Materials Solutions for Hydrogen Delivery in Pipelines

SECAT, INC.

Presented to
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Project Participants

Industrial Participants

SECAT (Lead)
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- Krishnaswamy Rangan

ASME
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Columbia Gas of Kentucky

Chemical Composite Coatings
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Oregon Steel Mills
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- Joseph Hayden

National Laboratory

Oak Ridge National Laboratory
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- V. K. Sikka
- Juan Ferrada
- Joe Strizak

University

University of Illinois
University of Kentucky

Organizations and Roles

Organization	Role in Project
SECAT, Inc.	**Project management and coordination**, specialized characterization, interaction with pipeline companies
ORNL	Computational thermodynamic and kinetic analyses, microstructural characterization using advanced techniques, alloy melting and processing, welding, mechanical testing at high H_2 pressures, financial analysis using FLOW
ATC	Testing using Stress-Strain Microprobe® technology
C3	Deposition of multi-component oxides
Schott NA	Processing and characterization of glassy coatings
Applied Thin Films	Development of Cereblak™ coatings and relevant processing techniques for coating on a variety of steel substrates
Hatch Moss MacDonald, Columbia Gas	Provide expertise on pipeline construction and maintenance
University of Illinois	Provide a fundamental understanding of hydrogen embrittlement in steels and model for life prediction
Oregon Steel Mils	Provide commercial material for testing, commercial pipe manufacturing facility, commercialize successful new technology
ASME	Provide team of industry experts to monitor and guide project, assist in incorporation of knowledge into codes and standards

Motivation

- Pipeline transmission is the most economical method for hydrogen delivery in large quantities
- Due to differences in energy values, calculations show that hydrogen needs to be delivered at pressures exceeding 2000 psi to be cost-effective
- There exists a network of existing natural gas pipelines built of pipeline steels that could potentially be used for the transport of hydrogen
- **QUESTION: Can these pipelines be used for the SAFE transport of hydrogen at high pressures (provided that the pipelines are otherwise designed for these pressures)?**

History of Hydrogen Pipeline Systems*

- Existing hydrogen pipelines are typically small diameter (below 20 cm) and operate at low pressures
- Longest line in Ruhr is constructed from seamless pipe and operates at low pressures of 150 to 240 psi
- High pressure lines:
  - Los Alamos line (2000 psi) made of Cr-Mo steel failed in service
  - NASA line at Kennedy Space Center operates at 6000 psi and is constructed of 316 Austenitic Stainless steel
  - Rocketdyne Division of Rockwell International (14,500 psi) made of 21Cr-6Ni-9Mn
- Successful high pressure lines were constructed of austenitic stainless steels which are less prone to hydrogen embrittlement

* A. W. Thompson, "Materials for Hydrogen Service," in Hydrogen: Its Technology and Implications," Vol. II Transmission and Storage, CRC press, 1977

High-Pressure Hydrogen Transport and Pipeline Steels

- Pipelines constructed of stainless steels have been preferred over those constructed from pipe line steels for the high pressure transport of hydrogen
- Experiments show that non-austenitic (ferritic/ferritic-pearlitic/martensitic steels), in general are more susceptible to hydrogen embrittlement when compared to austenitic stainless steels
- Constructing pipelines using stainless steels would be significantly more expensive
- There is a need to study the behavior of pipeline steels and their welds under high pressure hydrogen

Key Barriers to be Addressed

- Extent of hydrogen embrittlement of base material, and welds in pipeline steels and other common steels on exposure to high pressure H_2 is not known
- A comprehensive understanding of the mechanisms of hydrogen embrittlement along with the effect of metallurgical variables such as alloying element additions, and microstructure of steels is lacking; hence a clear path to remediation is currently not available
- Although it is known that barrier coatings are effective in reducing hydrogen embrittlement, detailed knowledge of the effectiveness of various metallic and non-metallic coatings in minimizing the deleterious effect of H_2 under high pressures is not known
- Very little information is available on the potential avenues for reducing the cost of construction of pipelines for transport of hydrogen and the cost of technologies to remediate the effect of hydrogen embrittlement

Project Goals and Objectives

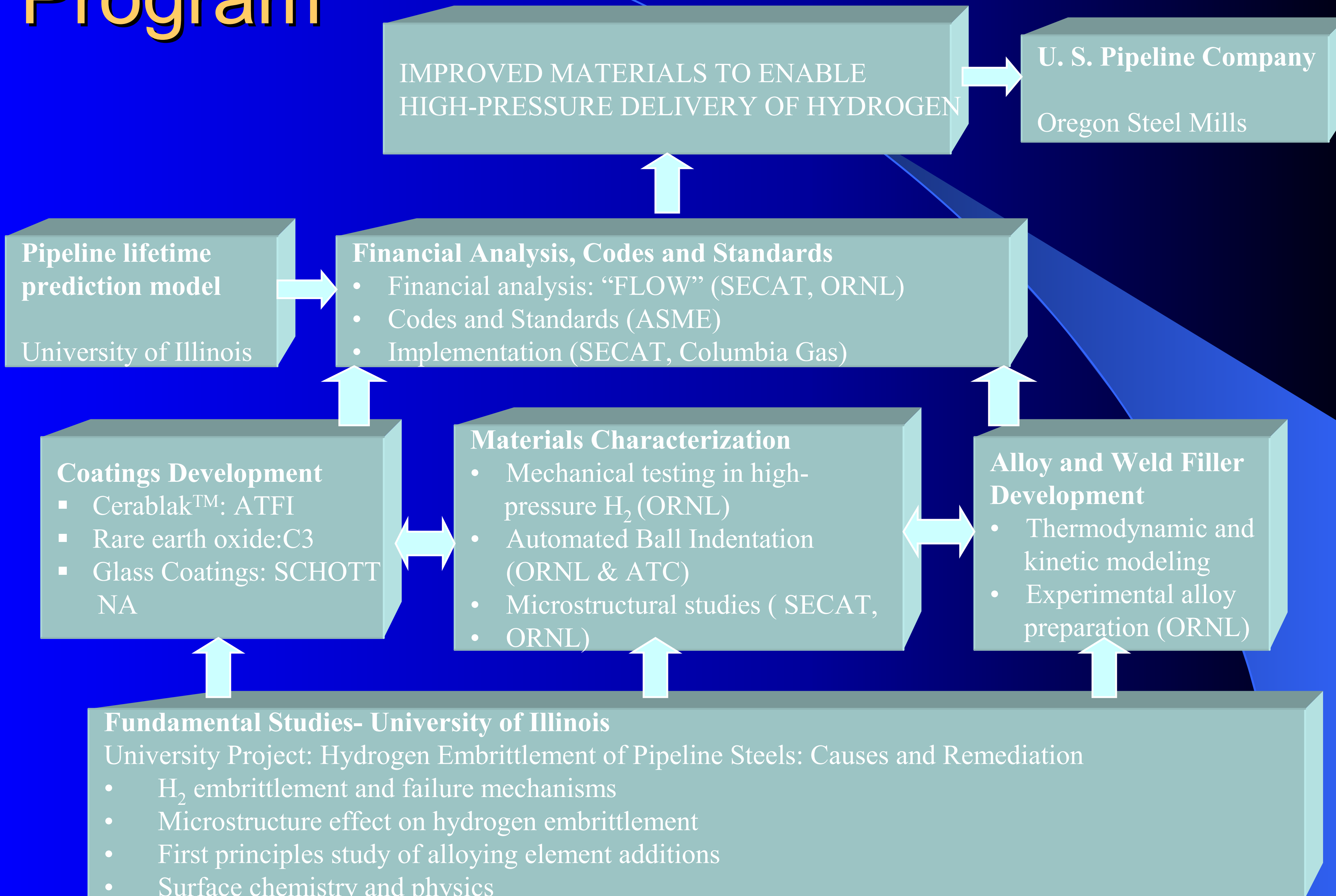
- Goal of the project is to develop materials technologies that would enable minimizing the problem of hydrogen embrittlement associated with the high-pressure transport of hydrogen

- The objectives of the project are:
  - To develop barrier coatings for minimizing hydrogen permeation in pipelines and to develop *in-situ* deposition processes suitable for these coatings
  - To identify steel compositions and associated welding filler wires and processes that would be suitable for new pipeline infrastructure
  - To understand the cost factors related to the construction of new pipelines and modification of existing pipelines and to identify the path to cost reduction

Major Tasks for Completion

- Complete negotiation with US DOE and Subcontractors
- Task 1: Evaluate hydrogen embrittlement characteristics of existing commercial pipeline steels under high-pressure hydrogen
- Task 2: Develop and/or identify alternate alloys and evaluate hydrogen embrittlement
- Task 3: Develop coatings to minimize dissolution and penetration of hydrogen
- Task 4: Evaluate the hydrogen embrittlement in alloys coated with selected coatings
- Task 5:Perform financial analysis and incorporate knowledge into codes and standards
- Task 6: Meetings and reports

Functional Organization of Research Program



Detailed Research Plan

- Detailed outline of experimental tasks and research plan
- Timelines and Major Milestones

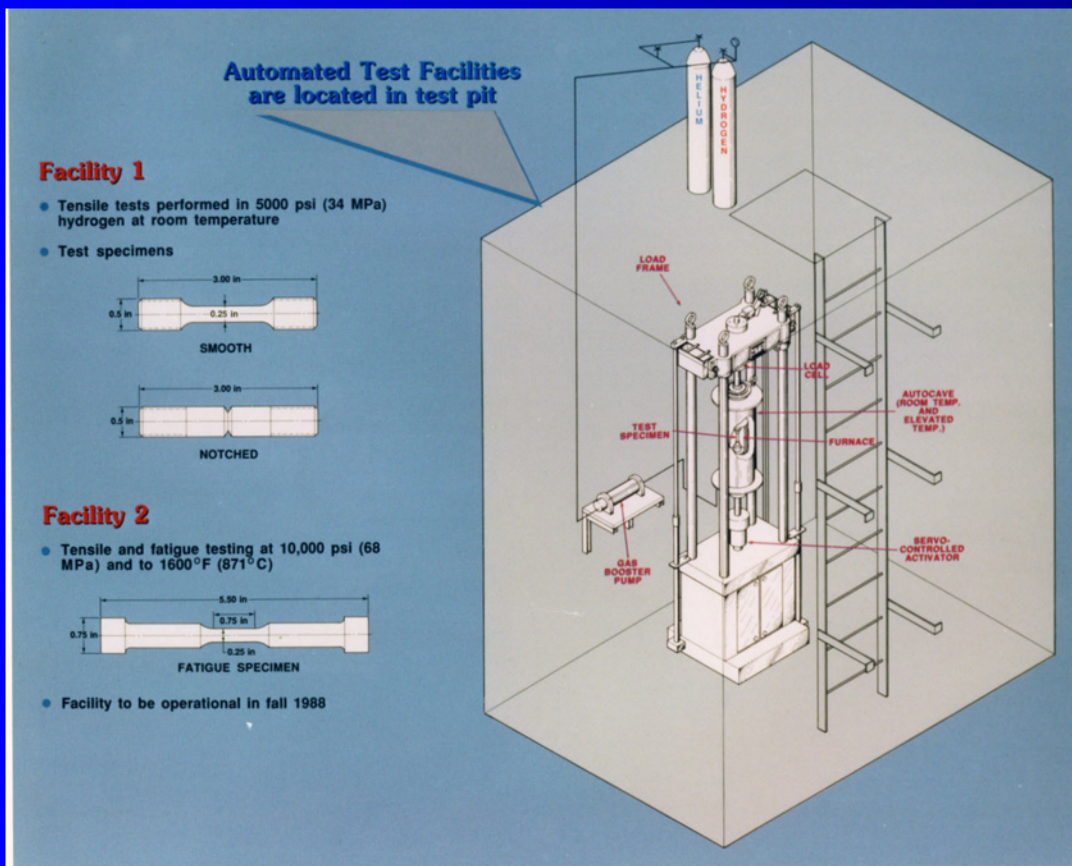
Hydrogen Embrittlement of Steels

- Hydrogen embrittlement is used to characterize any of the common effects of hydrogen at temperatures near room temperature such as
  - loss of ductility,
  - loss of true stress at fracture,
  - loss of load carrying capacity,
  - cracking and delayed cracking
- Hydrogen concentration in steels is proportional to $(p_{H2})^{1/2}$ where p_{H2} is the partial pressure of hydrogen in the environment
- Two major factors affect hydrogen embrittlement of steels: composition, and microstructure
- Microstructure is strongly influenced by thermal-mechanical processing and it is known that welds are especially susceptible to embrittlement, partially due to residual stresses
- Both instantaneous behavior (short-time exposure to high-pressure H_2) and long-term exposure to hydrogen where substantial amounts of hydrogen could be dissolved in the lattice are of interest

