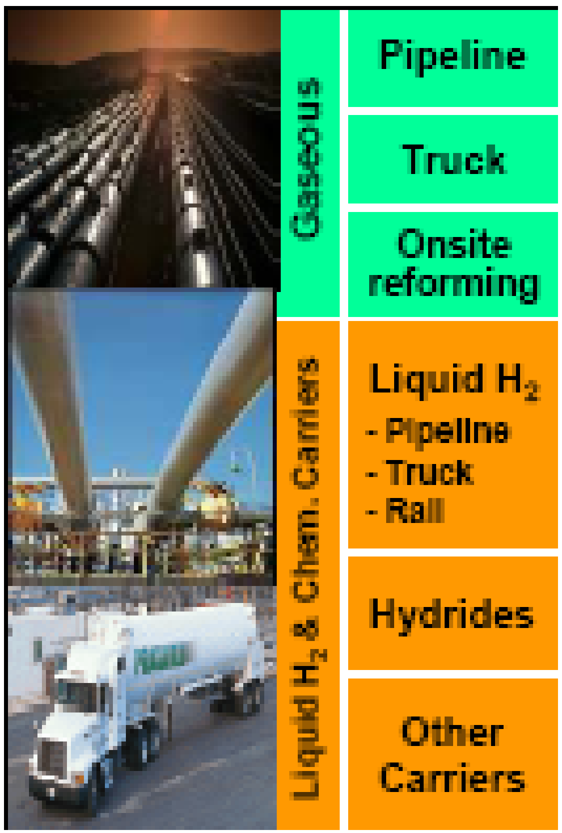
SRNL is Addressing the Major Challenges to a Hydrogen Economy

SRNL

- ***is a recognized expert in hydrogen production, separation and hydrogen storage R&D.***
- ***has ongoing R&D programs in several key areas of hydrogen technology.***
- ***has a good track record in working with industrial, academic, and other government agencies.***
- ***can provide complete solutions to customer problems (from research to process development to system demonstration).***

DOE Goal for Hydrogen Delivery

DOE Hydrogen Delivery Focus



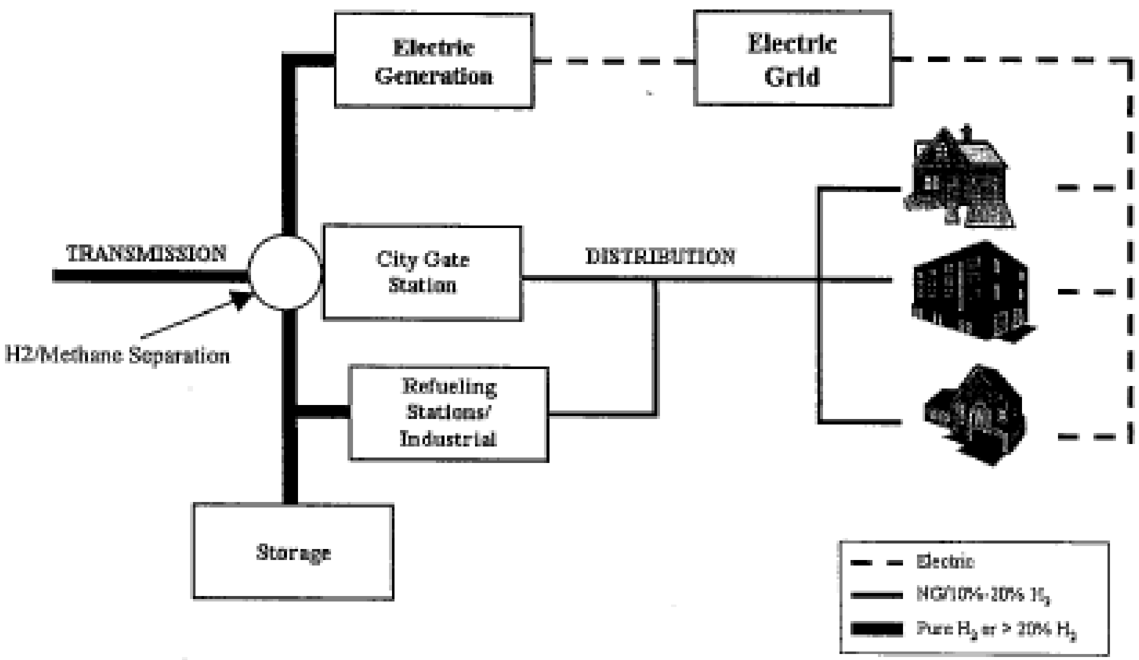
"Develop hydrogen fuel delivery technologies that enable the introduction and long long-term viability of hydrogen as an energy carrier for transportation and stationary power"

-*DOE Hydrogen Delivery Goal*

H_2/NG Distribution Systems

Use Existing NG Pipeline System for H2 or H2+NG Transport

H_2 or Mixed Gas H_2/NG Delivery System



- 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

H_2/NG Distribution Systems

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Current Hydrogen Pipeline Infrastructure

Location	Pipeline Material	Years of Operation	Diameter (mm)	Length (km)	Pressure (kPa) and Gas Purity (%)	Experience Reported	Status
AGEC, Alberta, Canada	Gr. 290 (5LX X42)	Since 1987	273 x 4.8 WT	3.7	3.790 kPA – 99.9	No	Operational
American Air Liquide Texas/Louisina, USA	API 5LX42, X52, X60 and others	?	3" to 14"	390	5100 kPa (740 PSI)	Yes	Operational
Air Products, Houston area, USA		Since 1969	114.3 – 324	100	345 – 5.516 (Pure H2)	No	Operational
Air Products, Louisiana	ASTM 106	1999 ?	101.6 – 304.8	48.3	3.447	Yes	Operational
Air Products, Sarnia (Dow to Dome plant)				3 app.		No	Operational
Air Products, Texas	Conv. natural gas line (steel)	>10	114.3	8	5,500 – Pure H2	Yes	Operational
Air Products, Texas	Steel, schedule 40	>8	219.0	19	1.400 – Pure H2	Yes	Operational
Air products, Nether land				45 Km	(throughput= 50 tons/day)		Operational
Chemische Werke Huis AG- Marl., Germany	Seamless equipment to SAE 1016 Steel	Since 1938	168.3 – 273	215	to 2,500: raw gas (throughput = 300 x 106 m^3)	Yes	Operational
Cominco B.C., Canada	Carbon Steel (ASTM 210 seamless)	Since 1964	5 x 0.8125 WT	06	>30,000.62 to 100% pure H2	No	Standby
Gulf Petroleum Cnd, (Petromont- Varnnes)	Carbon Steel, seamless, Sch. 40	--	168.3	16	93.5% H2; 7.5% methane	No	Operational
Hawkeye Chemical, Iowa	ASTM A53 Gr. B	3	152.4	3.2	2.757.6	Yes	Operational
ICI Billingham, UK	Carbon Steel	-	-	15	30,000 kPa, pure	No	-
L'Air Liquide, France, Netherland, Belgium	Carbon Steel, seamless,	Since 1966	sizes up to 12"	879	6,484 – 10,000 kPa; pure and raw	No	Operational
LASL, N.M.	ASME A357-Gr.5	-	25.4	6.4	13,788	Yes	Abandoned
Los Alamos, N.M.	5 Cr. – Mo (ASME A357 Gr. 5)	>8	30	6	13.790 pure	Yes	Abandoned
Linde, Germany	-	-	-	1.6 – 3.2	-	-	-
NASA-KSC, Fla	316 SS (austinitic)	>16	50	1.6-2	42,000 kPa	No	Operational
NSA-MSFC, Ala	ASTM A106-B	-	76.2	0.091	34470	Yes	Abandoned
Phillips Petroleum	ASTM A524	4	203.2	20.9	12,133-12,822	Yes	Operational
Praxair, Golf Coast, Tx, Indiana, California, Alabama, Louisiana, Michigan	Carbon Steel			450 Km	Commercial Purity H2 (500 MSCFD)		Operational
Rockwell International S.	SS-116	>10	250	-	>100,000 kPa; ultra pure	No	-
South Africa				80			?

TABLE 2: WORLD HYDROGEN PIPELINE EXDPERIENCE (MOHITPOUR ET AL, 1990 & 2003)

H_2/NG Distribution Systems

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Current National Hydrogen Pipeline Infrastructure

- Predominately Carbon Steel Materials
  - X42, X52, X60, A106 Grade B, A357 Grade 5
  - Transmission Pressure Limited to ≅ 800psi
  - Pipe Sizes up to 12”

Key Challenges for H_2 Delivery

Key Challenges

• Pipelines
– Retro-fitting existing NG pipeline for hydrogen
– Utilizing existing NG pipeline for Hythane
– New hydrogen pipeline: lower capital cost
--Leakage/Seals
-- Hydrogen Effects on Materials

• Lower cost and more energy efficient compression Technology

• Lower cost and more energy efficient liquefaction Technology

• Novel solid or liquid carriers

•Operational Challenges: Retrofitting Compression/Leakage
•Materials Challenges: Hydrogen Embrittlement

H_2/NG Distribution Systems Operational Challenges

Example - Compare H2 and Natural Gas Compression & Pipeline Transmission:

- Compress from $P_{initial}$ = 1 to P_{final} =1000 PSIG
- 4-stage, inter-cooled compression equipment
- Initial temp = 70 °F, Inter-stage temp = 90 °F
- Compress the same volumetric quantity of each gas, i.e. XX million SCF/day:

	Natural Gas	H_2
Delivered Energy consumed in the Compression Process	*0.31 %*	*1.33 %*

Hydraulic characteristics of H2 and Natural Gas are quite different:

- 100 miles of 20" I.D. Pipeline
- Gas temp = 70 °F = constant
- Initial Pressure = 1000 PSIG
- Find volume rates of Natural Gas and H2 delivered with 200 PSI ΔP:

	Natural Gas	H_2
Volume of Gas Delivered (SCFH)	*7.0 MM*	*18.4 MM*

Transporting Hydrogen across the existing Natural Gas Infrastructure may result in a capacity "de-rating" (on a delivered energy basis) of approximately 20-25%.

H2/NG Distribution Systems Operational Challenges

- *Combining Compression Energy and Hydraulic loss calculations:*

	Natural Gas	H_2
Volume of Gas Delivered (SCFH)	*7.0 MM*	*18.4 MM*
LHV Energy Delivered (BTU/Hr)	*6,391 MM*	*5,060 MM*
Less Compression Energy (BTU/Hr)	*(20) MM*	*(69) MM*
Net Energy Delivered (BTU/Hr)	*6,371 MM*	*4,991 MM*

Transporting Hydrogen across the existing Natural Gas Infrastructure may result in a capacity "de-rating" (on a delivered energy basis) of approximately 20-25%.

Leakage

- Gaskets and Seals are more critical (compared to Natural Gas)

- H2 (commercial purity) has no odor.
  - Adding odorants as for Natural Gas, LPG etc. adds a contaminant that is poisonous to many fuel cell technologies
  - This will add cost to the H2 energy picture, either in pretreatment to remove the contaminants, or in reduced service life of the affected systems.

- Owing to the lower ignition energy and wider flammability limits, H2 leaks are more likely to ignite than a Natural Gas leak.

- Lower flame temperatures produce fires that are less damaging than Natural Gas fires.