ORNL Has Facilities and Expertise for Mechanical Property Testing at High Hydrogen Pressures

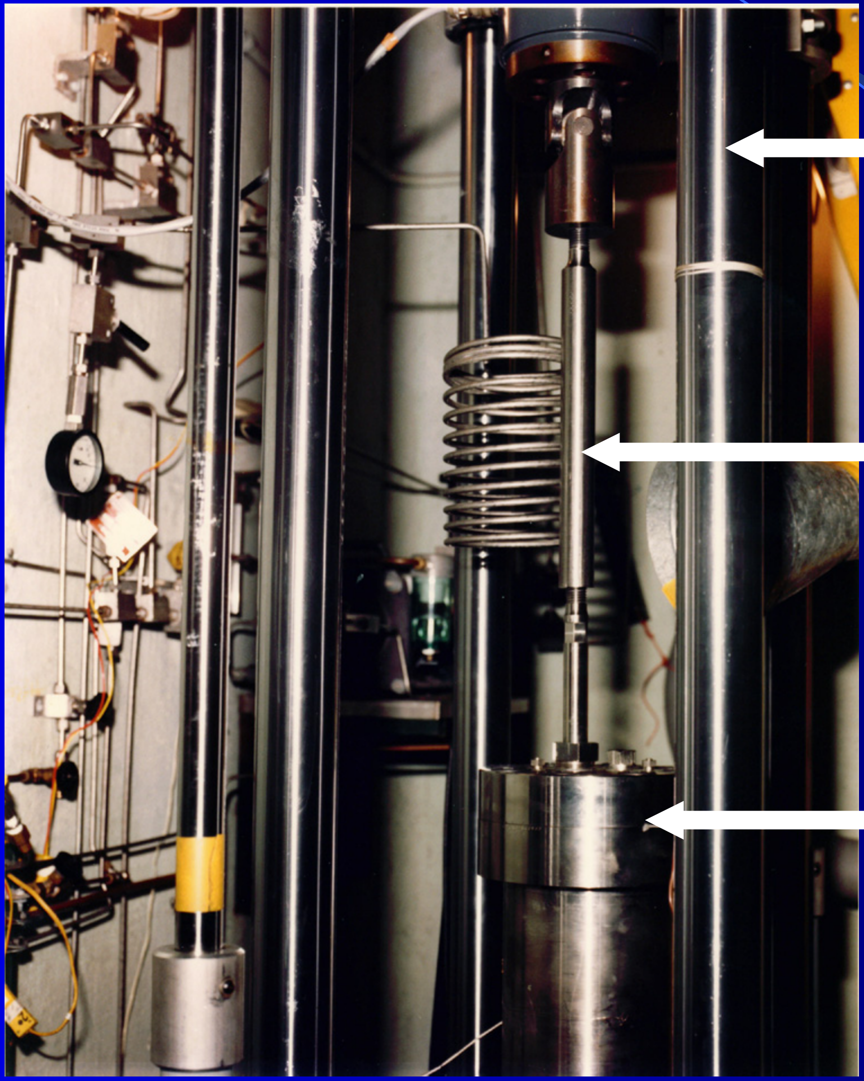
- In 1980’s, personnel from the Metals and Ceramics Division were involved in NASA programs: Space Shuttle, and National Aerospace Plane (NASP)
- Tensile and fatigue properties of Ni-based superalloys were tested in high pressure, high purity hydrogen
- One of five labs in the country that had this capability

Facilities Used for NASA Project

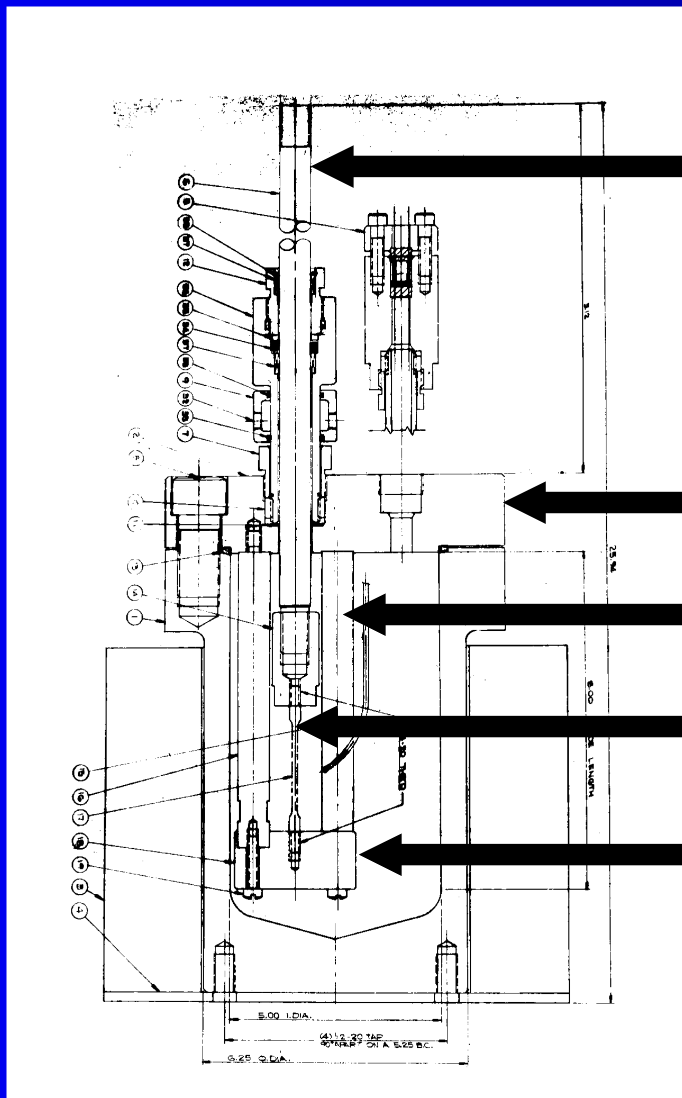


- Room temperature testing facility was designed and built by ORNL and is available now
- High-temperature, high pressure system was built for NASA and was returned
  - System can be rebuilt with some additional effort

System for Mechanical Testing at Hydrogen Pressures up to 5000 psi



Schematic Diagram of the System



Pull Rod

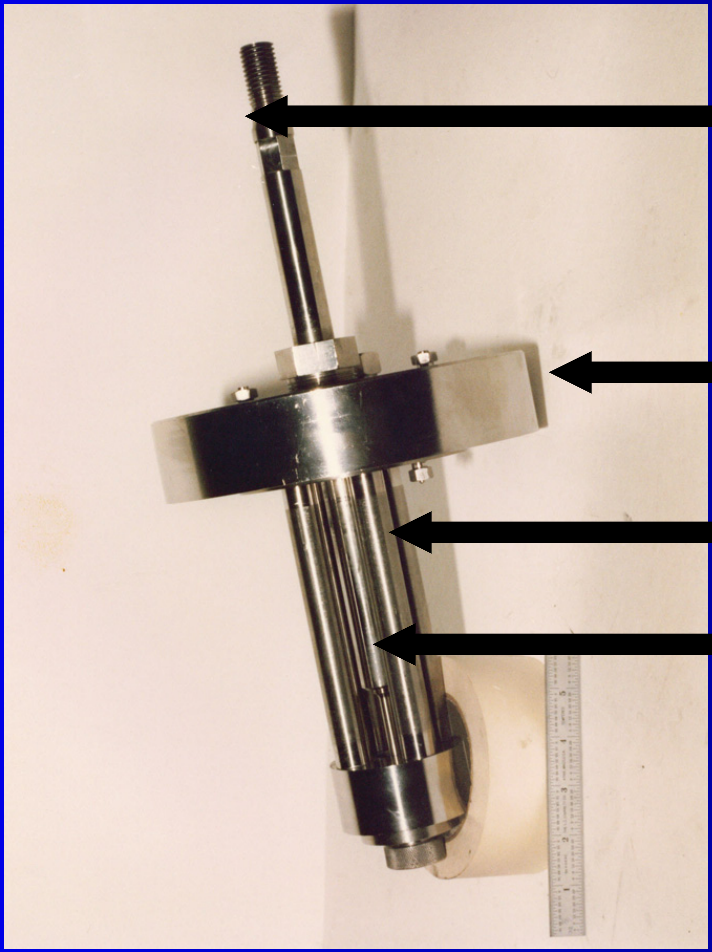
Top of Autoclave

Sample Holder Posts

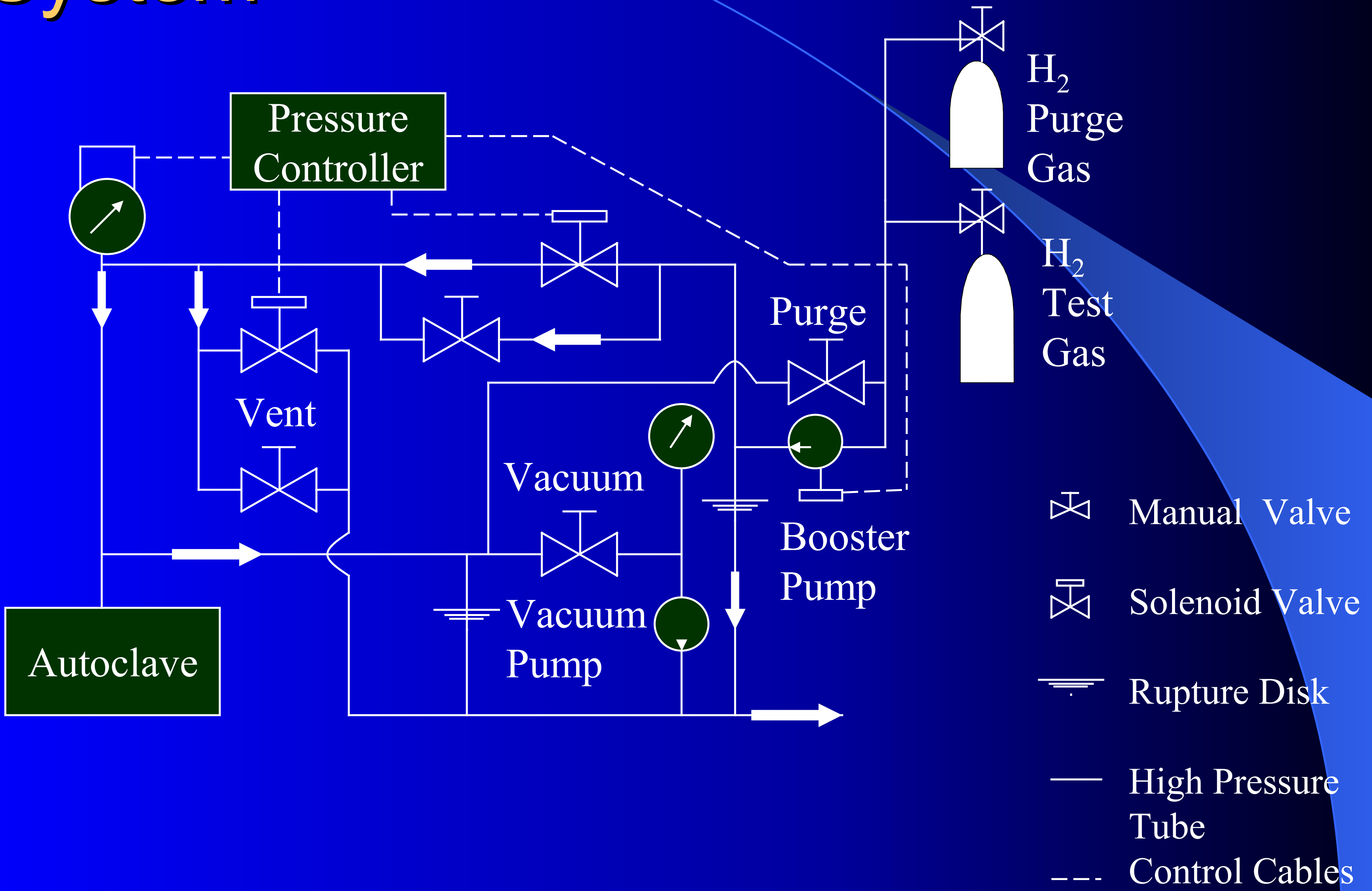
Sample

Sample Holding Stage

Image of Sample Holder Located Inside the Autoclave



Schematic of High-Pressure Testing System



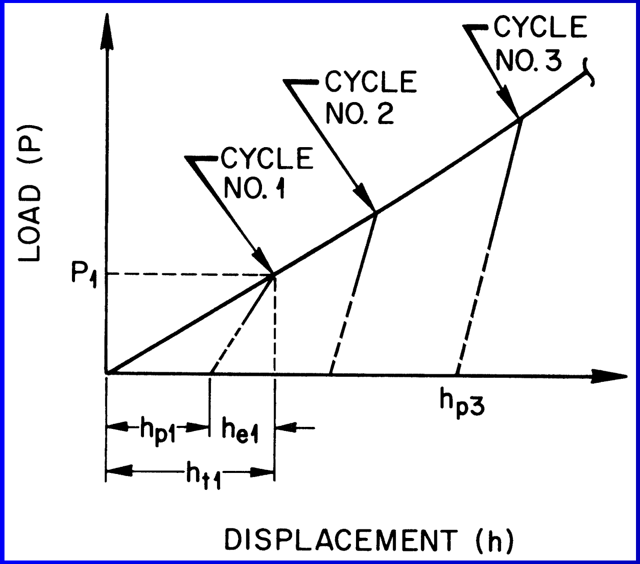
Status and Plans for the Development of the Proposed System

- Autoclave and test frame are already available
- Modifications will be performed to adapt hardware for the current study and to ensure that laboratory safety issues are properly addressed (total autoclave volume will be minimized)
- Data collection and operation will be automated and computerized
- Hydrogen sensors will be employed for leak detection and safe operation within the facility

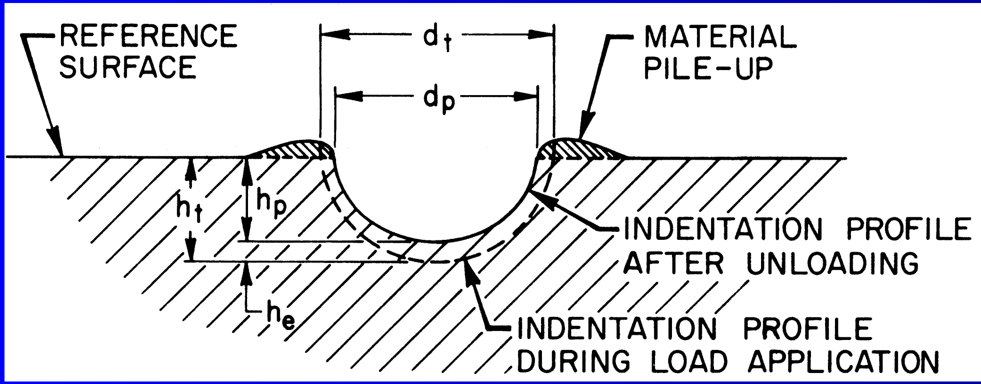
Stress-Strain Microprobe®(SSM) System

- A PATENTED testing system that uses Automated Ball Indentation (ABI) tests to measure tensile and fracture toughness properties on any metallic material of interest
- An ABI test consists of progressive indentations on the substrate using a ball indenter with intermediate partial unloadings until the desired maximum depth is reached, after which the indenter is fully unloaded
- The indentation load-depth data are collected continuously and recorded using a 16-bit data acquisition system
- The incremental values of load and deformation depth are converted to incremental values of true-stress and true-plastic-strain according to elasticity and plasticity theories
- The ABI test is completely automated and a single test can be completed in less than two minutes depending on the strain rate (strain rates of $1\times10^{-5}\ s^{-1}$ to $1.0\ s^{-1}$)

Cyclic Loading and Unloading of Ball Indenter into Material



(a) Schematic of Applied Load versus Penetration Depth



(b) Indentation Geometry During Load Application and After Load Removal

Mechanical Properties Obtained Using SSM System

- The SSM system can be used to determine:
  - True-Stress/True-Plastic-Strain
  - Yield Strength
  - Work-Hardening Exponent and Strength Coefficient
  - Estimated Engineering Ultimate Tensile Strength
  - Fracture Toughness
  - Brinell Hardness
- Comparison between tensile tests and ABI tests

Tensile Test

Two Data Parameters:

(1) Tensile Load,

(2) Sample Extension

Stress = Load / Cross-Sectional Area

Strain = $\Delta L / L_o$

ABI Test

Two Data Parameters:

(1) Compressive Load,

(2) Progressive Indentation Depth

Stress = Load/ Effective Indentation size

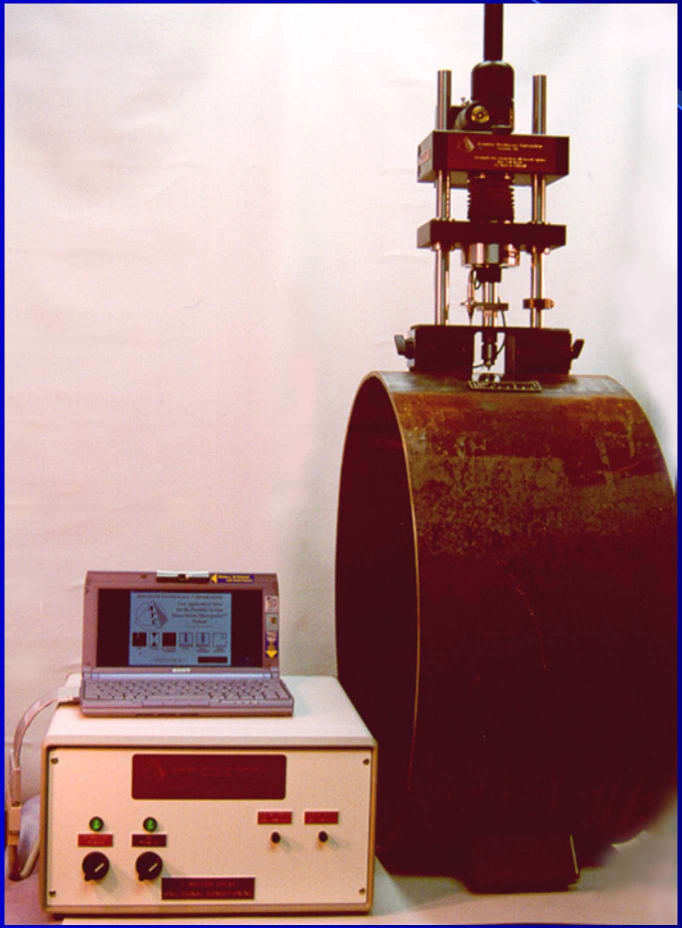
Strain = Constant x (Progressive indentation diameter / Indenter diameter)

Equations for Calculating the Yield Strength and Stress-Strain Properties from ABI Tests

(1) True Plastic Strain: $\epsilon_t = 0.2\frac{d_p}{D}$	Strain range: 0-0.2 or 0% to 20% Empirical (Tabor's 1940's), Analytical (Prof. McClintock, 1960's)
(2) True Stress: $\sigma_t = P_m \frac{1}{\psi(\phi)} = \frac{P}{(\pi d_p^2/4)} \frac{1}{\psi(\phi)}$ Constraint factor: $\psi = \begin{cases} 1.12 & \phi \le 1 \\ 1.12 + \tau \ln\phi & 1 < \phi \le 27 \\ \psi_{max} & \phi > 27 \end{cases}$	ϕ = indentation variable: $\phi = \frac{\epsilon_p E_2}{0.43\sigma_\tau}$ $\psi_{max} = 2.87\alpha_m$ $\tau = (\psi_{max} - 1.12) / \ln (27)$ α_m = constrain factor index
(3) Meyer's Law (1908): $\frac{P}{d_t^2} = A(\frac{d_t}{D})^{m-2}$	P = load d_t = total diameter of the indentation m = Meyer's index D = indenter diameter A = yield parameter (P/d_t^2 at $d_t/D = 1$)
(4) Indentation plastic diameter: $d_p = \left\{\frac{C(D/2)[h_p^2 + (d_p/2)^2]}{[h_p^2 + (d_p/2)^2 - h_p D]}\right\}^{\frac{1}{3}}$	$C = 5.47\, P(1/E_1 + 1/E_2)$ E_1, E_2 = Young's moduli for indenter and test material h_p, d_p = Plastic indentation depth, plastic chordal diameter
(5) Yield Stress: $\sigma_y = \beta_m A + b_m$	β_m = Material yield slope, b_m = material yield constant

True Stress = Engineering Stress (1 + Engineering Strain)
True Plastic Strain = *ln* (1 + Engineering Strain)

In-Situ **Stress-Strain Microprobe®** (SSM) System, Model SSM-M1000

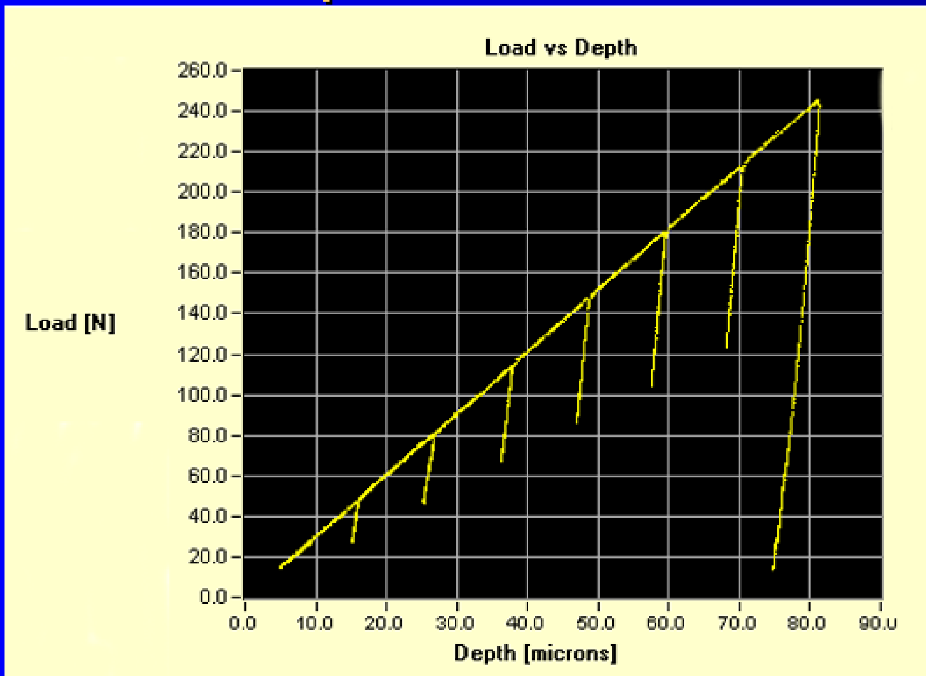


The testing head of the SSM system is mounted with manual magnets on a 24-inch diameter X52 pipeline.