H2/NG Distribution Systems Operational Challenges

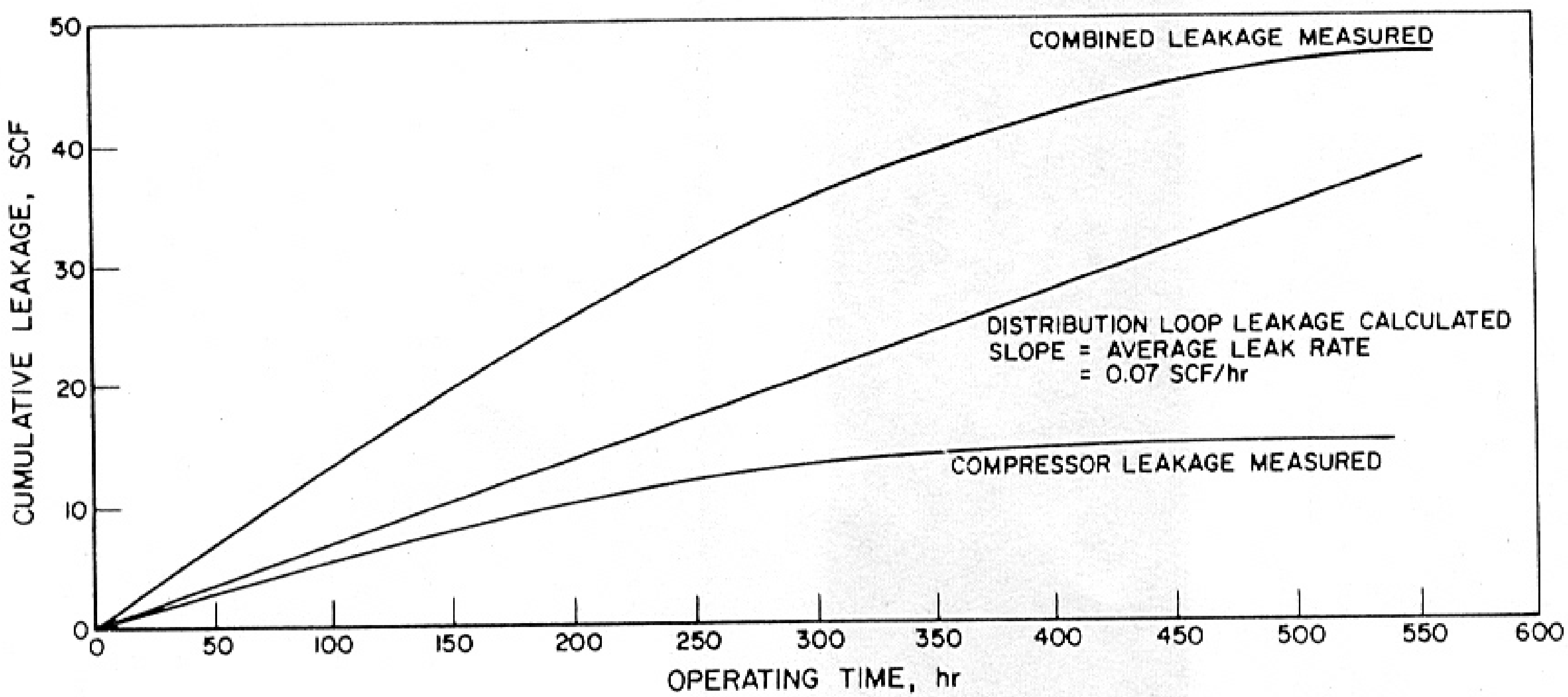

Figure 8. BASELINE NATURAL GAS LEAKAGE FOR INDUSTRIAL TEST LOOP

Adapted from Jasionowski et al,, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Operational Challenges

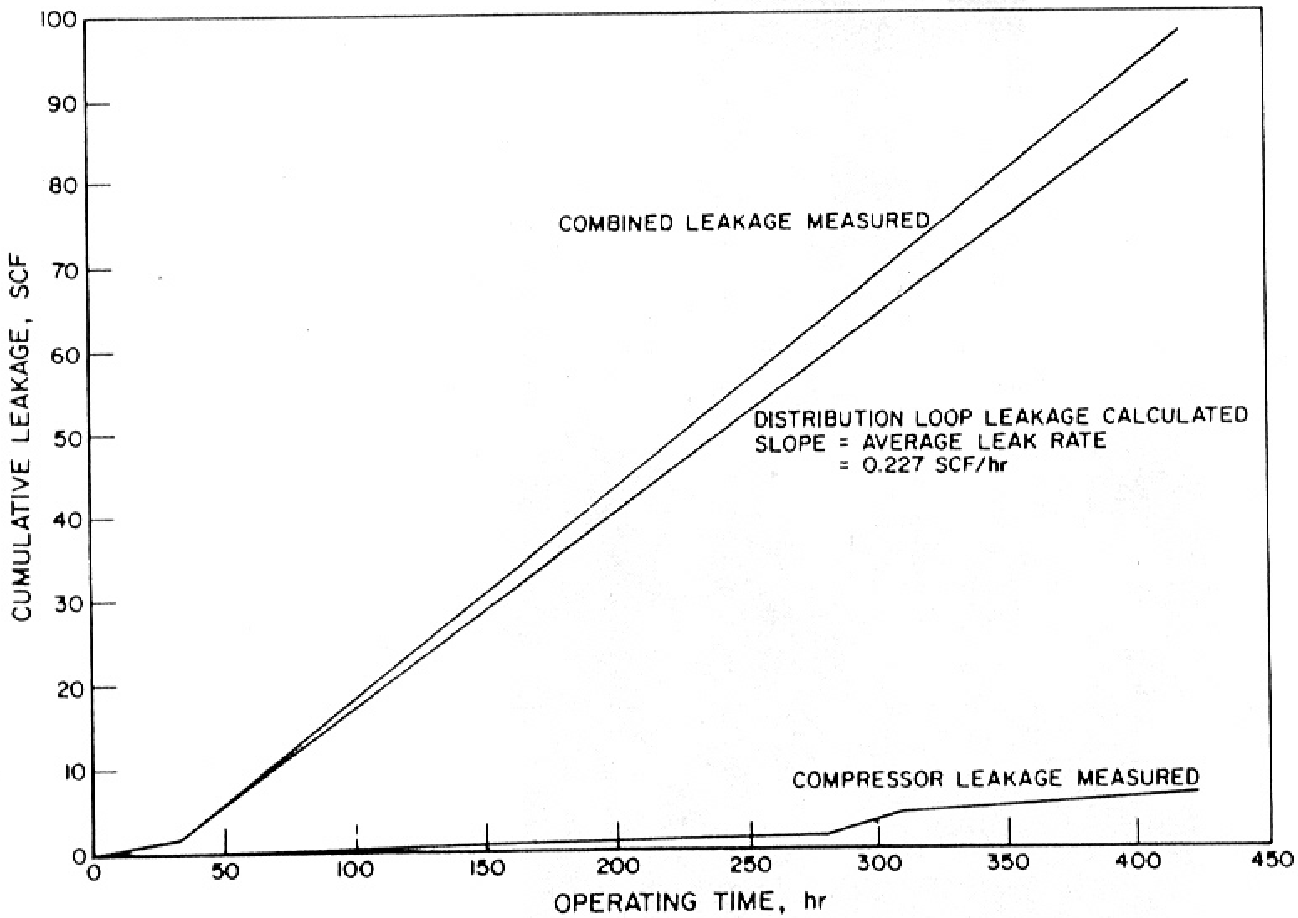

Figure 9. LEAKAGE CHARACTERISTICS OF THE INDUSTRIAL TEST LOOP IN HYDROGEN OPERATION

Adapted from Jasionowski et al,, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Operational Challenges

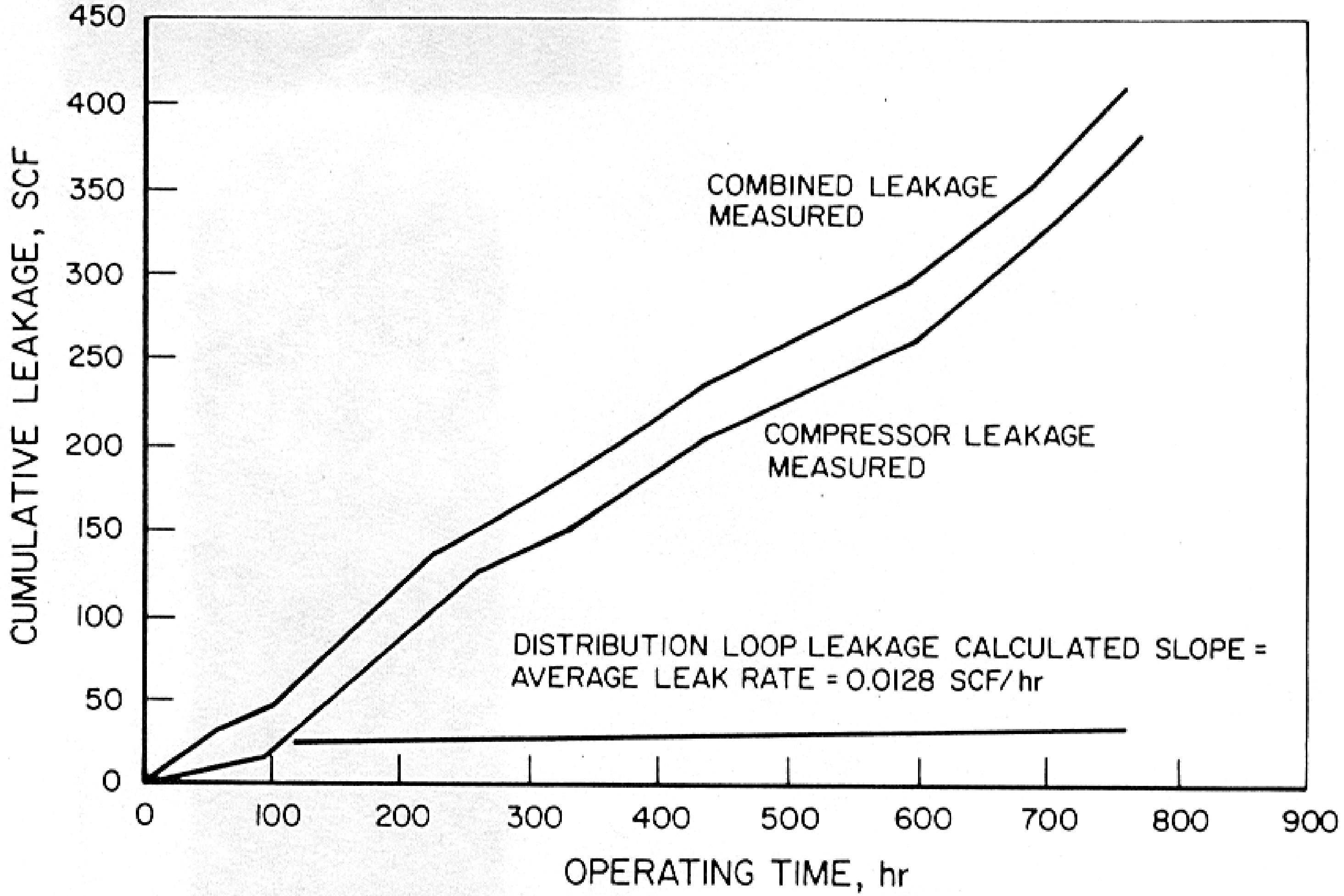

Figure 10. BASELINE NATURAL GAS LEAKAGE OF THE RESIDENTIAL/COMMERCIAL MODEL

Adapted from Jasionowski et al,, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Operational Challenges

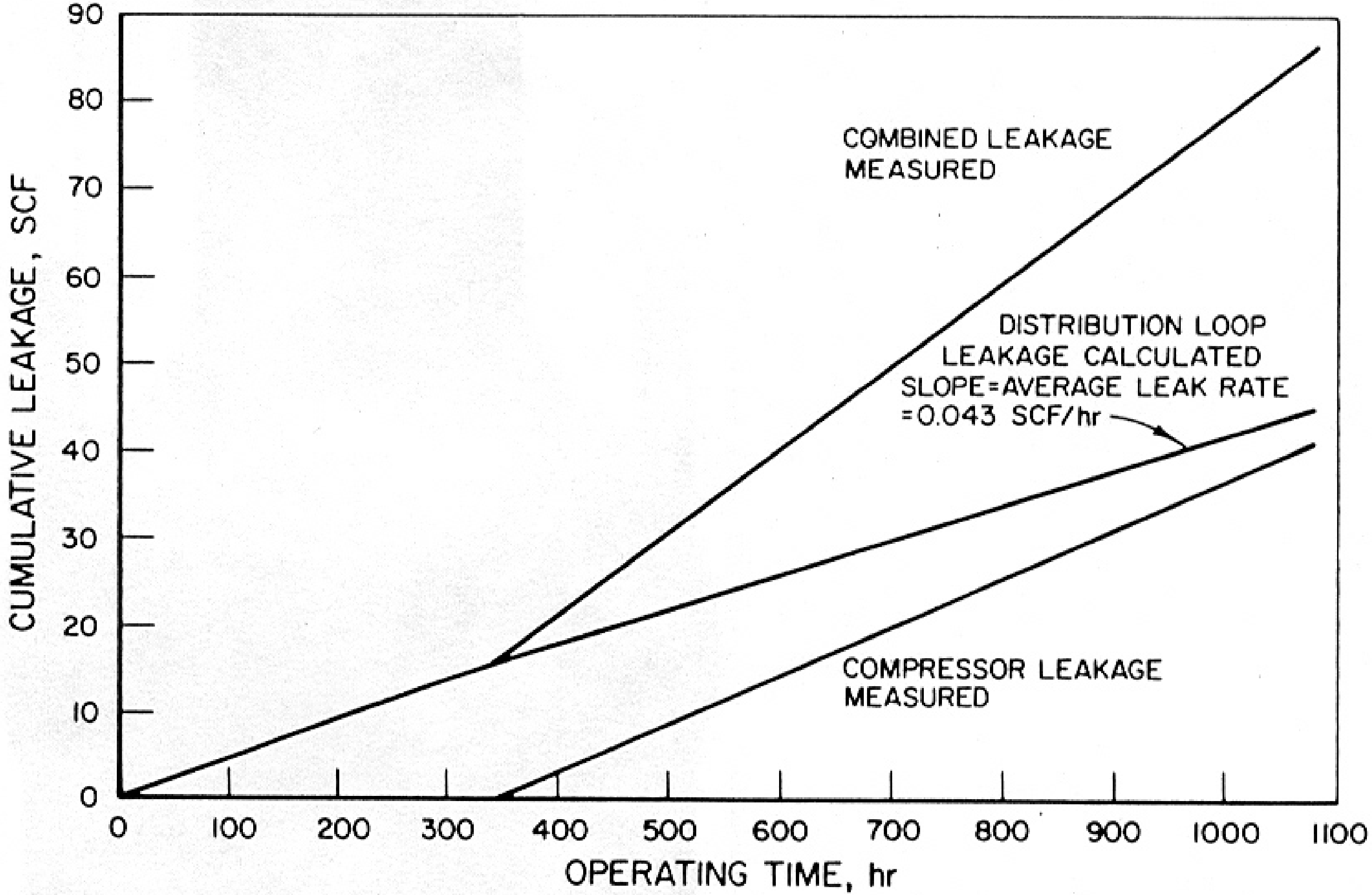

Figure 11. HYDROGEN LEAKAGE OF THE RESIDENTIAL/COMMERCIAL MODEL

Adapted from Jasionowski et al,, Hydrogen for Energy Distribution, 1978

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H_2/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

Potentially Catastrophic Failure of Pipelines!