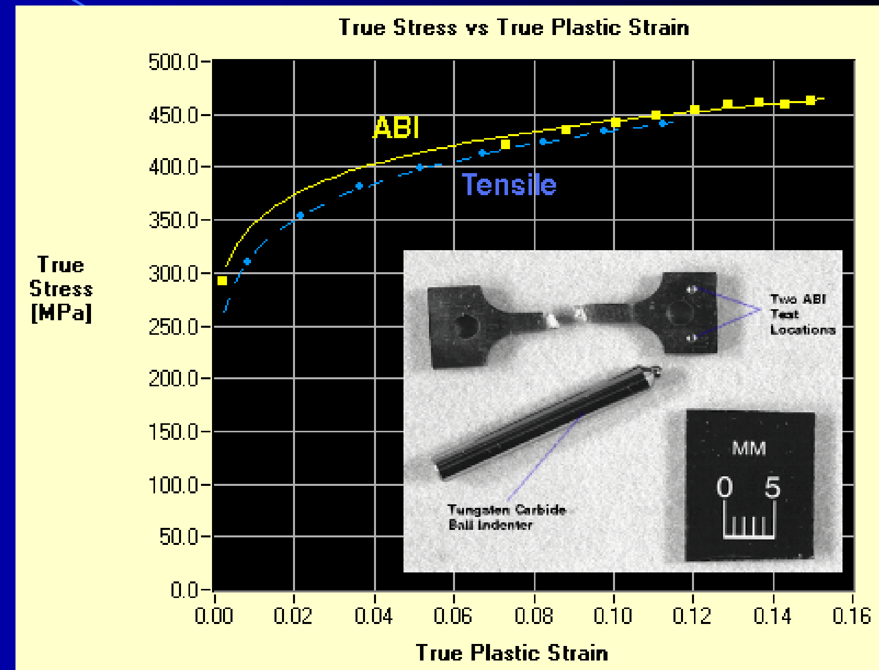
SSM-M1000^{TM} testing in-service Kerosene pipelines in Alexandria, Egypt

(Testing head is mounted using DC electric magnets.)

Stress-Strain Curves Obtained From X42 Ferritic Steels using ABI Test Compare Well with Results from Tensile Tests

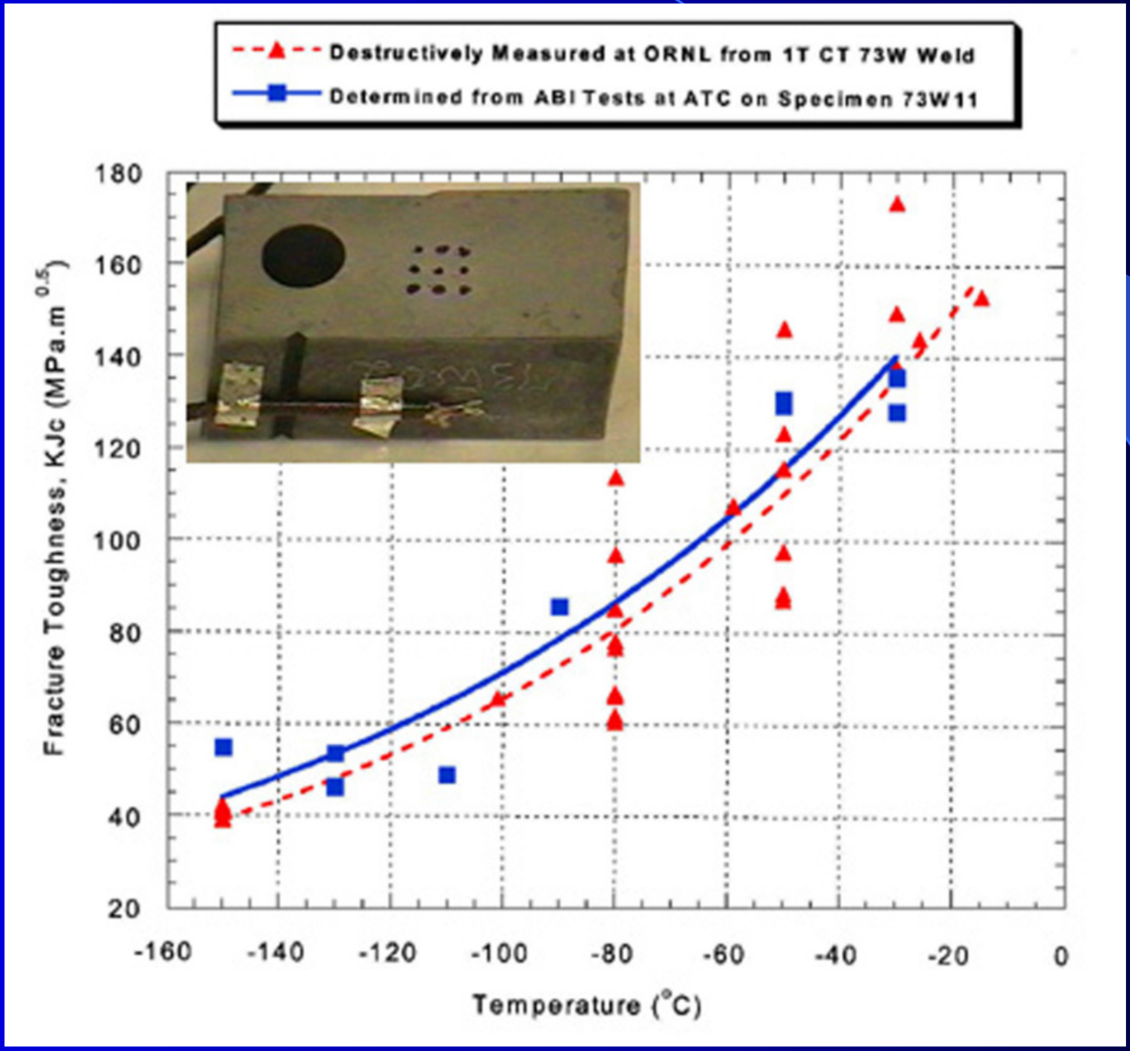


Indentation Load versus depth in an ABI test using a 0.51-mm (0.02-inch) diameter tungsten carbide indenter on X42 ferritic steel material.



True-Stress versus True-Plastic-Strain curves from ABI and tensile tests on X42 pipeline steel. A miniature tensile specimen is shown with two indentations made with a 1.57-mm (0.062-inch) indenter.

Nondestructively ABI-measured $(K_{Jc})^{ABI}$ Results Compare well with Destructive CT Fracture Toughness Test Results



Advantages of the SSM® System

- The localized capability of the ABI test is valuable for determining property gradients in welds, heat-affected-zones, and base metal
- Testing is essentially nondestructive and provides an ***in-situ*** testing capability to monitor the integrity of structures as a function of service time
- Properties can be evaluated without significant sample preparation and in the field without service interruption
- Properties obtained using the ABI technique compare well with those obtained from traditional testing techniques
- Tests can be performed on pipes of different sizes to determine the effect of pipe diameter and fabrication on embrittlement

Task 1: Evaluate Hydrogen Embrittlement of Existing Commercial Pipeline Steels in High Pressure Hydrogen

- Although significant work has been carried out in the past on the effect of hydrogen introduced through cathodic charging on various alloys, very little information is available on the effect of exposure of these alloys to H_2 at pressures greater than 2000 psi
- As part of this work, a careful assessment of existing data on hydrogen embrittlement of commercial alloys (various grades of pipeline steels and other candidate alloy systems) will be performed
- Based on this data, four of the best candidate alloys will be down-selected for further detailed study

Task 1 (Continued)

- Hydrogen embrittlement in the alloys will be characterized using two types of tests:
  - Mechanical tests (short-term tests) of these alloys will be carried out in high pressures of H_2 (upto 5000 psi) as a function of metallurgical variables such as heat treatments, grain size, and processing, including typical welding processes
  - SSM® tests will also be carried out on flat specimens and fabricated pipes with and without weld joints
- Thermodynamic and kinetic modeling will be combined with microstructural characterization to understand the relationship between hydrogen embrittlement and microstructure
- Failed specimens will be characterized to understand the failure mode and compare with existing knowledge of failure modes

Role of SSM® in the Current Work

- SSM® technology will be used to measure time-dependent long-term effects on embrittlement and will complement traditional mechanical testing under high hydrogen pressures which studies short term effects

- Pipeline sections will be internally pressurized (5000 psi and higher) with hydrogen for different periods of time

- Exposure to hydrogen will be interrupted periodically and ABI tests will be performed on the outer surface to study the effect of exposure on mechanical properties including fracture toughness

- This data will be correlated with short term and lon-term data obtained from tensile tests in high pressure hydrogen

Task 2: Develop Alternate Alloys and Evaluate Hydrogen Embrittlement

- With increase in transmission pressures through pipelines, there may be a need to use higher strength steels to enable use of lower wall thicknesses
- Steels with higher strength are typically more susceptible to hydrogen embrittlement, both in the matrix and at welds
- Minor alloying element additions to pipeline steels to improve hydrogen embrittlement resistance has been attempted in the past and will guide this work
- One additional alloy composition will be identified which could potentially have a better resistance to hydrogen embrittlement
- Mechanical tests will be carried out in high pressure H_2 to evaluate the susceptibility of matrix and welds
- Steel compositions of acceptable resistance to H_2 embrittlement will be evaluated for development of filler wire and coated electrodes

Effect of Alloy Composition on Susceptibility to Hydrogen Embrittlement*

- It is difficult to separate out purely the effect of composition from the microstructure since the composition of the alloy has a large influence on the microstructure
- A comprehensive understanding of the effect of the various elements is lacking along with information on the desired composition windows of these elements
- The mechanism by which some elements influence hydrogen embrittlement are known:
  - Some elements are effective traps (atomic or through formation of precipitates)
  - Some elements such as sulphur are detrimental due to formation of inclusions that act as crack nucleation sites
- Design of new alloys could be accomplished by adding elements with known positive effects and decreasing the amounts of elements with negative effects

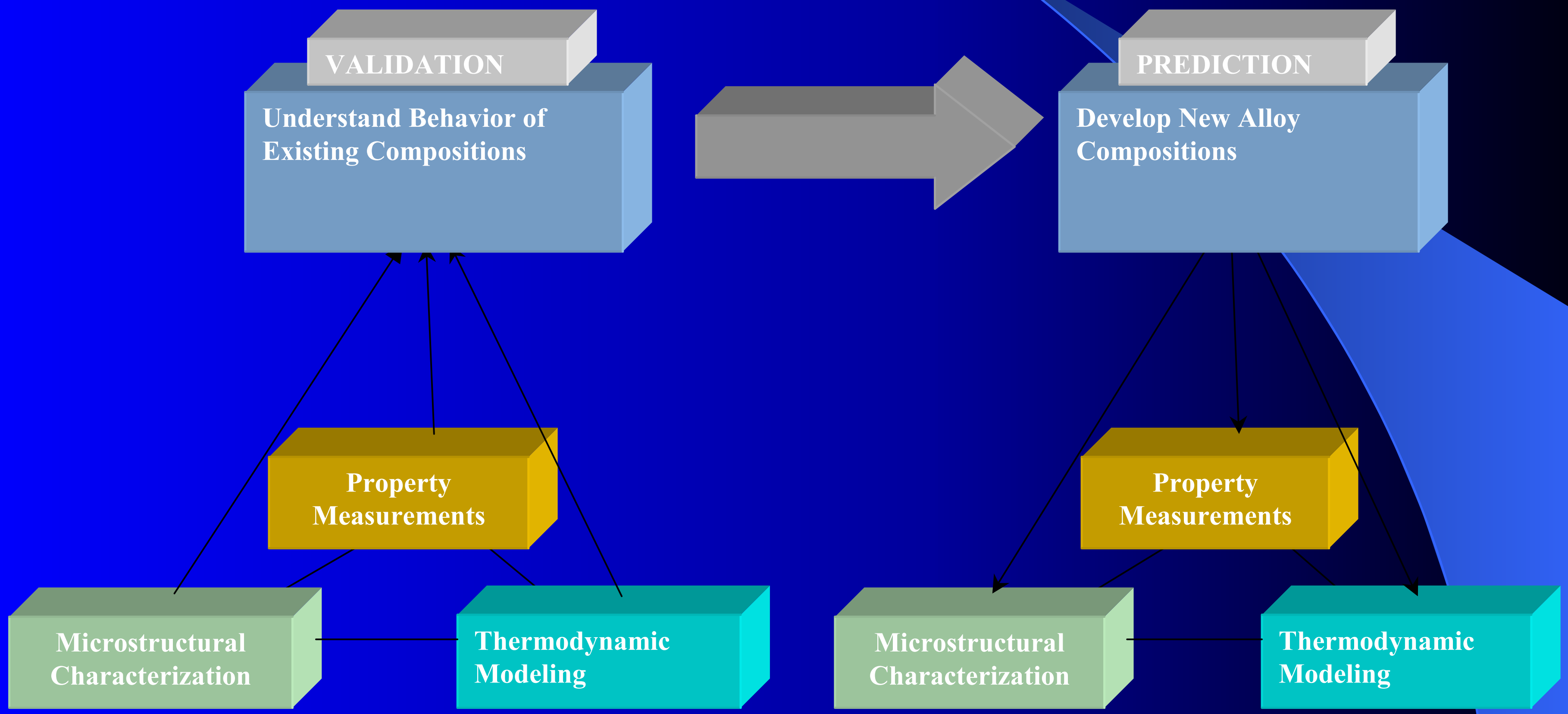
Alloying Element	**General Susceptibility**
Manganese	Increases
Sulfur and Phosphorus	Appears to increase
Carbon (in carbon martensites)	Appears to increase
Chromium	Increases
Titanium	Reduces
Titanium in Maraging Steels	Increases
Silicon	Reduces
Molybdenum	No consistent behavior
Nickel	Not known
Tungsten	Not known
Vanadium	Not known

*A. W. Thompson, and I. M. Bernstein, “The Role of Metallurgical Variables in Hydrogen-Assisted Environmental Fracture,” in Advances in Corrosion Science and Technology, Vol. 7, Eds. M. G. Fontana, and R. W. Stahle, Plenum Press, NY, 1975

Effect of Microstructure on Susceptibility to Hydrogen Embrittlement

- Certain microstructures in ferritic steels are known to be more resistant to hydrogen embrittlement and would be preferred in pipelines
- The following is the order of microstructures with increasing tendency for embrittlement
  - Quenched + tempered/spheroidized
  - Normalized + tempered
  - Normalized
  - Untempered bainite
  - Untempered martensite
- Internal interfaces, particularly those of carbides, and other traps are extremely critical in determining susceptibility
- Grain refinement is known to improve resistance to embrittlement
- Inclusions have a significant role to play along with microstructural banding and segregation
- Preference will be given to achieving microstructures with better resistance to hydrogen embrittlement though appropriate thermal-mechanical treatment

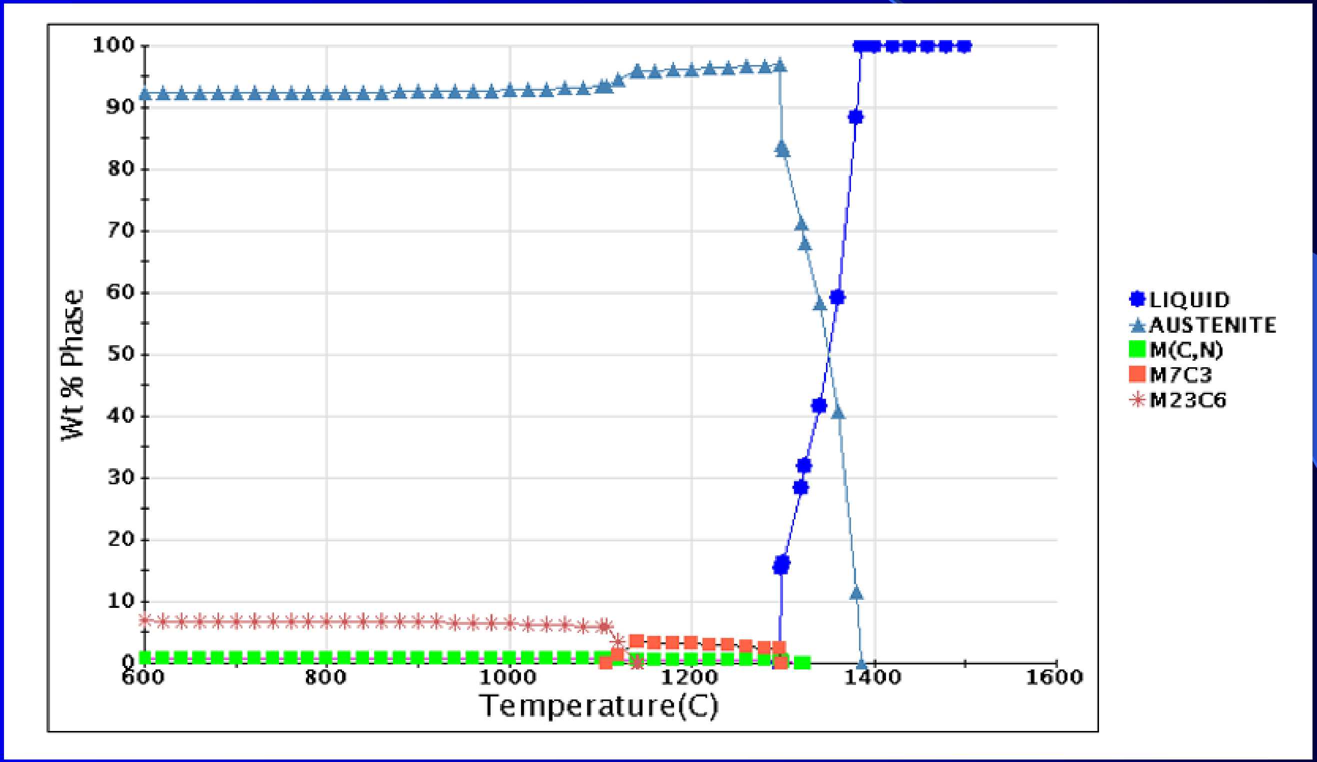
A Generalized Scheme for the Rapid Development of New Alloys



Methodology Used for Designing New H-Series Austenitic Stainless Steels Alloys

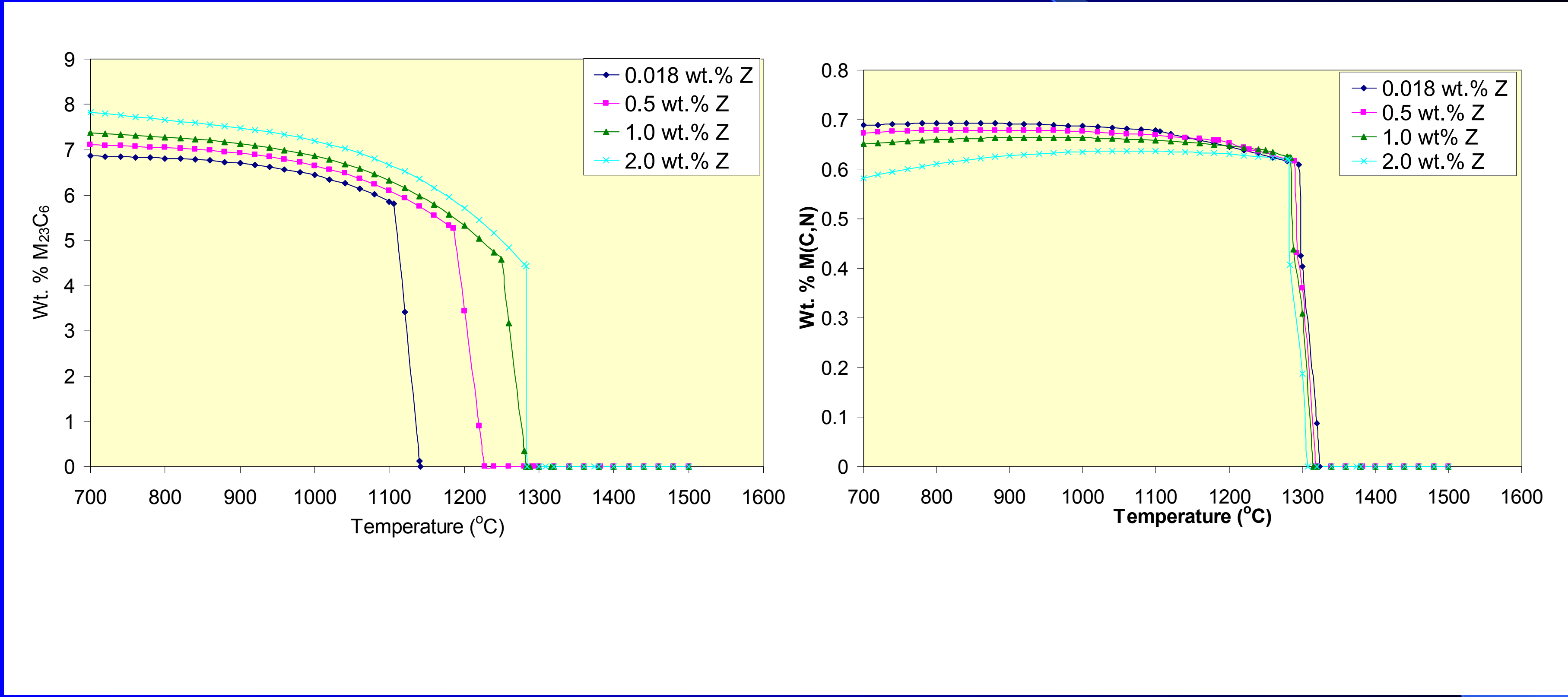
- Identified the carbide phases critically needed for optimum creep properties in the validation stage of the work
- Identified potential alloying element additions that coud stabilize the desired phases at temperatures of interest
- Thermodynamic calculations were used to obtain equilibrium phases present as a function of temperature and alloy compositions
- Alloy composition space was sampled to seek composition ranges that would stabilize desired phases and eliminate the formation of deleterious phases over a selected temperature range
- Accelerated development of new alloys was possible since only a few alloys had to be experimentally tested