Higher Strength Materials are more susceptible to Hydrogen Embrittlement.

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

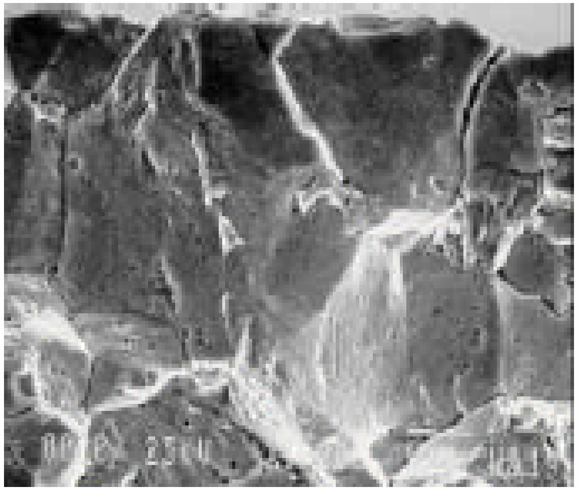

Photo Courtesy of NASA/Kennedy Space Center Materials Lab

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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

H2/NG Distribution Systems Materials Challenges

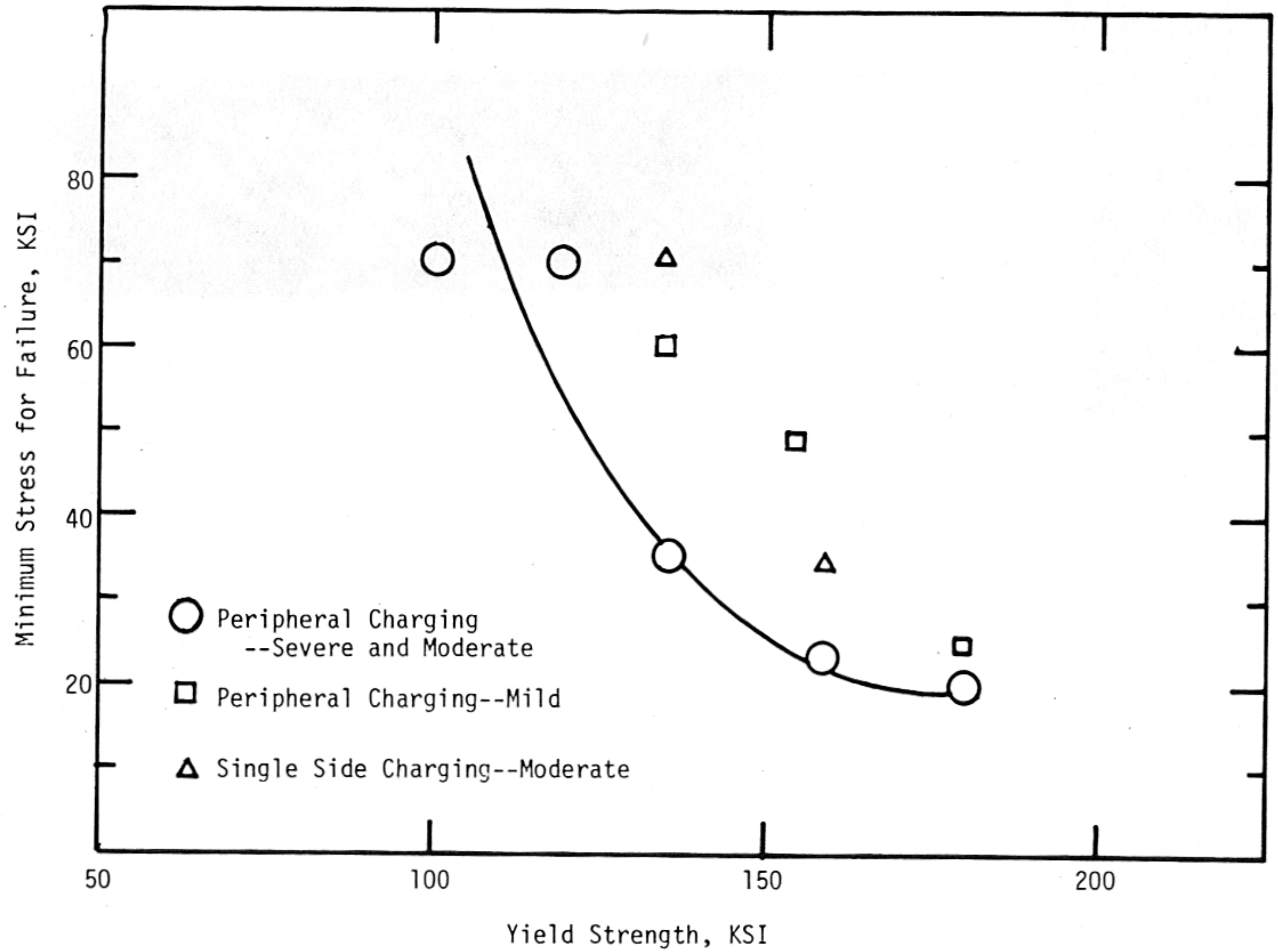


Figure 1. Yield strength dependence of delayed failure in cathodically charged carbon-manganese steels.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges

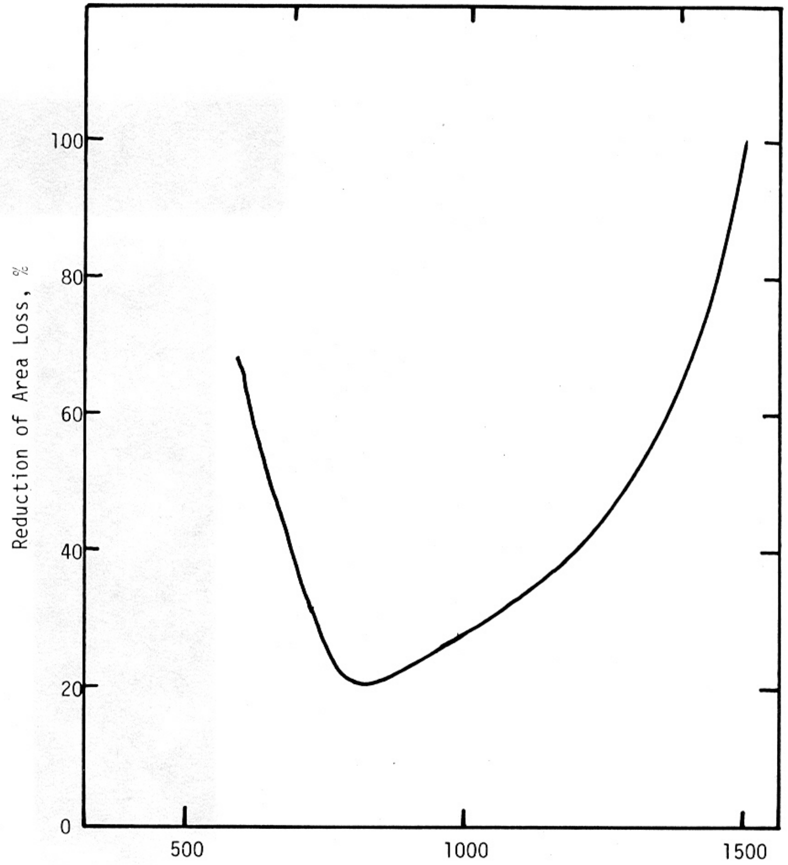


Figure 3. Hydrogen caused ductility loss in a Cr-Mo steel tempered to different strength levels.[7] Figure after Ref. 34.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges

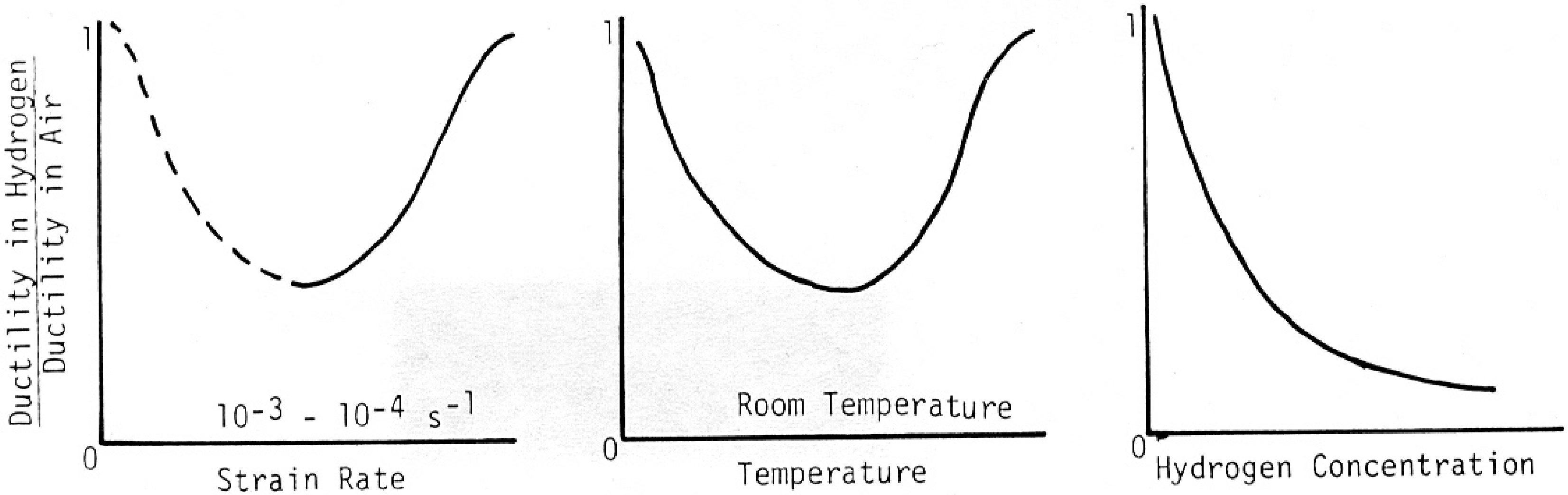
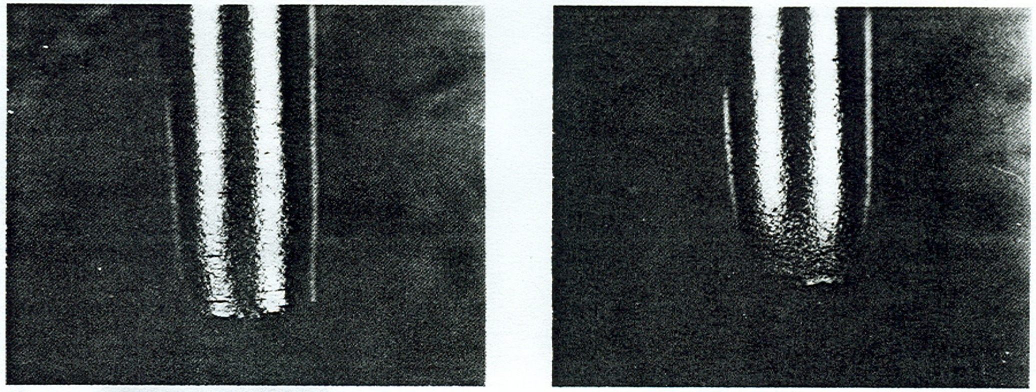


Figure 4. Schematic illustration of the strain rate, temperature, and hydrogen concentration effects upon ductility losses in hydrogen.

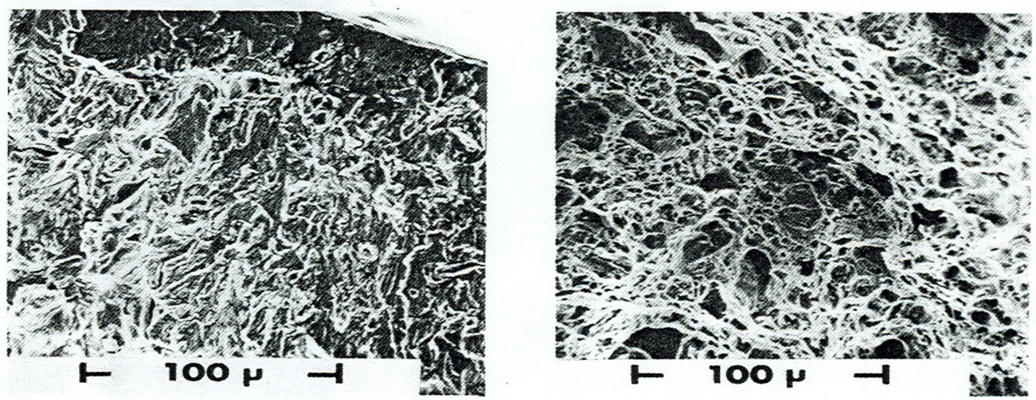
Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges



A516 Steel
Thermal Charge
Test in 4.1 MPa (600 psig) H_2

A516 Steel
No Charge
Air Test



Photographs and Fractographs of A516 Alloy Specimens Tested in Air and in Hydrogen (Surface cracking is noticeable on the specimen tested in hydrogen, and the corresponding fractograph shows an area of the fracture surface exhibiting quasi-cleavage.)