Predicted Phase Equilibria in HP-11

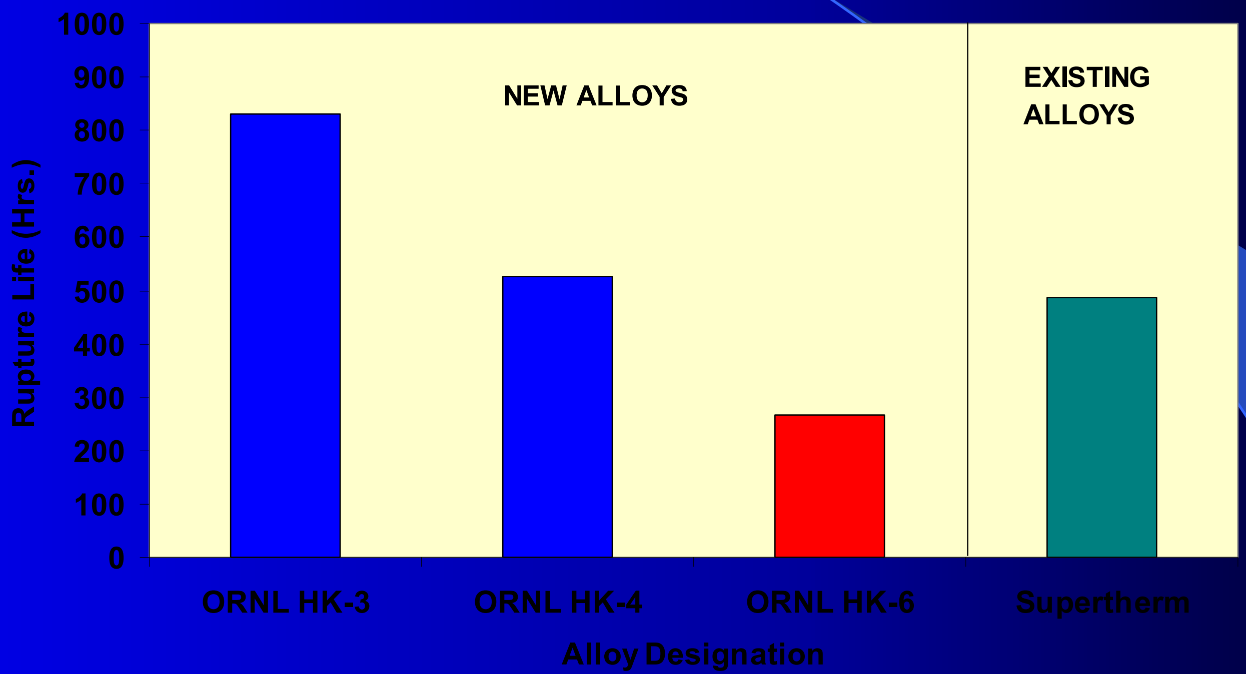


Base Alloy Composition: Fe-22.5Cr-33.5Ni-1.4Mn-0.9Si-0.4Nb

Effect of Additions of an Alloying Element on the Stability of $M_{23}C_6$ and MC



New HK-Type Alloys* Show Better Creep Life at 1204°C, 500 psi Compared to Supertherm™



New alloys have reduced Ni content and no Co resulting in lower costs

*G. Muralidharan, V. K. Sikka, P. J. Maziasz, and R. I. Pankiw, U.S. Patent Application in Process

Methodology For Developing Alternate Steels

- A multi-faceted approach will be used to identify steels with potentially improved properties
  - Novel steels developed at ORNL with high strengths will be tested for their hydrogen embrittlement characteristics
  - Trends in composition-microstructure-hydrogen embrittlement relationships and prior knowledge of the effect of alloying elements will be used to explore composition space for desired microstructures using thermodynamic-kinetic modeling
    - Need to know "good" and "bad" microstructures
  - Fundamental understanding of the role of carbide-ferrite matrix interface developed in parallel work at U of I will also be used to guide the selection of alloying elements

Task 3: Develop Coatings to Minimize Dissolution and Penetration of Hydrogen

- One way to reduce the effect of hydrogen on mechanical property degradation is to minimize the amount of hydrogen that could dissolve in the steel

- Use of direct external barriers with low solubility for hydrogen and with low hydrogen diffusivity (low hydrogen permeability) will
  - minimize direct contact of the steel surface with hydrogen
  - reduce the amount of hydrogen that will be available to dissolve in the steel substrate by diffusion through the barrier layer
  - Reduce the catalytic adsorption of hydrogen

- Previous studies have shown that surface barrier coatings (both metallic and non-metallic) including stainless steel liner materials are effective in reducing hydrogen embrittlement due to an external source of hydrogen
  - 50 nm thick sputtered Al_2O_3, Si_3N_4, and TiO_2 are known to be effective

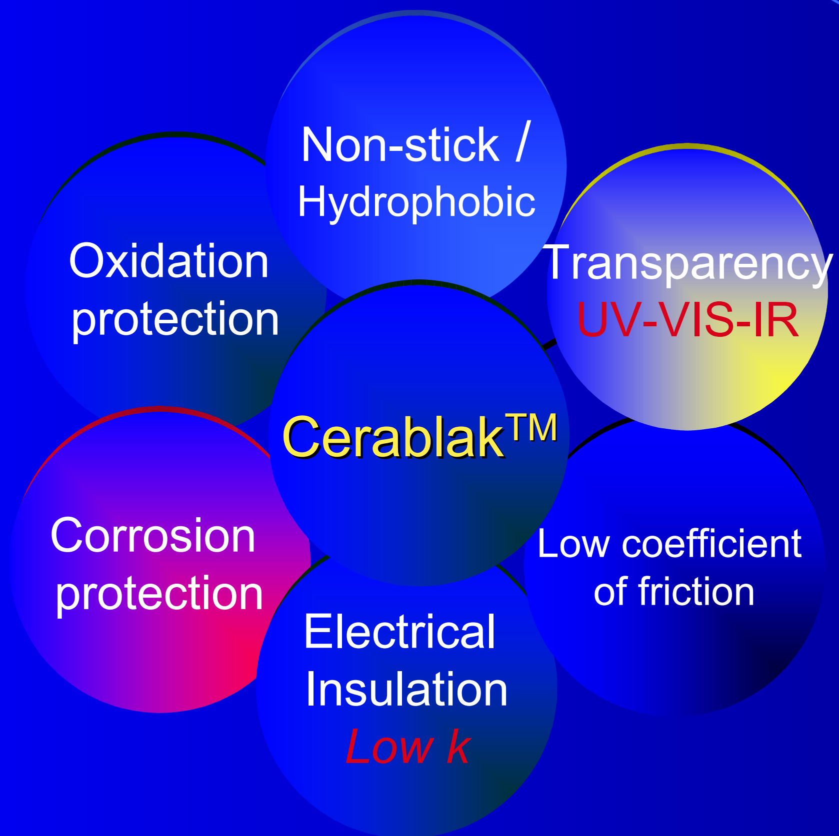
- This study will optimize compositions and processes to deposit three kinds of coatings: Cerablak™ from ATFI (oxides), rare earth oxide coatings from C^3, and glass coatings from Schott North America

Characteristics of Cerablak^{TM} Coatings

- Cerablak^{TM} is a multifunctional thin glassy film based on an aluminum phosphate composition
- Essentially "Dip and Cure Films": The coatings are produced *in-situ* from a nanoscale-designed, clear, and stable organic-based (VOC-free) precursor solution
- Cerablak™ has been coated onto a wide variety of substrates, including stainless and mild steel, glass and aluminum
- Doping with other oxides are possible
- US Patents: 6,036,762 & 6,461,415

"One of the top ten new advanced materials in the market"
Frost & Sullivan (2003)

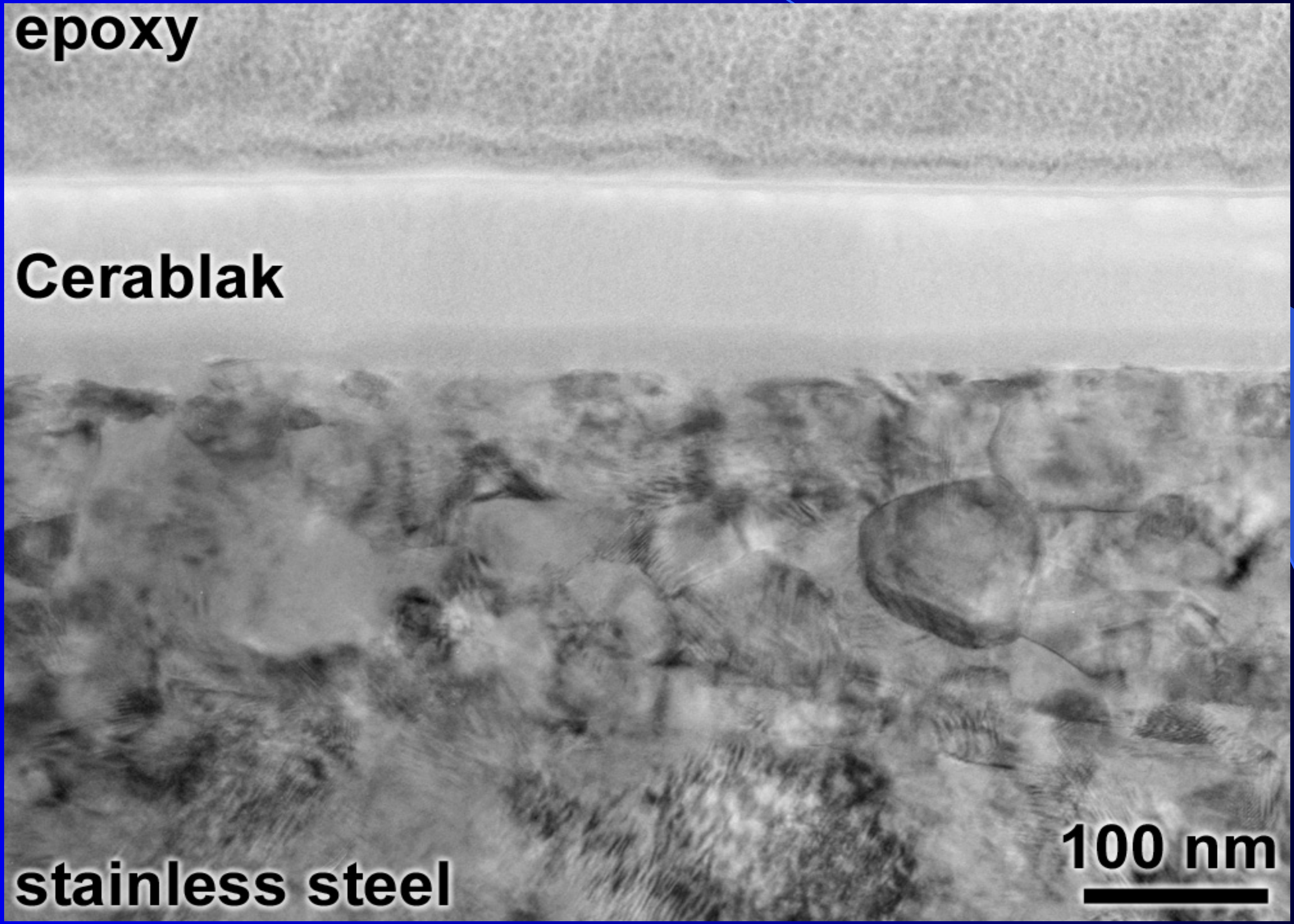
Processing, Properties, and Functionality



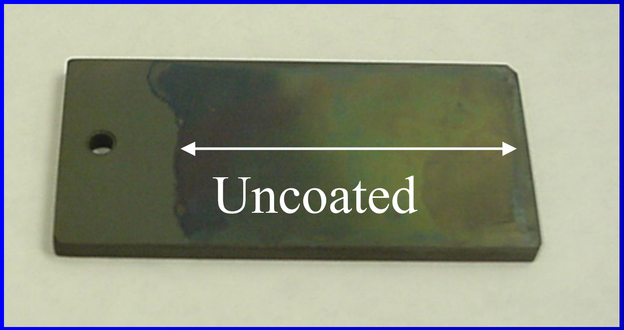
- Dip/Spray/Brush/Flow
- Brief cure @ 300-500°C, air (portable)
- Curable using heat gun or IR
- One liter of precursor provides up to 1000 Sq. ft. coverage
- Excellent adhesion
- Hermetic, pin-hole free
- Thin, flexible, hard, scratch-resistant
- Thermal cycling/ design tolerance
- Field repair possible