Figure 6. Tensile bar appearance and fracture surface morphology for a carbon-manganese steel tested in high pressure hydrogen.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges

TABLE II. TENSILE DATA FOR CARBON STEELS TESTED IN HYDROGEN

Material	Specimen Configuration	Test Environment	0.2% Yield Strength (psi)	Ultimate Strength (psi)	True Stress at Failure, psi	Uniform Elongation %	% Reduction of Area	Notched Strength Ratio †	Unnotched Strength Ratio †
A515-70(1)	Smooth	Air	52,100	80,700		19.9	63.0		0.99
	Smooth	600 psi H_2	48,400	79,800		15.6	37.2		
	Notched(1)	Air	61,500	99,100		4.6	22.3		
	Notched(1)	H_2 Charged +600 psi H_2	70,800	87,500		2.9	6.0	0.88	
A515(2)	Smooth	104 psi He	-	-	-	42	67		
	Smooth	104 psi H_2	-	-	-	29	35		
	Notched	104 psi He	-	-	-				
	Notched	104 psi H_2	-	-	-			0.73	
A516-70(1)	Smooth	Air	43,700	74,000	-	21.0	75.7		~0.99
	Smooth	Charge + 600 H_2	46,700	73,300	-	17.6	35.4		
	Notched	Air	60,100	102,700	-	8.6	46.3	0.85	
	Notched	Charge + 600 H_2	70,600	86,800	-	2.7	17.6		
A106-B	Smooth	103psi N_2	52,300	75,350	154,700	16.1	61.4		>1 (Scatter)
	Smooth	103 psi H_2	63,100	79,230	126,750	10.8	54.0		
	Notched	Air	88,400	108,700	-	3.4	21.5		
	Notched	103 psi H_2	84,600	105,300	-	3.7	13.8	~ 0.97	

(1) Unpublished results, present author; notch acuity, ρ ~.005 inch.

(2) W. T. Chandler, R. J. Walter; notch acuity: ρ ~ .001 inch, † Based on ultimate strength.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges

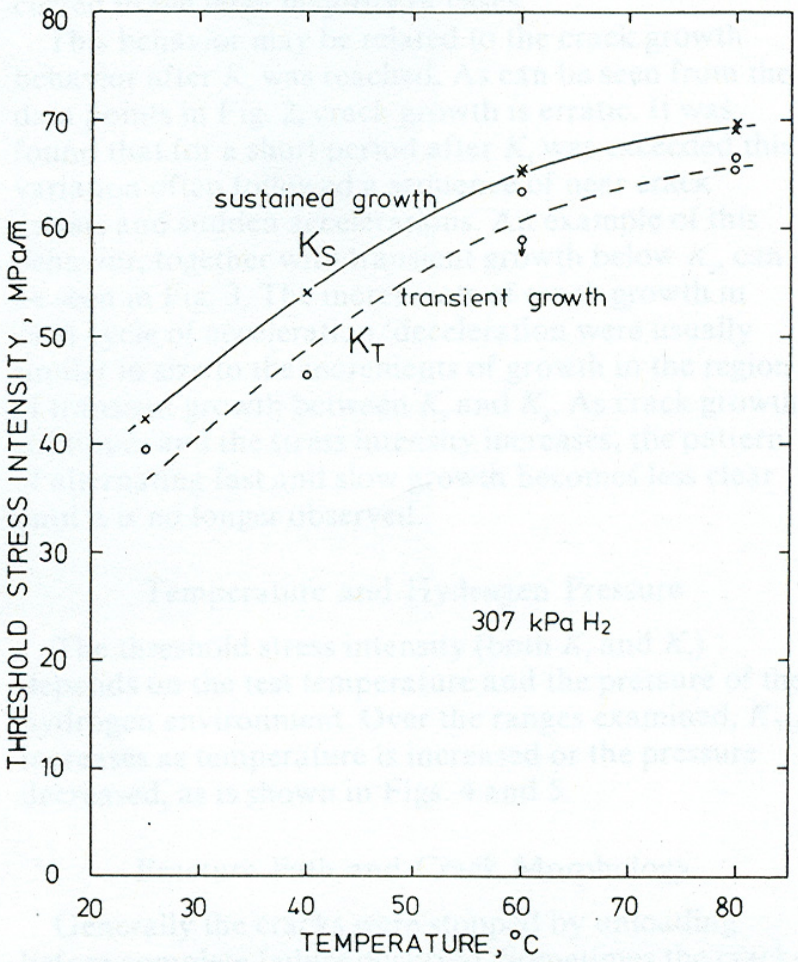


Fig. 4—Influence of temperature on the threshold stress intensity of the $3^1/_2$ NiCrMoV steel in 307 kPa (30 psig) hydrogen.

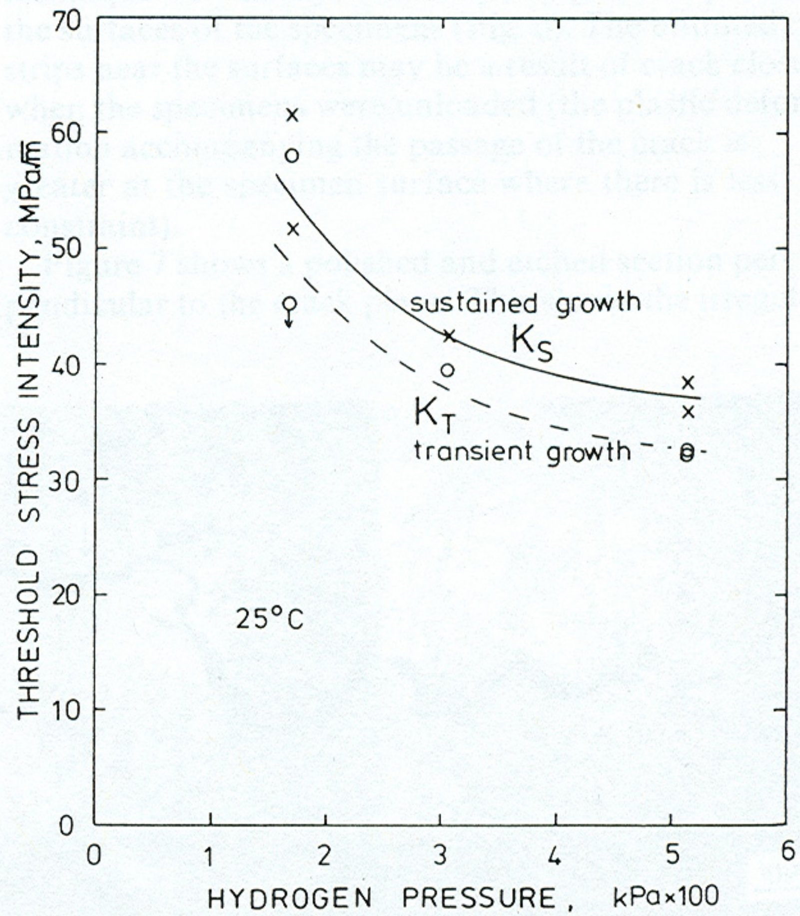


Fig. 5—Influence of hydrogen pressure on the threshold stress intensity of the $3^1/_2$ NiCrMoV steel at 25 °C.

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

H2/NG Distribution Systems Materials Challenges

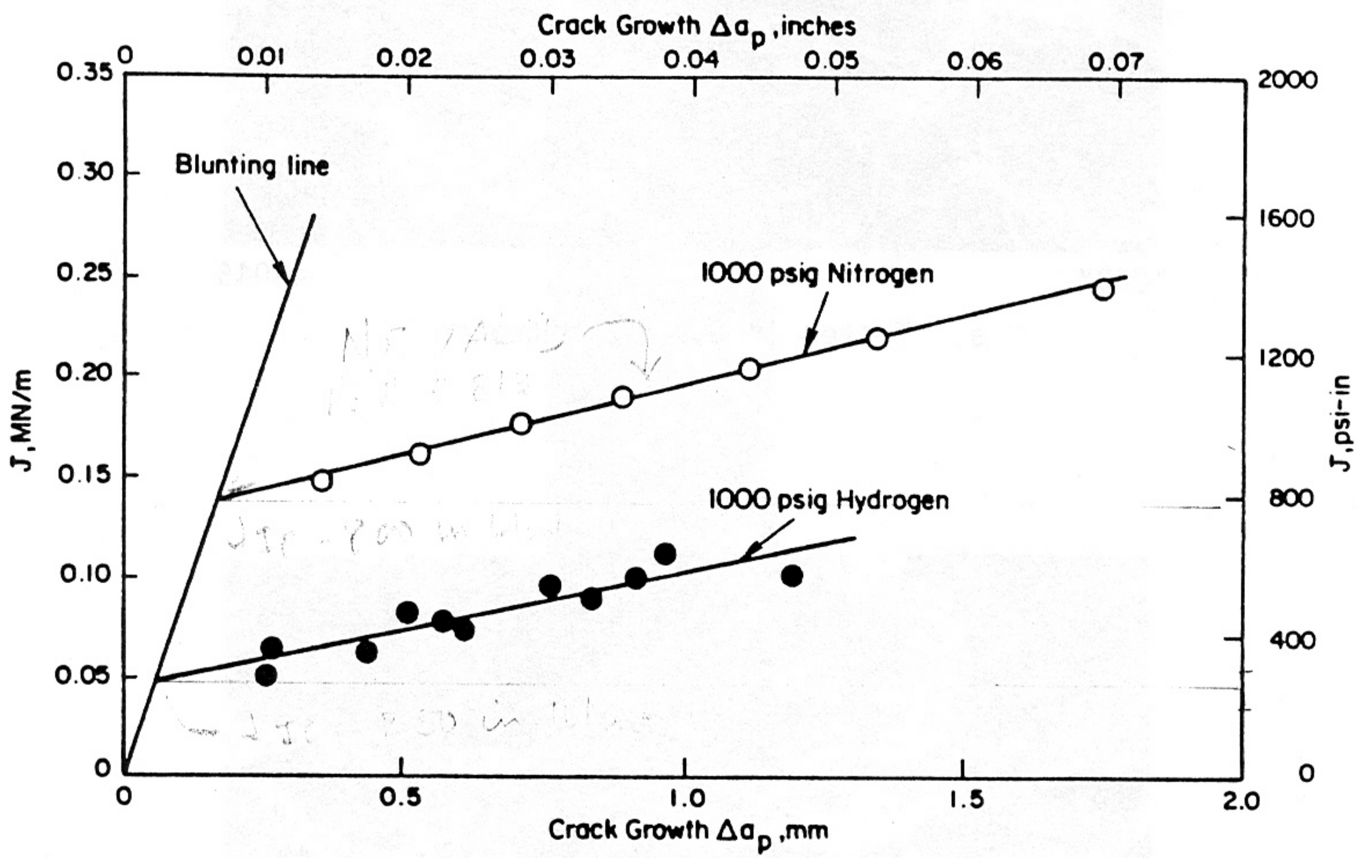


FIGURE 9. J-RESISTANCE CURVES FOR X42 STEEL BASE METAL TESTED IN 1000 psig HYDROGEN AND IN 1000 psig NITROGEN

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

H2/NG Distribution Systems Materials Challenges

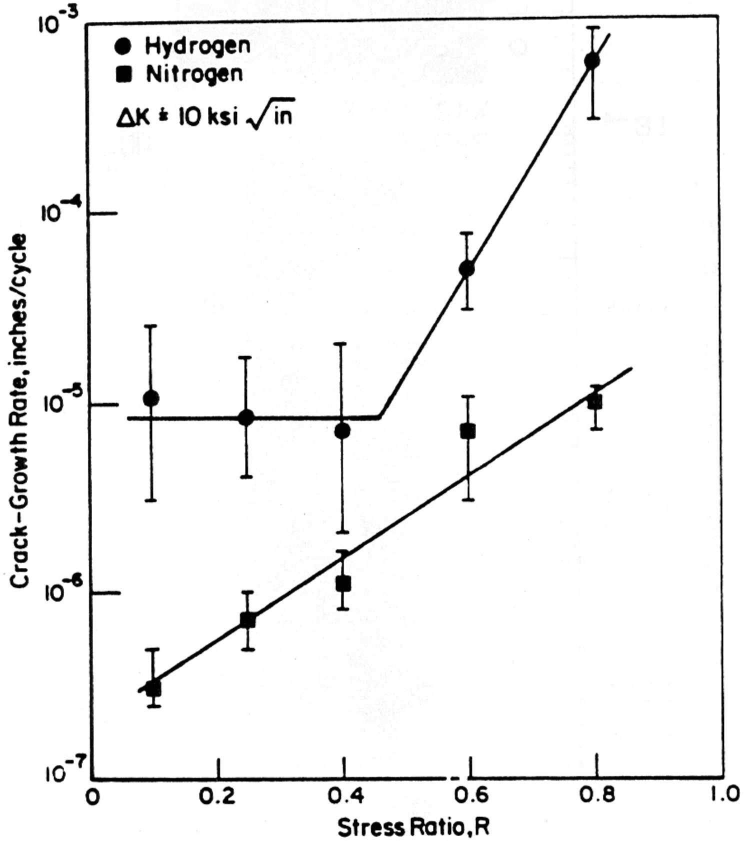
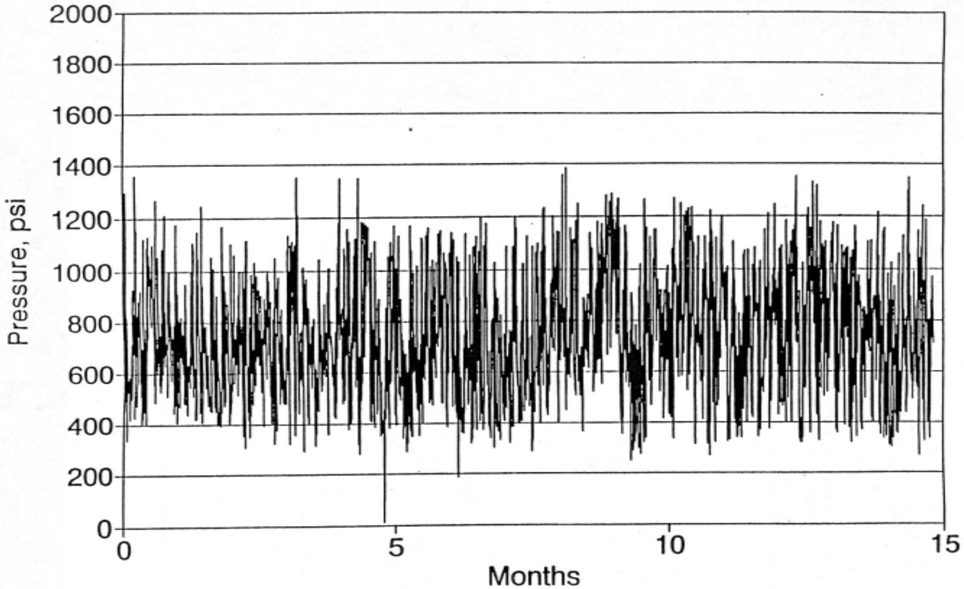


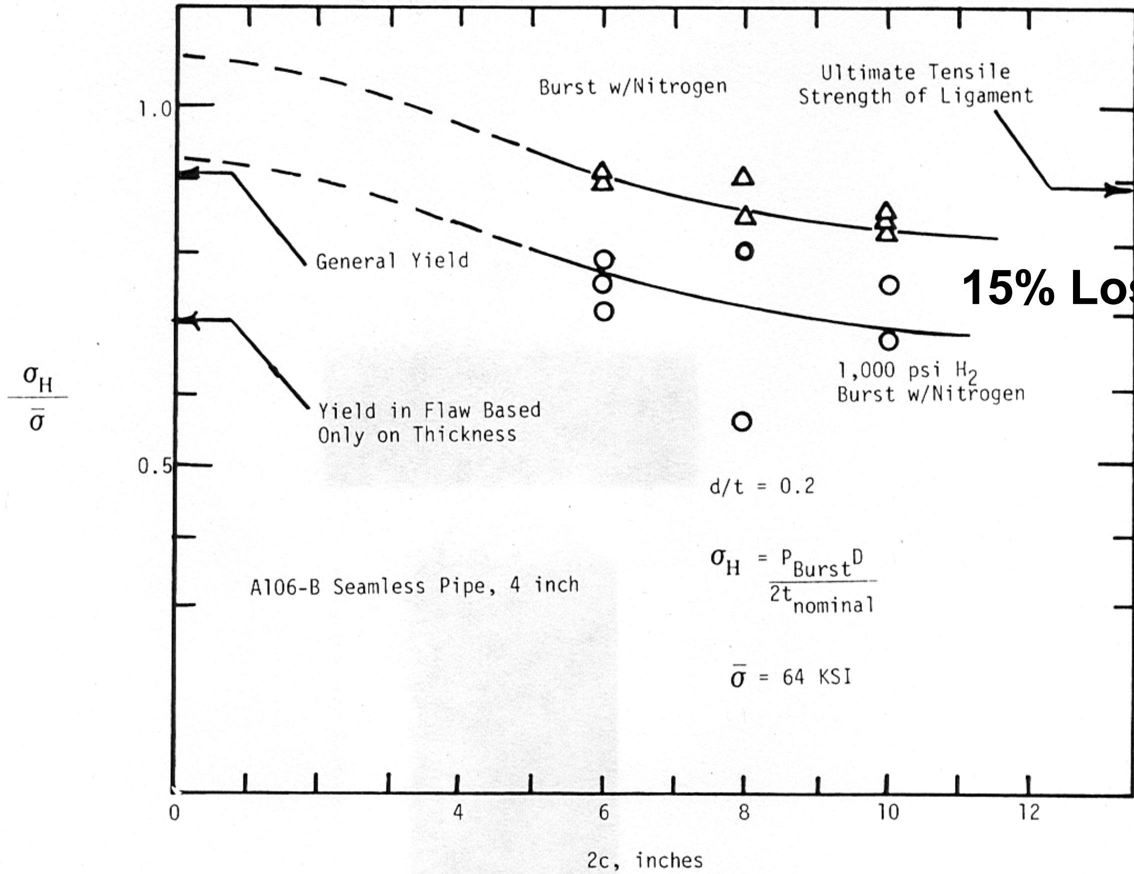
FIGURE 6. FATIGUE-CRACK-GROWTH RATE IN X42 PIPELINE STEEL AS A FUNCTION OF STRESS RATIO



PRESSURE VERSUS TIME FOR A TYPICAL PETROLEUM PRODUCTS PIPELINE

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

H2/NG Distribution Systems Materials Challenges

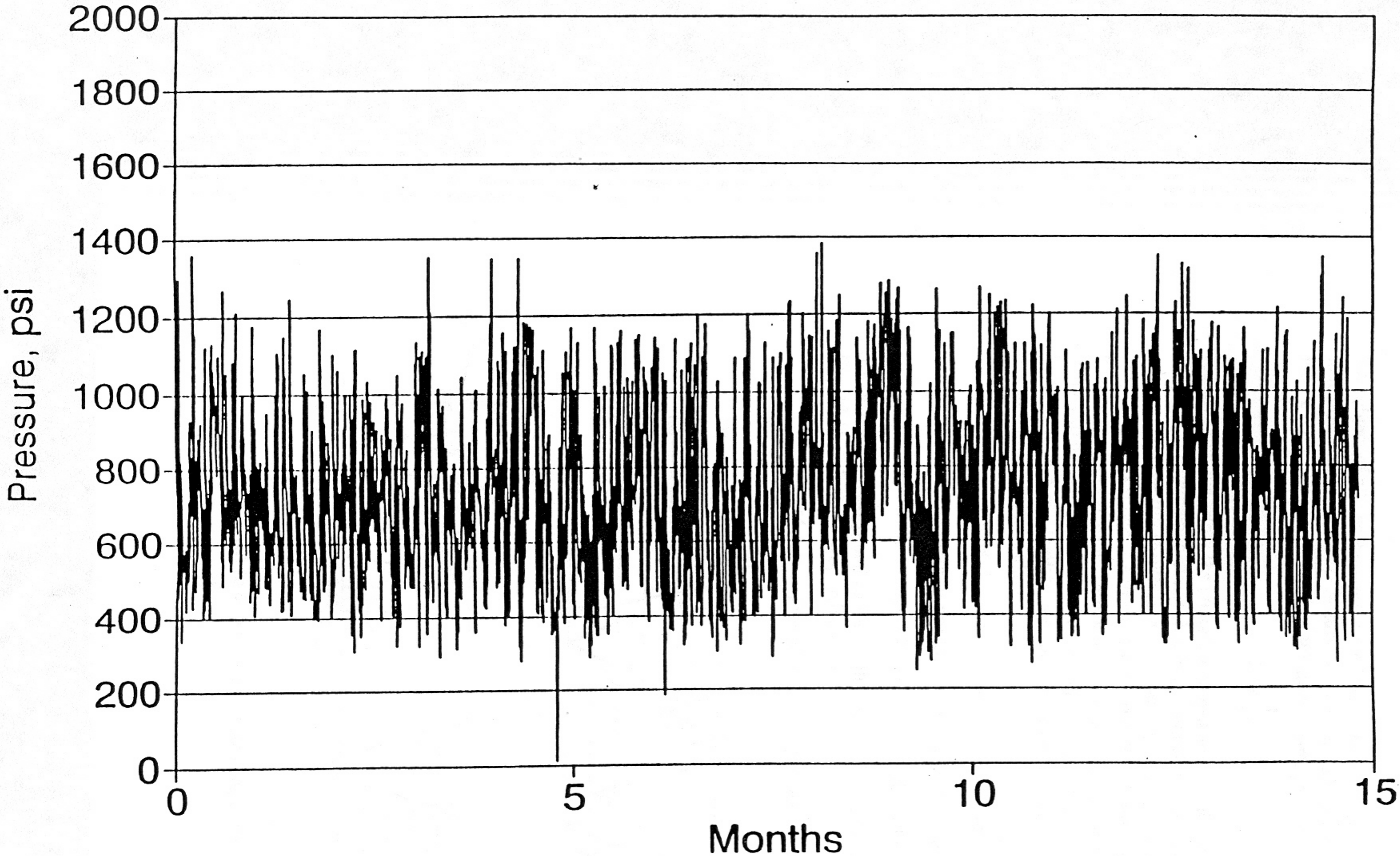


15% Loss of Hoop Stress in H2

Figure 9. Burst test data for internally flawed pipe showing a 15% loss of hoop stress at failure when exposed to 1000 psi hydrogen.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges



PRESSURE VERSUS TIME FOR A TYPICAL PETROLEUM PRODUCTS PIPELINE

H2/NG Distribution Systems Materials Challenges

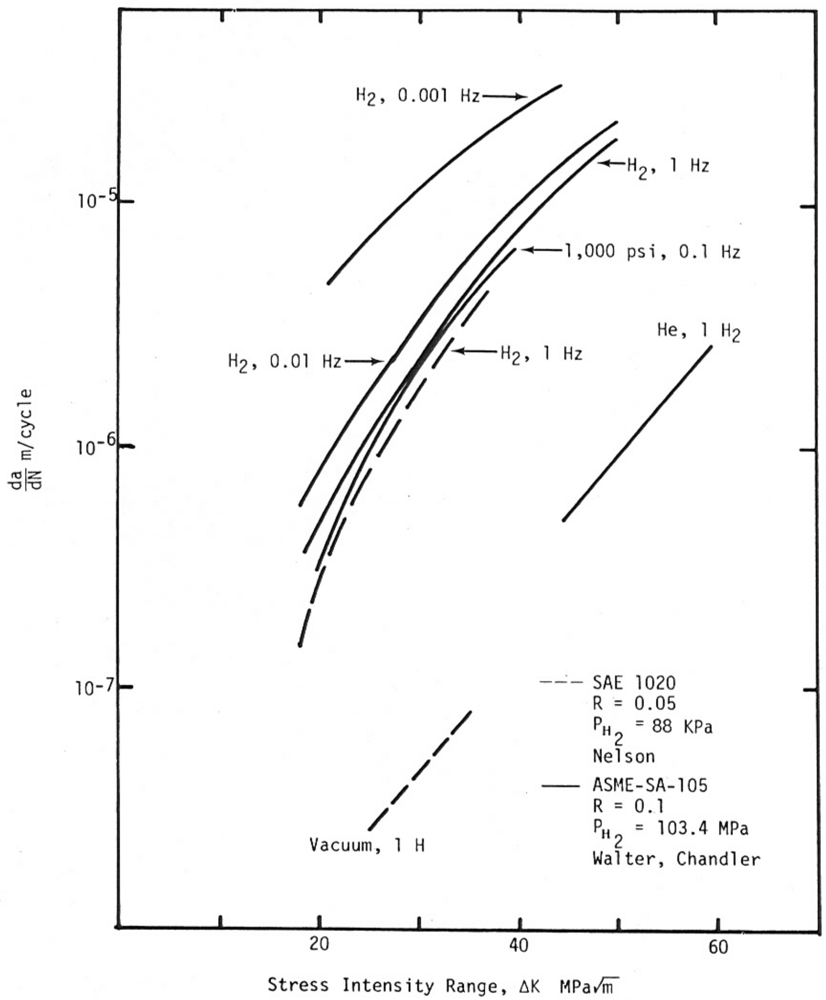


Figure 5. Acceleration of fatigue crack growth rates in carbon manganese steels fatigued in high pressure hydrogen.