Low-Cost, easy-to-use, multifunctional ➤ ***"Unlimited Possibilities"***

Cerablak™ Nano Films

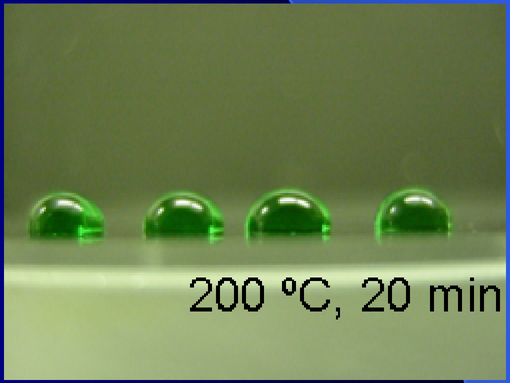


Examples of Coating Performance



Stainless steel coupon partially coated and annealed to 800°C for 3h

Stainless steel foils exposed to 800°C for 4h

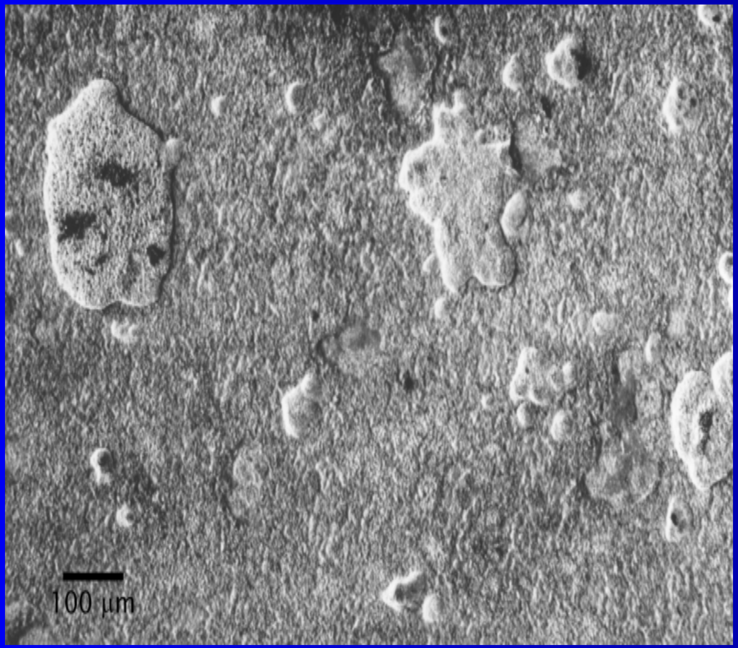


Contact Angle >90°

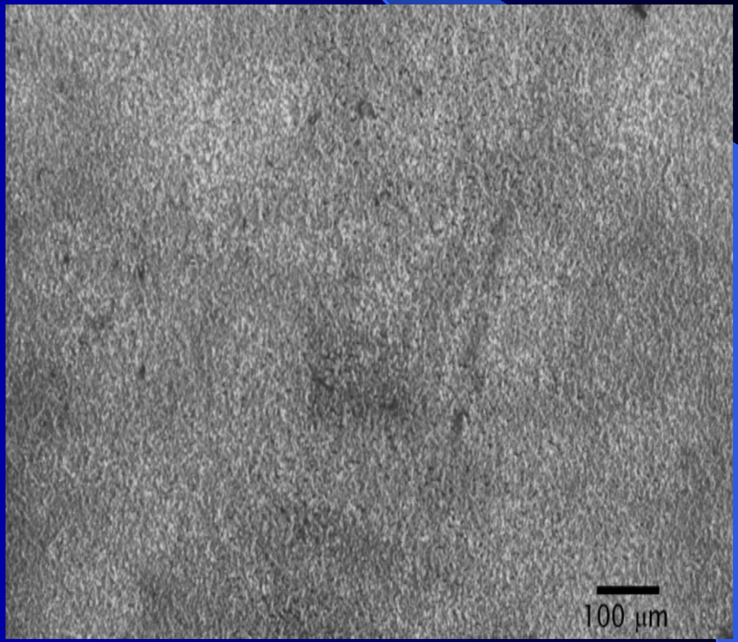
Improved Oxidation Resistance in Cerblak^{TM} - coated Stainless Steels

SEM micrographs of 304 steel annealed at 1000°C, 10 h

Uncoated



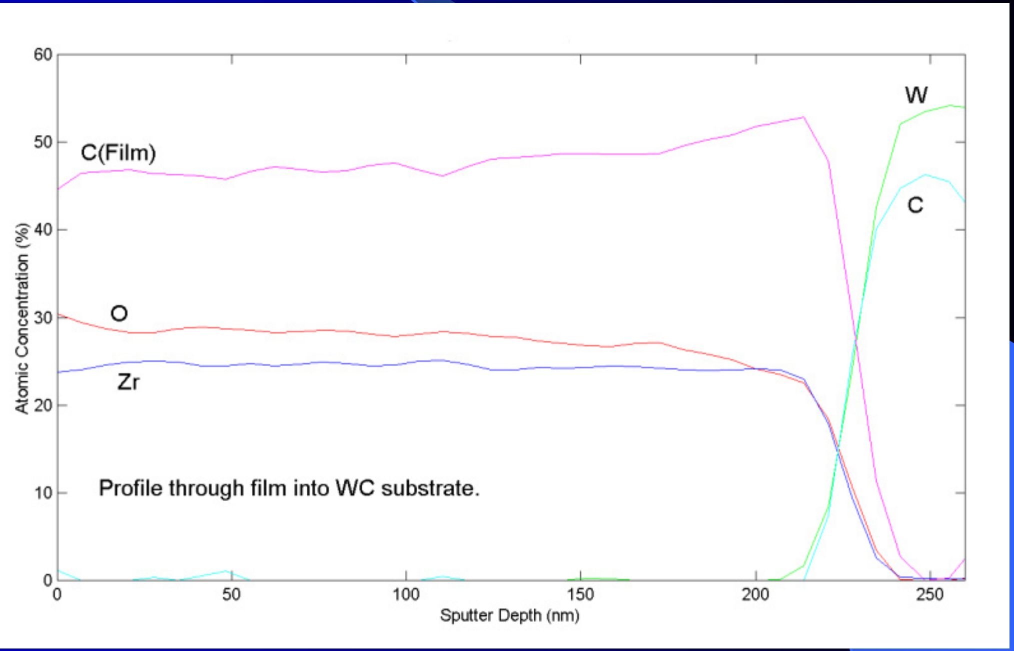
Coated



Coatings are an excellent barrier to oxygen penetration

Rare Earth Oxide Coatings from C^3

- Proprietary coatings consisting of many rare earth oxides have been developed by Chemical Composite Coatings International (C^3)
- Coatings are applied through a liquid precursor solution
- Curing below 450°C is sufficient
- Coating thicknesses is ~ 200-225 nm



Glassy Coatings

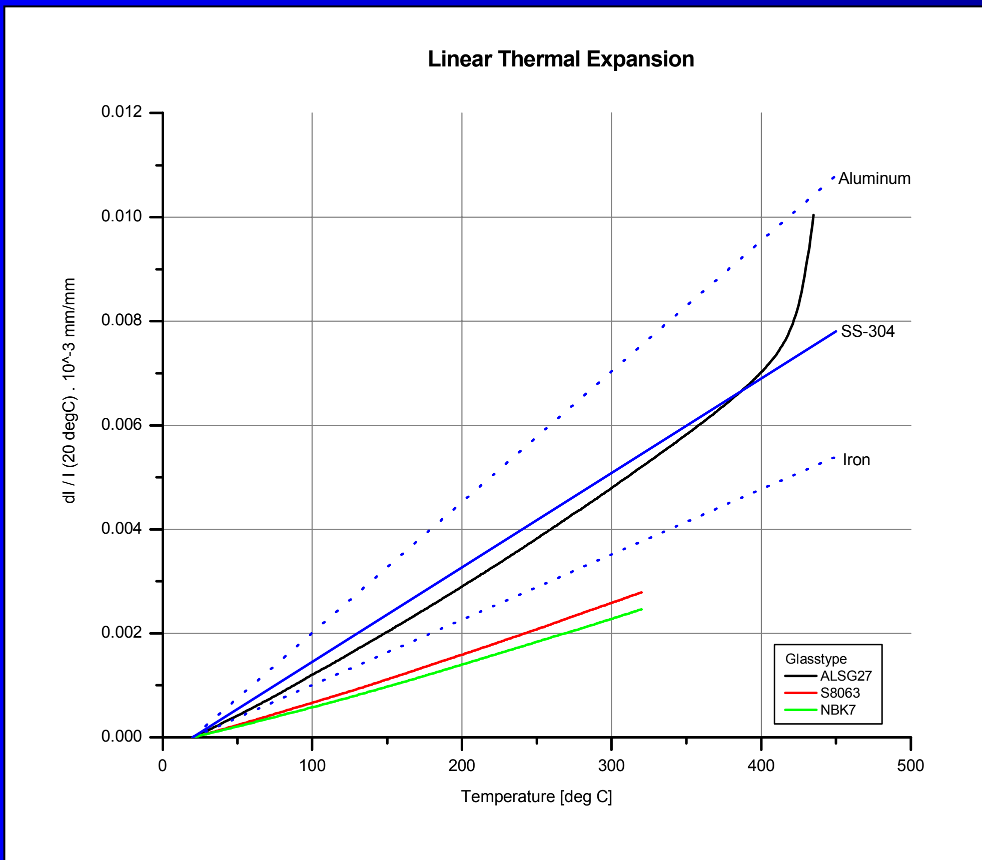
- Certain glasses and glass ceramics used as hermetic seals for vacuum applications and electronic packaging exhibit a comparatively low permeation rate for gases like helium or hydrogen over a wide temperature range

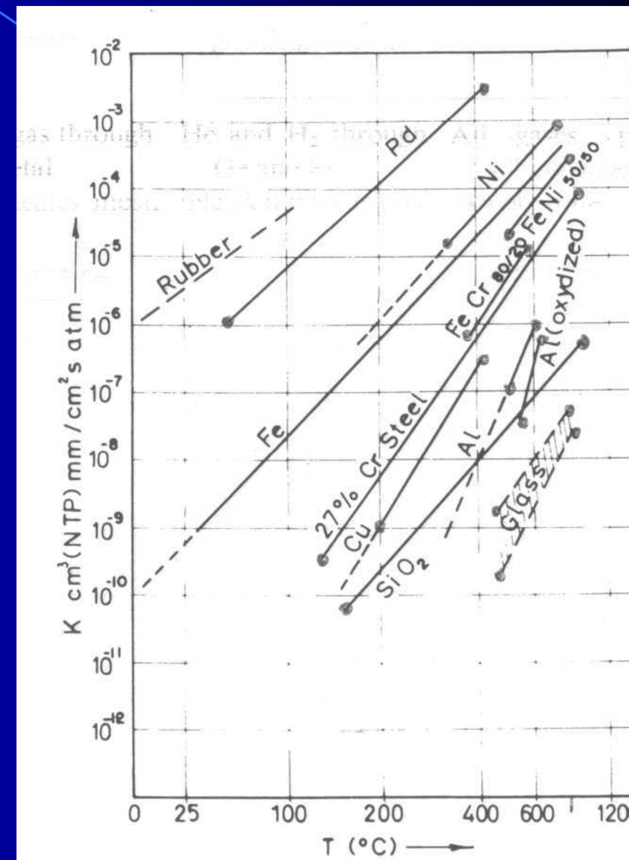
- These glasses can be designed to possess
  – a low melting point,
  – low hydrogen permeability,
  – increased durability,
  – a coefficient of thermal expansion that matches well with that of the substrate

- Recently a proprietary process consisting of easy application and curing has been developed to apply expansion-matched, thin, glassy coatings to a variety of steels

- Six glass families will be considered and one family will be down-selected and optimized in this study: lead borates, sodium borosilicates, iron phosphates, phosphate sealing glasses, fluorophosphates, and high durability ultra-phosphates.