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

H2/NG Distribution Systems Materials Challenges

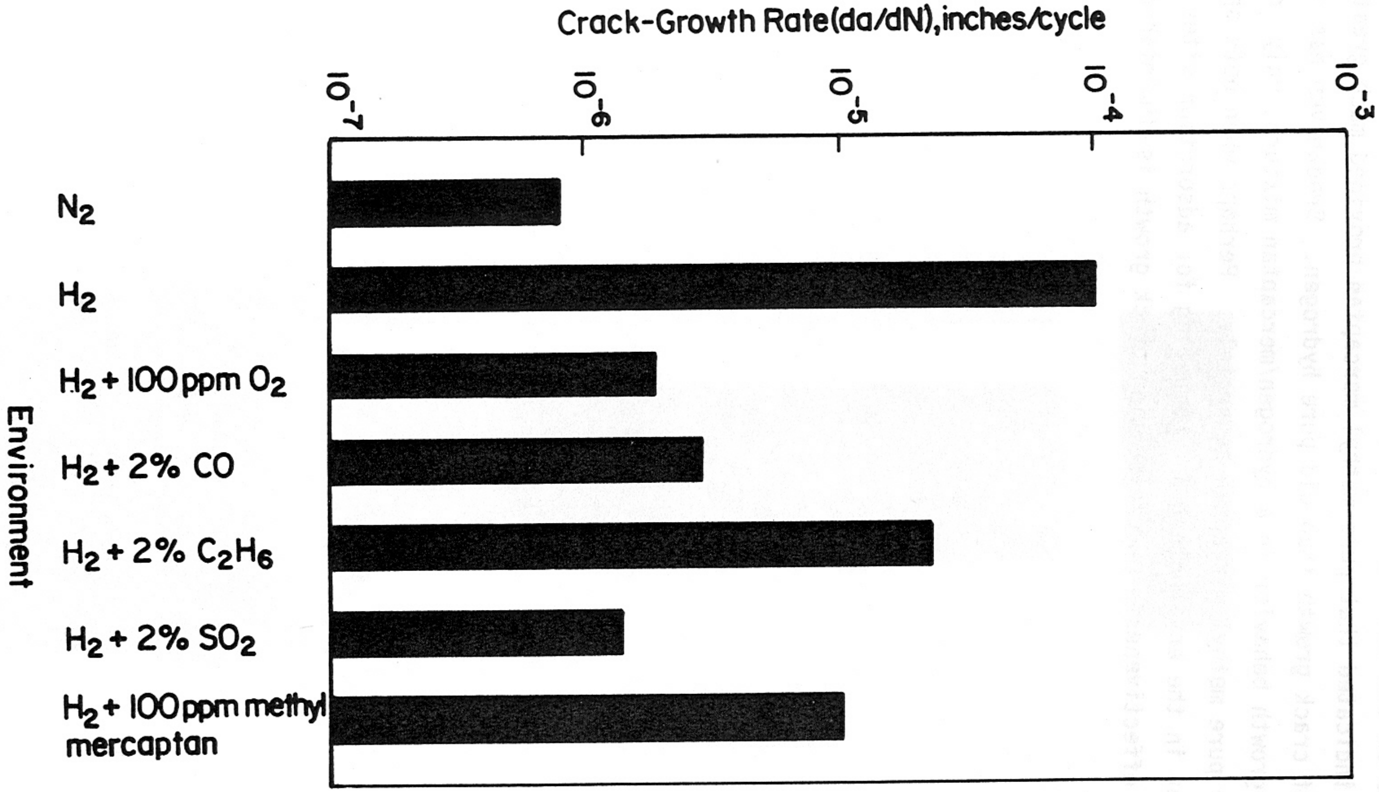


FIGURE 19. FATIGUE-CRACK-GROWTH RATE FOR X42 STEEL IN VARIOUS GASES

$\Delta K = 15 \text{ ksi}\sqrt{\text{in}}, R = 0.1$

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

H2/NG Distribution Systems Materials Challenges

“Rule of Thumb” Control of Hydrogen Embrittlement

- Avoid High Strength Steels
- Avoid Pressure Cycles of the Pipeline
- Limit Hardness of Pipe and Weld Materials

There is no consensus within the Technical community on specific limits discussed above. Additional research to establish design, construction and operating limits will be beneficial.

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

To Mitigate the Effect of Hydrogen Embrittlement

- Select materials for which sufficient performance data and industry consensus for suitability in hydrogen service is available.

  - Evaluate welding procedures used in manufacturing and field joints for fitness for service in hydrogen environment

  - Avoid sources of stress concentration

  - Proper surface finish

  - Incorporate a thorough integrity management plan.
  - Incorporate appropriate in service inspection method to discern hydrogen assisted cracking, and embrittlement

  - Explore the Use hydrogen attack inhibitors/permeation barriers

H2/NG Distribution Systems Materials Challenges

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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
- 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

SRNL H2 Pipeline Program

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Evaluation of Natural Gas Piping Materials for Hydrogen Service

- SRNL Program Focused on Hydrogen Embrittlement Effects of Archival NG Piping Materials
  - Initial Two-Year Program Beginning in FY05
  - FY05 Funding Level: $150K Fully Burdened
  - Archival NG Piping Provided by South Carolina Electric and Gas

- SRNL Program Scope for FY05
  - Baseline and H_2 Exposed Mechanical Property Measurements
  - Hydrogen Threshold Stress Intensity Measurements
  - Burst Prediction Modeling Development and Verification

- SRNL Year-Two Program Scope
  - Fracture Toughness –Constraint Modified J-R Curve Testing
  - Fatigue Testing
  - Weld Effects Testing

SRNL H2 Pipeline Program

- *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($A^{.2}/U^{.9}$)*

Table 2A—PSL 1 Chemical Requirements for Heat and Product Analyses by Percentage of Weight

(1)	(2)	(3)	(4)		(5)	(6)	(7)
			Phosphorus				
Grade & Class	Carbon, Maximum[a]	Manganese, Maximum[a]	Minimum	Maximum	Sulfur, Maximum	Titanium, Maximum	Other
Seamless							
A25, Cl I	0.21	0.60		0.030	0.030		
A25, Cl II	0.21	0.60	0.045	0.080	0.030		
A	0.22	0.90		0.030	0.030		
B	0.28	1.20		0.030	0.030	0.04	b, c, d
X42	0.28	1.30		0.030	0.030	0.04	c, d
X46, X52, X56	0.28	1.40		0.030	0.030	0.04	c, d
X60[f],	0.28	1.40		0.030	0.030	0.04	c, d
X65[f], X70[f]	0.28	1.40		0.030	0.030	0.06	c, d
Welded							
A25, Cl I	0.21	0.60		0.030	0.030		
A25, Cl II	0.21	0.60	0.045	0.080	0.030		
A	0.22	0.90		0.030	0.030		
B	0.26	1.20		0.030	0.030	0.04	b, c, d
X42	0.26	1.30		0.030	0.030	0.04	c, d
X46, X52, X56	0.26	1.40		0.030	0.030	0.04	c, d
X60[f]	0.26	1.40		0.030	0.030	0.04	c, d
X65[f]	0.26	1.45		0.030	0.030	0.06	c, d
X70[f]	0.26	1.65		0.030	0.030	0.06	c, d

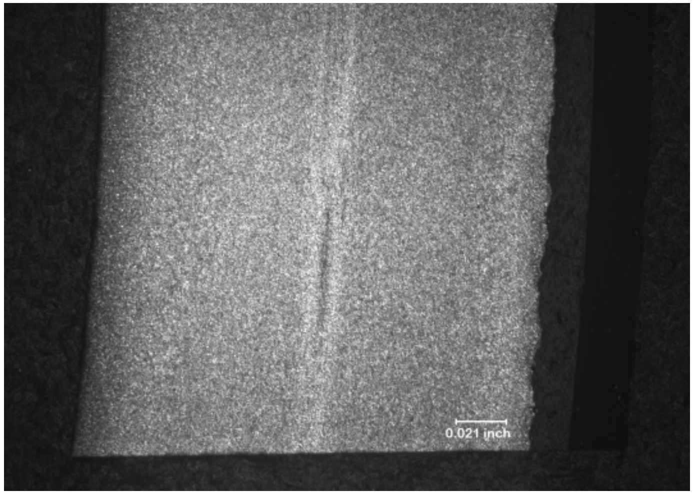
Table 2B—PSL 2 Chemical Requirements for Heat and Product Analyses by Percentage of Weight

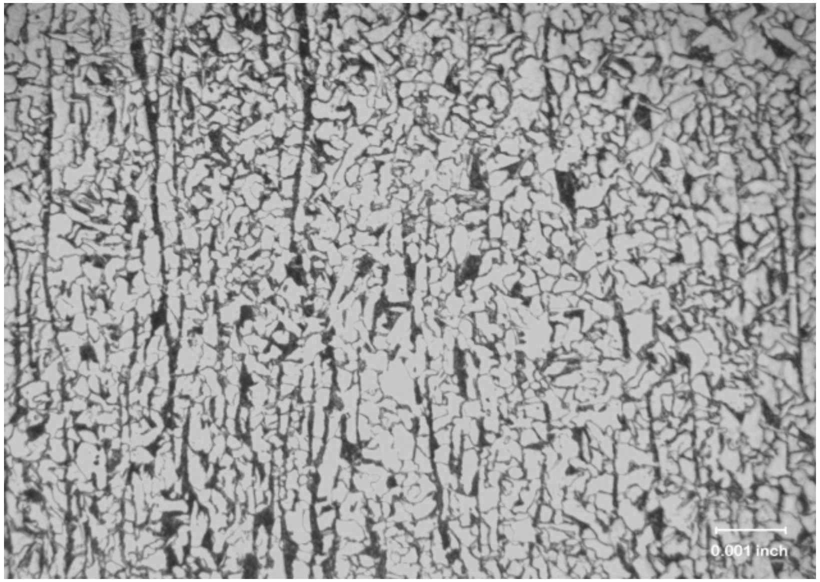
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Grade	Carbon, Maximum[a]	Manganese, Maximum[a]	Phosphorus, Maximum	Sulfur, Maximum	Titanium, Maximum	Other
Seamless						
B	0.24	1.20	0.025	0.015	0.04	d, e
X42	0.24	1.30	0.025	0.015	0.04	c, d
X46, X52, X56, X60[f]	0.24	1.40	0.025	0.015	0.04	c, d
X65[f], X70[f] X80[f]	0.24	1.40	0.025	0.015	0.06	c, d
Welded						
B	0.22	1.20	0.025	0.015	0.04	d, e
X42	0.22	1.30	0.025	0.015	0.04	c, d
X46, X52, X56	0.22	1.40	0.025	0.015	0.04	c, d
X60[f]	0.22	1.40	0.025	0.015	0.04	c, d
X65[f]	0.22	1.45	0.025	0.015	0.06	c, d
X70[f]	0.22	1.65	0.025	0.015	0.06	c, d
X80[f]	0.22	1.85	0.025	0.015	0.06	c, d

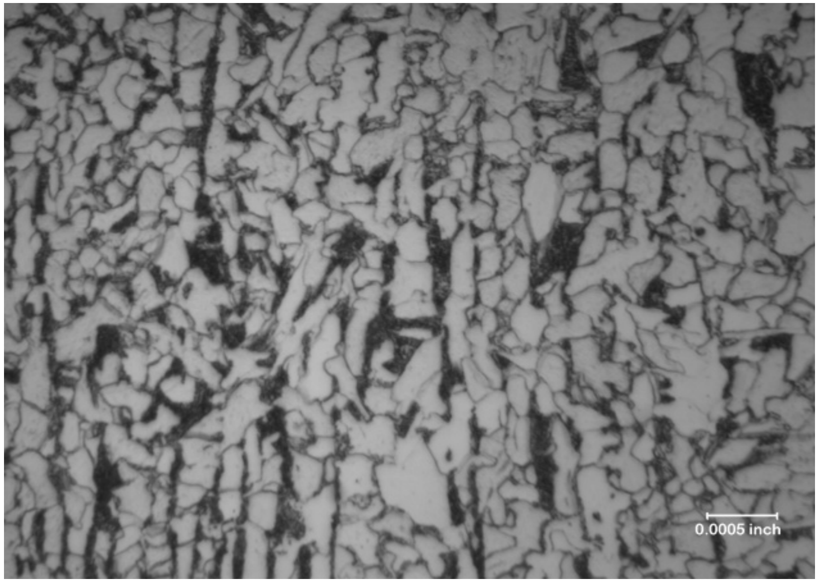
- API 5L-Spec 2004
- X-42
    - C:0.22 max
    - Mn: 1.30max
    - P:0.025max
    - S:0.015max
    - Ti:0.04max
    - Other: <0.15%

SRNL H2 Pipeline Program

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







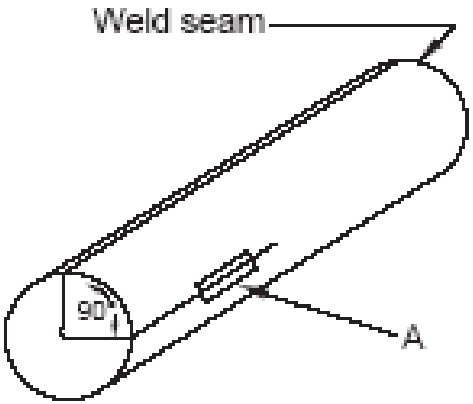
H_2/NG Mechanical Property Testing

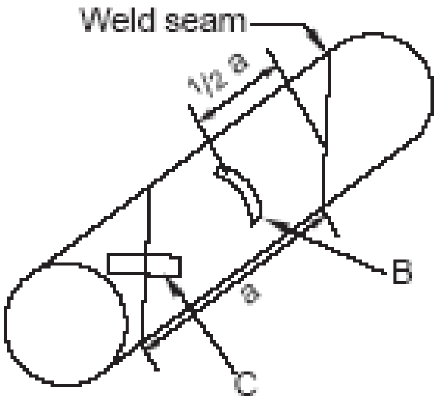
•Mechanical Property Testing will be Conducted in Both Ar and Hydrogen

•Both Longitudinal and Transverse Samples will be Harvested from Archival NG Pipe

•Testing will be conducted at pressures in the range of 100-1000 psi

•Testing will be conducted at Room Temperature ≅ 25°C





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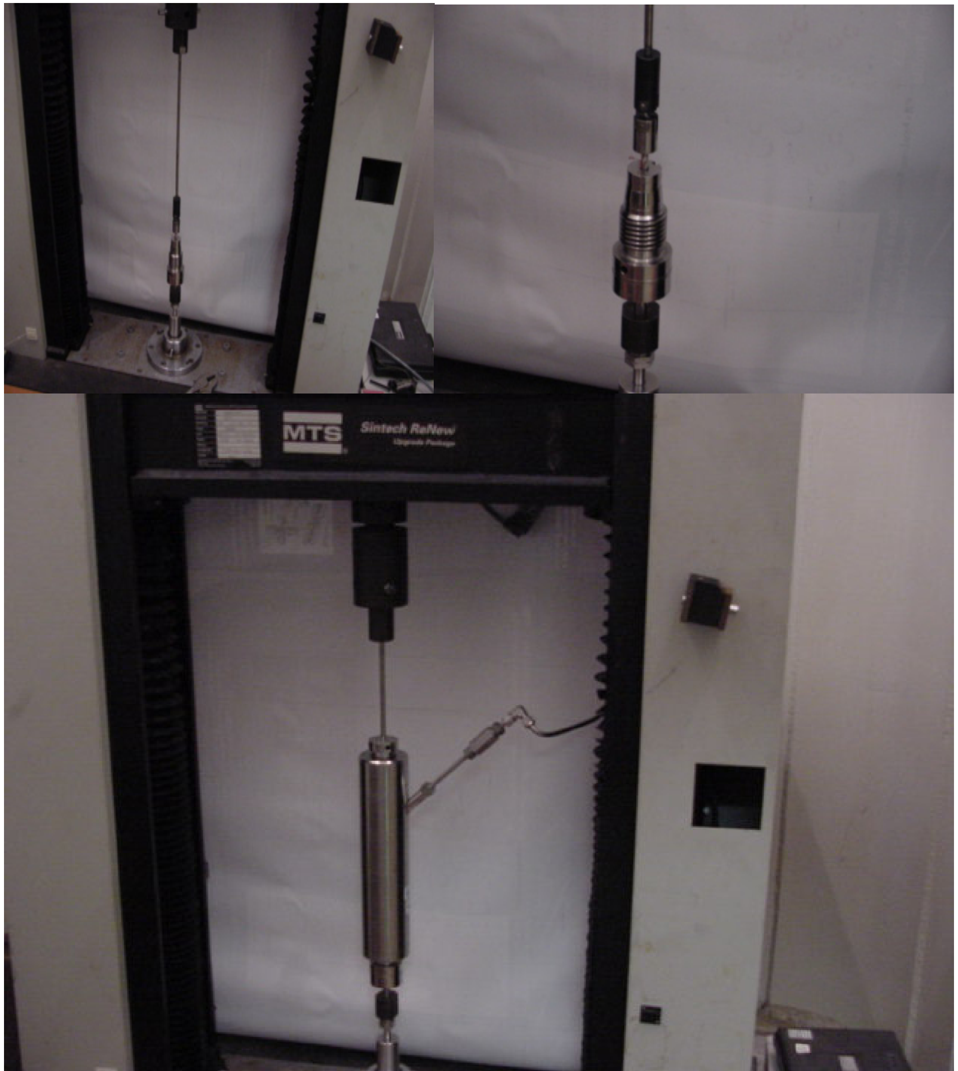
H_2/NG Mechanical Property Testing



SRNL High Pressure Hydrogen Facility

- Mechanical Property Testing in Hydrogen
    - Temperature: Up to 350°C
    - Pressure : Up to 30,000psi
    - Sub-miniture Specimens: 1” gage length

- Fracture Toughness Testing
    - C-Shaped Specimens

SRNL H2 Pipeline Program

TABLE 2. SMOOTH-BAR TENSILE PROPERTIES OF PIPE STEELS*

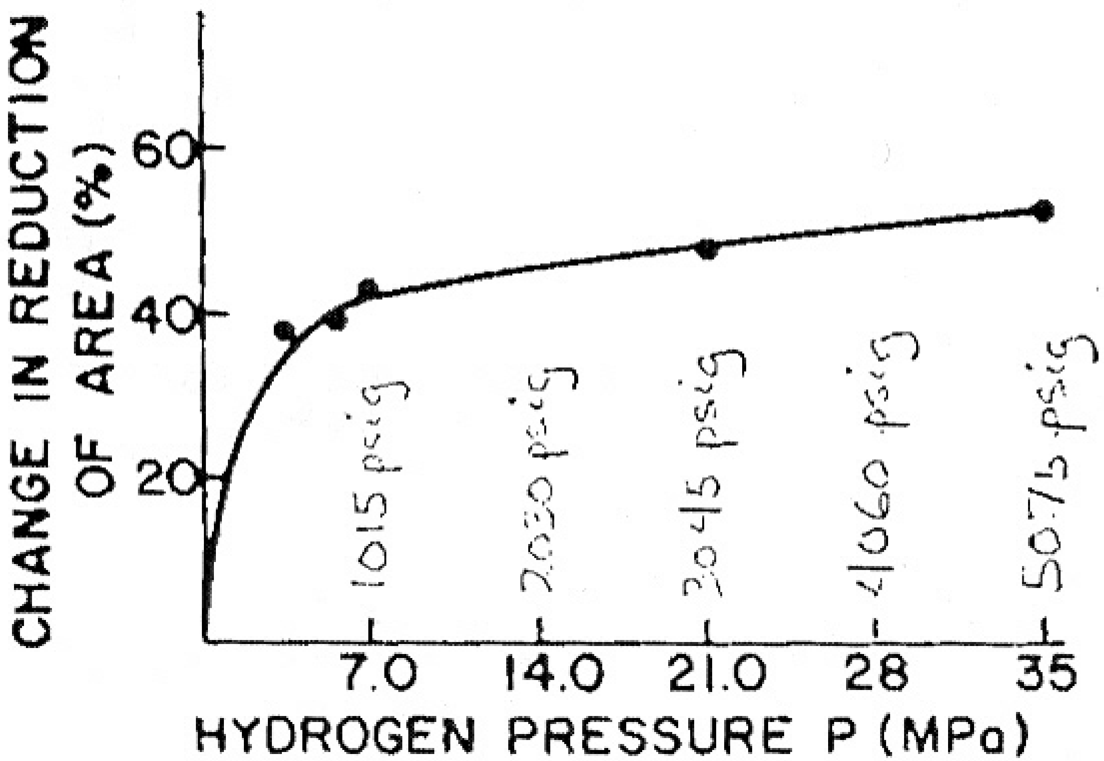
API-5LX Pipe Grade	Test Environment	0.2-Percent-Offset Yield Strength, MPa (ksi)	Ultimate Tensile Strength, MPa (ksi)	Percent Elongation in 1 inch	Percent Reduction of Area
		Axial (Longitudinal) Orientation			
X42	Air	366 (53)	511 (74)	21	56
	6.9 MPa H_2	331 (48)	483 (70)	20	44
X70	Air	584 (85)	669 (97)	20	57
	6.9 MPa H_2	548 (79)	659 (95)	20	47
		Transverse Orientation			
X42	Air	311 (45)	490 (71)	21	52
	6.9 MPa H_2	338 (49)	476 (69)	19	41
X70	Air	613 (89)	702 (102)	19	53
	6.9 MPa H_2	593 (86)	686 (99)	15	38

* Tests conducted at an engineering-strain rate of 10^{-4} sec^{-1}.

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

Figure 1.

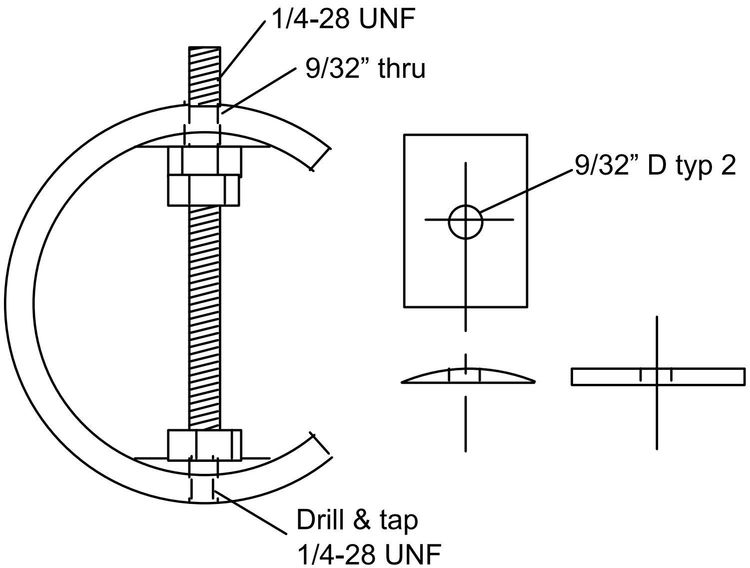
HEE observed in double-notched tensile specimens.



Adapted from Gutierrez-Solana and Elices, ASM, 1982

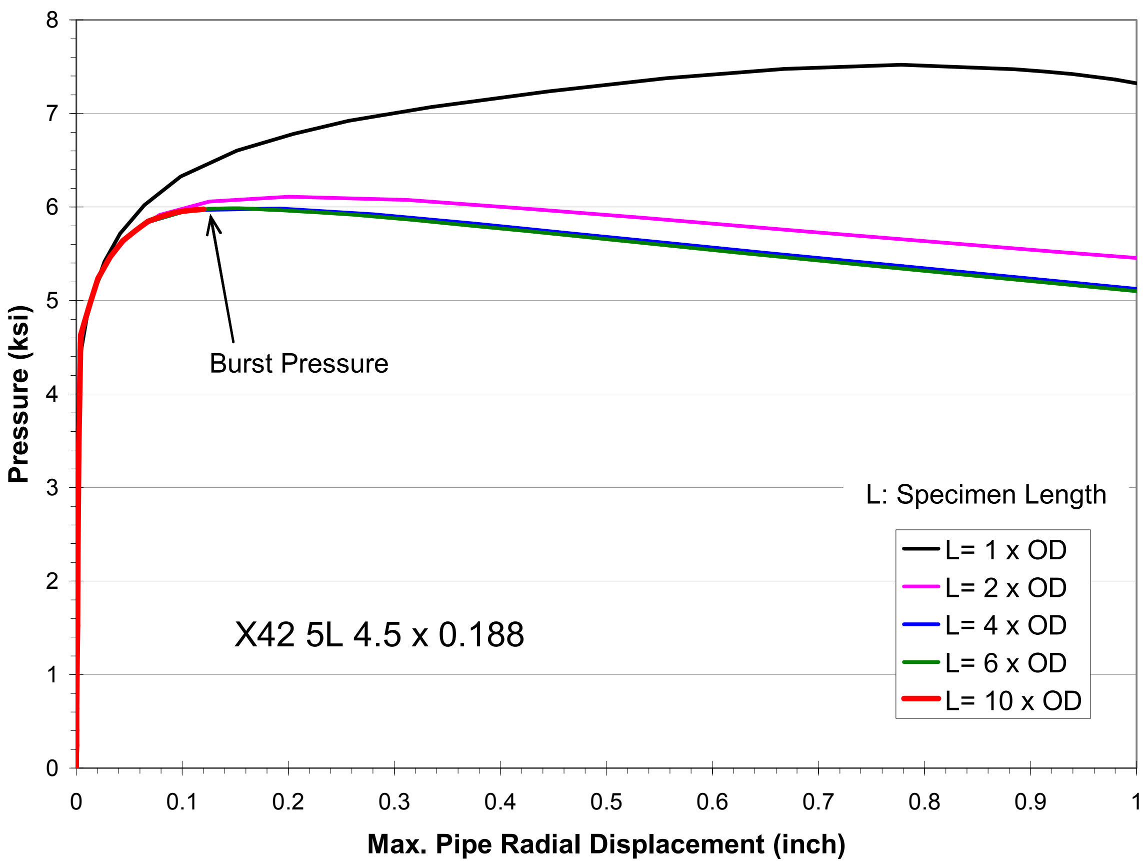
H_2/NG Threshold Stress Intensity Testing