Linear Thermal Expansion* and Hydrogen Permeation Properties** of Selected Materials





*SCHOTT Proprietary data

**Roth, A, "Vacuum Technology", North Holland Publishing Company, Amsterdam, New York, Oxford, 1982

Results of First Coating Experiments ("Proof-of-Concept")

- Steel coupons were coated with a variety of glasses previously developed for metal-to-metal seals
- Preliminary Results
  - Thin, bubble- and crack-free coating possible at processing temperatures below 600°C
  - Thermal cycling of coated steel in ambient atmosphere upto 400°C has no visible effect
  - No visible attack of the steel substrate
  - Coating can be removed by sandblasting
  - Several application methods viable, including "dip-coating" and "spray-on-coating"

Characterization and Optimization of Coating Compositions

- Structural and chemical characterization will be performed on all coatings as necessary
- Hydrogen permeation properties of the coatings will be measured at high hydrogen pressures and compositions with the lowest hydrogen permeation rates will be selected for further optimization whenever possible
- In the case of glassy coatings, CTE, density, Tg, refractive index, stability of material against devitrification will all be measured and coatings optimized for a combination of properties
- Two of the compositions with the best performance will be down-selected for further testing and optimization

Task 4: Evaluate the Hydrogen Embrittlement in Alloys Coated with Selected Coatings

- Down-selected coatings will be deposited on steel substrates and pipes
- Short-term effect of coatings on hydrogen embrittlement will be evaluated using tensile tests
- Long-term barrier properties and effectiveness in minimizing hydrogen embrittlement will also be characterized using mechanical tests and ABI tests on pipes
- Microstructural characterization will be carried out to study the effect of the coatings on failure mechanisms

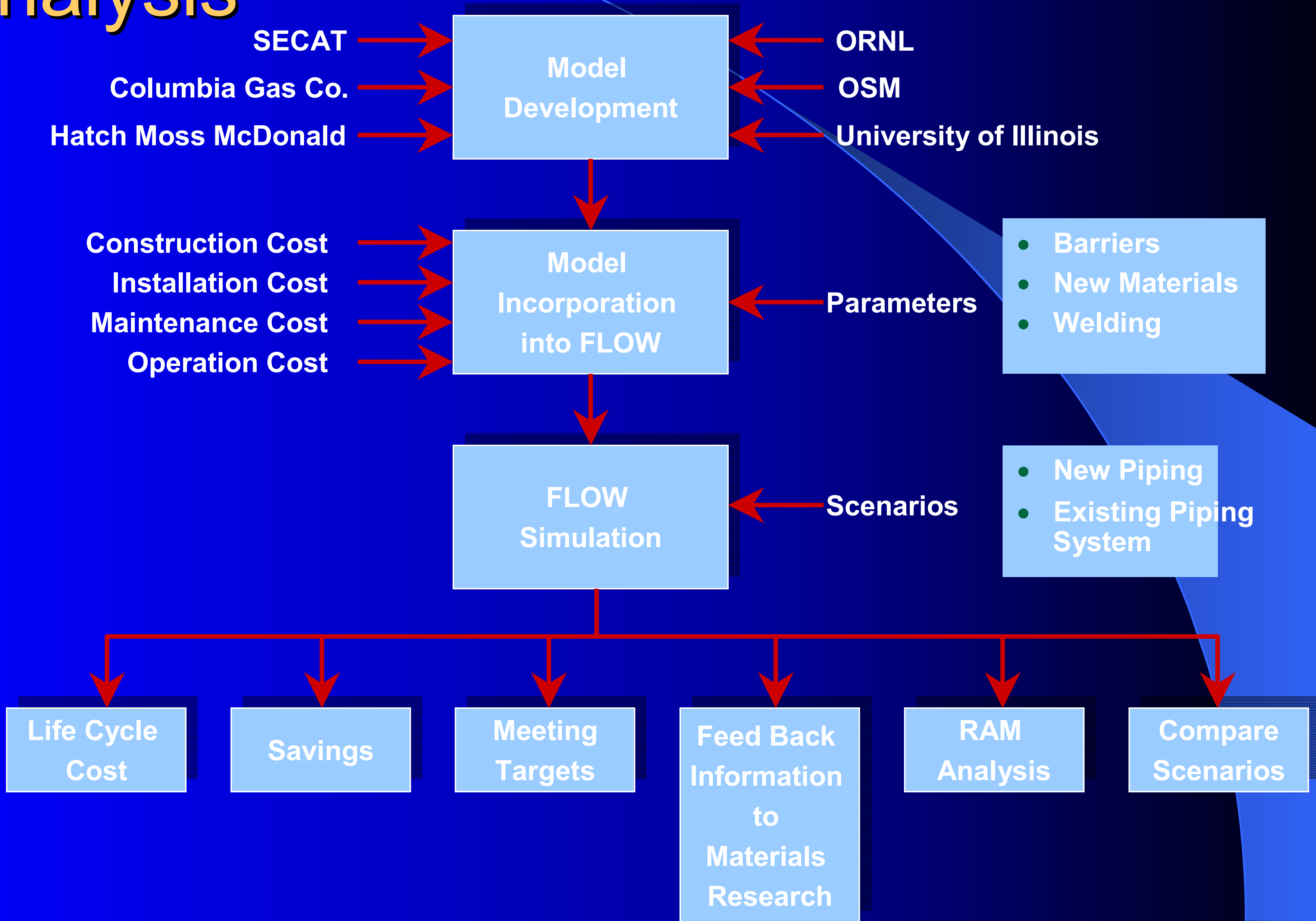
Task 5: Financial Analysis and Technology Implementation

- Cost is an important factor in the construction and maintenance of pipelines
- There is a drive to reduce the capital costs of hydrogen trunk pipelines from $ 1.4 Million/mile in 2003 to $ 1.2 Million/mile in 2005 (14.2% reduction), and $ 600K/mile in 2010 (57% reduction)
- The cost of a typical pipeline installation includes that of materials, construction costs, inspection, engineering survey, right of way permits, and overhead costs of which some may not be reduced significantly
- In addition to construction costs, lifetime of pipelines, costs of routine maintenance will all need to be considered in the total cost of ownership of the pipeline
- As part of this project, we will analyze the various cost components of pipeline construction and maintenance, analyze potential savings that could be feasible, and methods to achieve cost reductions

Methodology for Financial Analyses

- First step in the analysis will be the development of a model (function) that describes the total cost
  - The cost function could include piping installation, piping maintenance, and operation costs and could also incorporate reliability factors
- The model for the costs will then be incorporated into an ORNL-developed software FLOW
- Using the FLOW software various scenarios can be analyzed and the sensitivities to various parameters can be evaluated
- Potential avenues feasible for achieving cost savings can be derived
- Cost functions can be updated as new information on developed technologies become available and the scenarios can be reevaluated

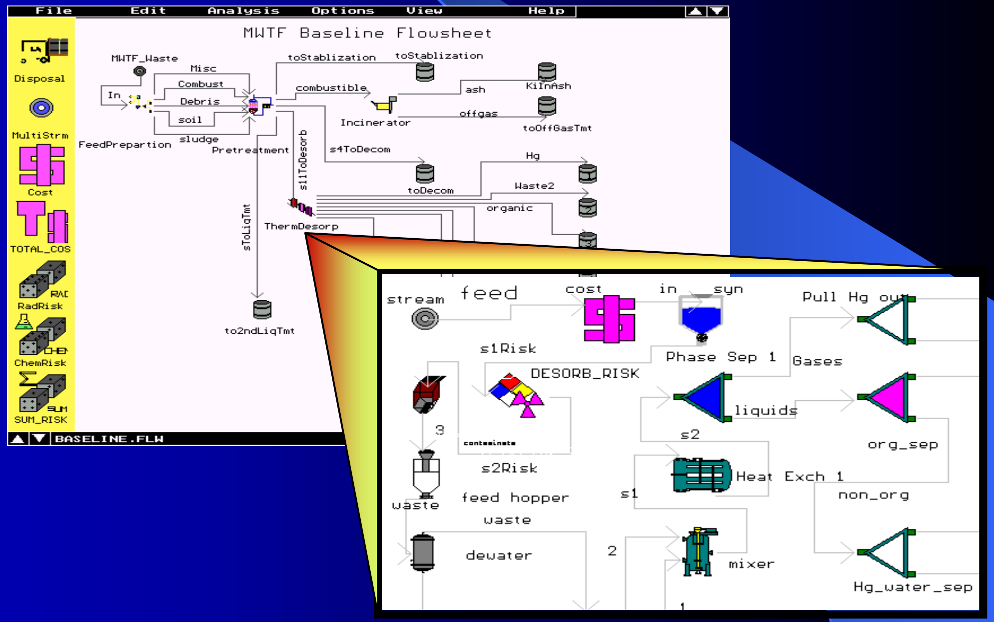
Schematic Showing Steps in Financial Analysis



Features of Flow Software

- **Fast Model Prototyping**
- **Sensitivity Analysis**
- **Uncertainty Analysis**
- **Graphic Interface**
- **Collapsing of Complicated Flowsheets into single objects**
- **Control Objects for Feed Back Information**
  - Used for Optimization by varying input values

Example of Nesting Flowsheets Into a Single Object



One single process icon can represent a complete flowsheet, thus simplifying representation of complicated flowsheet systems.

A Preliminary Assessment of Potential Sources of Cost Reduction

Item	Opportunity for Cost Reduction
Materials	➢ Ability to use higher strength material without problems related to hydrogen embrittlement will result in use of thinner pipes ➢ Cost reduction possible based due to use of coatings on new materials that would minimize hydrogen penetration in substrate and weldment regions
Pipeline Construction (digging, welding, installing, testing, restoring)	➢ Use of materials that may not require a lower number of fabrication steps will reduce cost of construction
Inspection	➢ Reduction in inspection costs possible if better reproducibility and hence better control can be achieved in joining through automation and better predict

Technology Implementation

- Technology transfer
  - New alloys developed will be made available through arrangement with our industrial partner Oregon Steel Mills
  - Proprietary technologies will be made available by the individual companies

- Incorporation into codes and standards
  - A technical review committee will be formed under the ASME Codes and Standards Technology Institute (CSTI) from ASME's established network of volunteers, as well as from other interested and qualified experts
  - Experts within our Council on Codes and Standards from the B31 Code for Pressure Piping Standards Committee and its section committees with applications in hydrogen infrastructure will be involved
  - Findings from this study will be incorporated into the appropriate standards

Breakdown of Major Activities by Year

YEAR 1

- Evaluation and down-selection of alloys for further study
- Development of coatings and processes
- Initial evaluation of pipeline costs and development of cost models

YEAR 2

- Modeling and microstructural characterization of alloys
- Evaluation of mechanical properties of uncoated alloys in high H_2 pressures
- Characterization of structure and chemistry of coatings
- Down-selection of best coatings and coating of alloys
- Evaluation of costs of new technologies

YEAR 3

- Microstructural characterization of alloys
- Evaluation of mechanical properties of coated alloys in high H_2 pressures
- Optimization of structure, chemistry of coatings and coating processes
- Incorporation of cost of new technologies into pipeline models
- Incorporation of findings into ASME codes and standards

Major Milestones

- Year 1:
  - Down-select compositions of commercial and ORNL alloys for further study
  - Evaluate the components of current pipeline construction and identify potential avenues of savings
- Year 2:
  - Develop coating compositions and processes, and characterize coatings
  - Complete thermodynamic modeling, and microstructural characterization of down-selected alloys
  - Complete mechanical testing of uncoated, down-selected alloys and weldments in high-pressure hydrogen (short-term testing)
- Year 3:
  - Complete mechanical testing of coated alloys and weldments in high-pressure hydrogen
  - Complete long-term testing of coated and uncoated pipelines
  - Evaluate impact of new technologies on pipeline costs
  - Incorporate findings on pipeline construction into ASME codes