- Hydrogen Threshold Stress Intensity Testing—Bolt Loaded Sample
  - Multiple Samples with Load Range from 0-500 lbs.
  - Crack Dimensions: a/W≅0.5, Root Radius≅0.003in
- C-shaped Samples will be Harvested from 4.5” and 2” Archival NG Pipe
- Testing will be conducted at pressures of 500, 1000, and 1500psi
- Testing will be conducted at Room Temperature ≅ 25°C
- Hydrogen Concentration will be Estimated Analytically Using DIFF
- K_{TH} will be Reported for Initial Conditions (i.e., crack growth initiation)



H2/NG Threshold Stress Intensity Testing

Determination of Burst Pressure



Finite Element Analysis of Burst Pressure

- For defected, repaired, or welded pipelines with geometry and material discontinuities
- For degraded pipelines with local material property variation due to previous NG service or hydrogen exposure
- For actual material tensile property input (full stress-strain curves up to failure)

Year-Two Program Focus

Component Fatigue and Hydrogen Environments

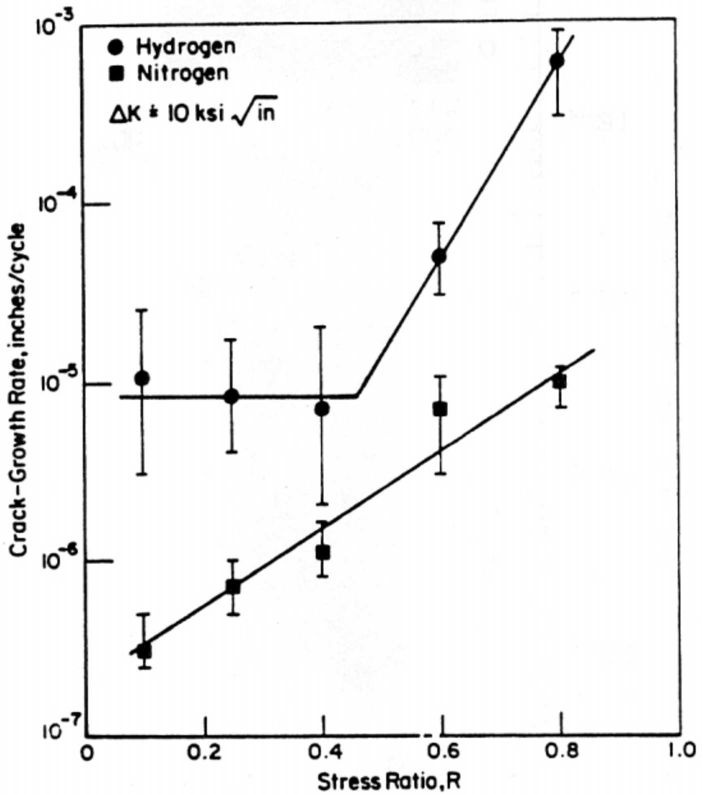
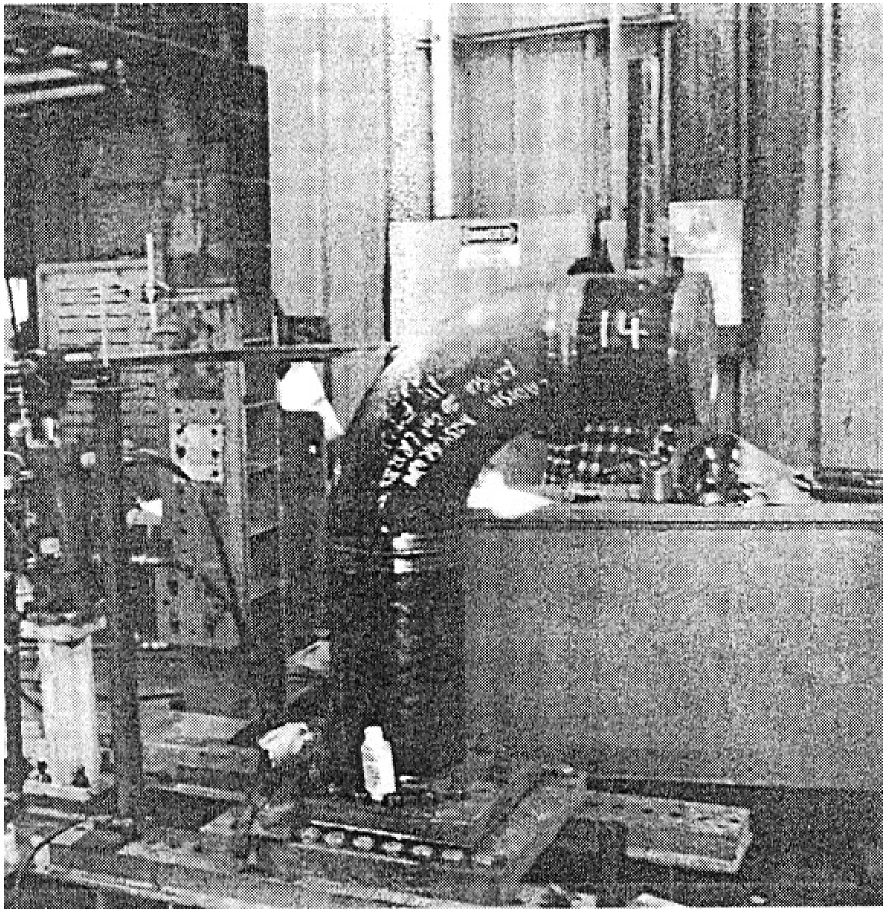


FIGURE 6. FATIGUE-CRACK-GROWTH RATE IN X42 PIPELINE STEEL AS A FUNCTION OF STRESS RATIO



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

Year-Two Program Focus

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Welds and Weld Metal Embrittlement Effects

TABLE VI. TENSILE DATA FOR FILLER METALS AND PROCESSES, TESTED IN HIGH PRESSURE HYDROGEN

Process	Test Environment	0.2% Yield Strength, 1000 psi	Ultimate Strength, 1000 psi	Uniform Elongation	Total Elongation	% R.A.
	(Smooth Bar Tests)					
Base Metal	Air	57.9	82.5	19.3	30.5	71.6
	103 psi H_2	56.8	81.0	14.0	16.6	24.7
GTA†	Air	64.8	84.4	7.3	12.5	71.3
GTA	103 psi H_2	62.4	86	8.2	11.0	38.0
SMA††	Air	56.3	79.1	8.0	13.0	68.7
SMA	103 psi H_2	53.6	79.1	9.6	14.1	47.6

† GTA : GAS - Tungsten Arc, AWS, E70S-2 Filler

†† : Shielded Metal Arc, AWS - E7018 Low H_2 Filler

Adapted from S. L. Robinson, Hydrogen for Energy Distribution, 1978

Year-Two Program 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.**

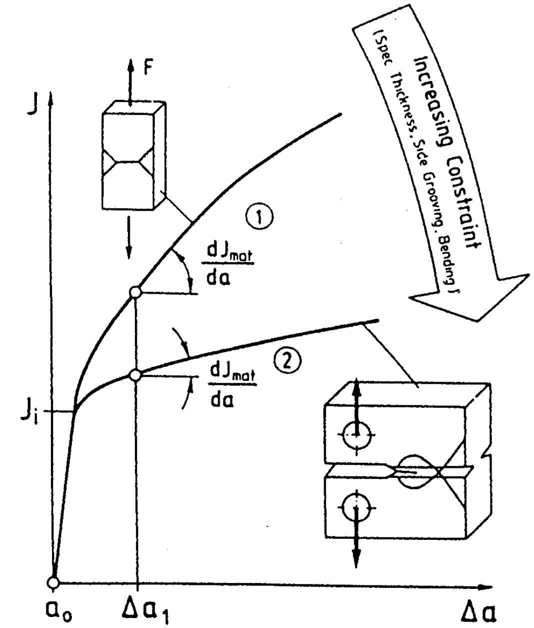
Year-Two Program Focus

Advanced Fracture Modeling

Constraint Modified J-R Curves

Traditional ASTM J-R Curve:

$$J(\Delta a) = C_1(\Delta a)^{C_2}$$



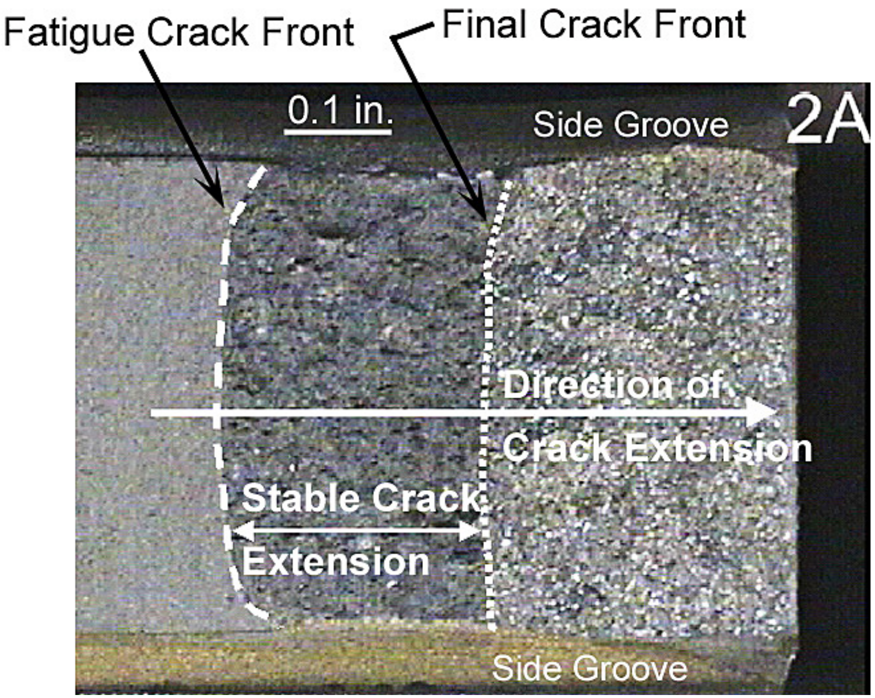
Constraint Modified J-R Curve:

$$J(\Delta a, A_2) = C_o(A_2) + C_1(A_2)(\Delta a)^{C_2(A_2)}$$

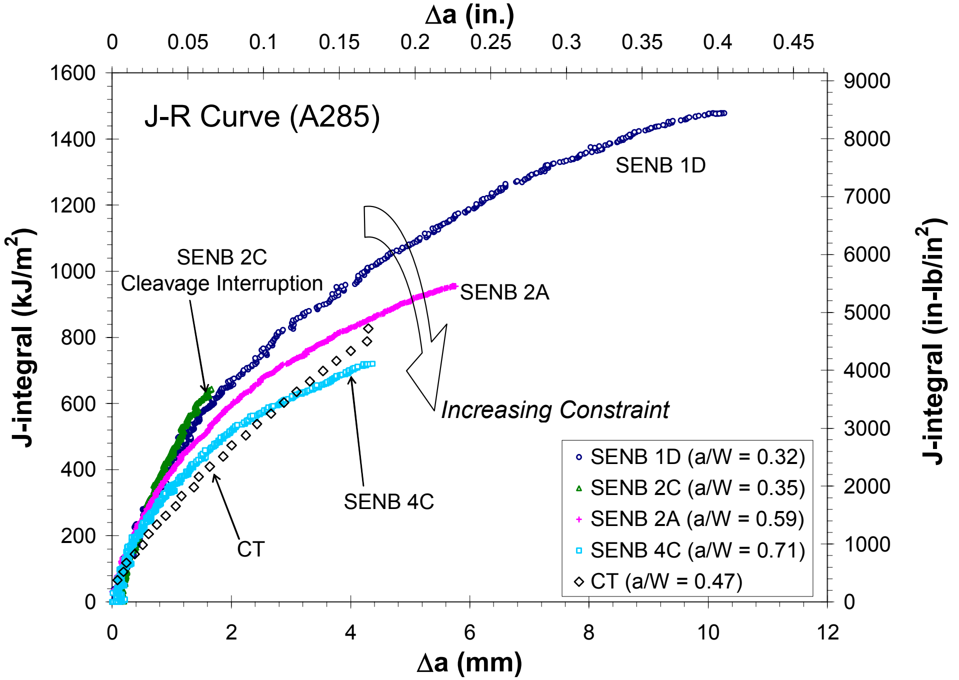
The results can have full transferability from test specimen to large structure

SRNL Fracture Testing for A285 Crack Resistance (J-R) Curves

Typical fracture surface



Specimen size-dependent J-R curves



REF:

Lam, P.S., Chao, Y.J., Zhu, X.K., Kim, Y., Sindelar, R.L., "Determination of Constraint-Modified J-R Curves for Carbon Steel Tanks," J Press Vessel Tech, 12, pp.136-143, 2003

SRNL H2 Pipeline 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
- 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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Thaddeus Reown