Materials Solutions for Hydrogen Delivery in Pipelines

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This presentation does not contain any proprietary or confidential information

Project ID # PD35

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Overview

Timeline

- Project start date: 05/2005 (Tentative)
- Project end date: 04/2008
- Percent complete: 0%

Budget

- Total project funding
  - $1650K
  - $1110K (contractor share)
- Funding received in FY04: None
- Funding for FY05:

  Requested: $550K

  Projected: $200K

Barriers and Targets

Barriers addressed

D. High capital cost and Hydrogen Embrittlement of Pipelines

Technical Targets (2015):

– Capital cost ($0.8 Million/Mile)

– Cost of delivery of hydrogen <$1.00/gge

– High Reliability of operation with metrics to be determined

Partners

- Advanced Technology Corporation
- Applied Thin Films
- ASME Standards and Technologies, LLC
- Chemical Composite Coatings Intl
- Columbia Gas
- Hatch Moss MacDonald
- Oak Ridge National Laboratory
- Oregon Steel Mills
- Schott North America
- University of Illinois

Objectives

- Overall 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 overall objectives of the project are:
  - To identify steel compositions and associated welding filler wires and processes that would be suitable for construction of new pipeline infrastructure
  - To develop barrier coatings for minimizing hydrogen permeation in pipelines and to develop *in-situ* deposition processes suitable for these coatings
  - 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

- Objectives of the current year are:
  - To study the embrittlement of existing pipeline steels when exposed to H_2 at high pressures
  - To develop initial coating chemistries and processes to deposit barrier coatings for steels
  - To develop a baseline cost model for pipeline construction

Key Technical Barriers

- 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
- Only a limited understanding of the mechanisms of hydrogen embrittlement along with the effect of metallurgical variables such as alloying element additions, and microstructure of steels is available at the present time; hence the path to remediation and control is not well defined
- 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

Approach

Our approach consists of the following major tasks:

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 analyses and incorporate knowledge into codes and standards

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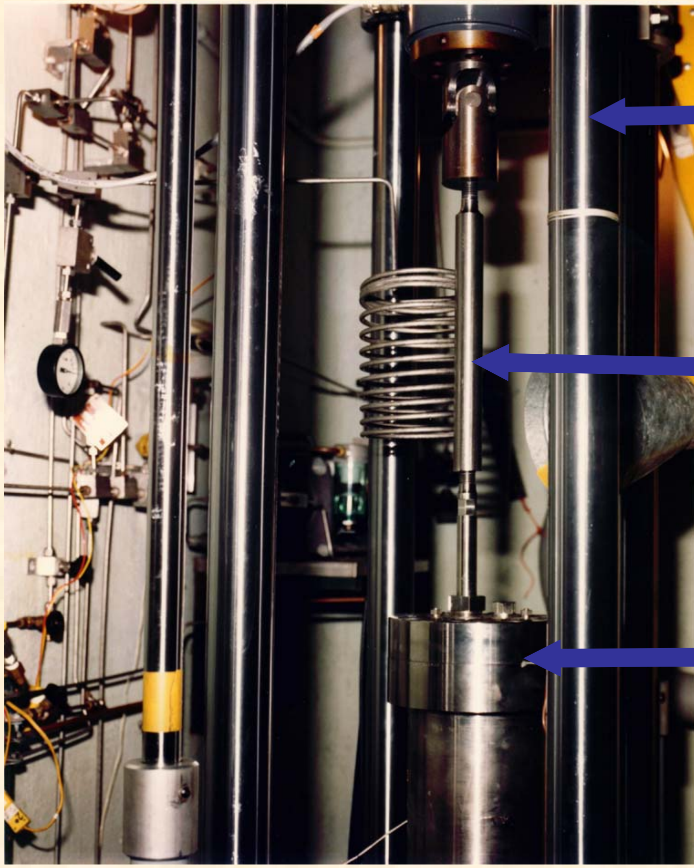
Details of Approach- Task 1

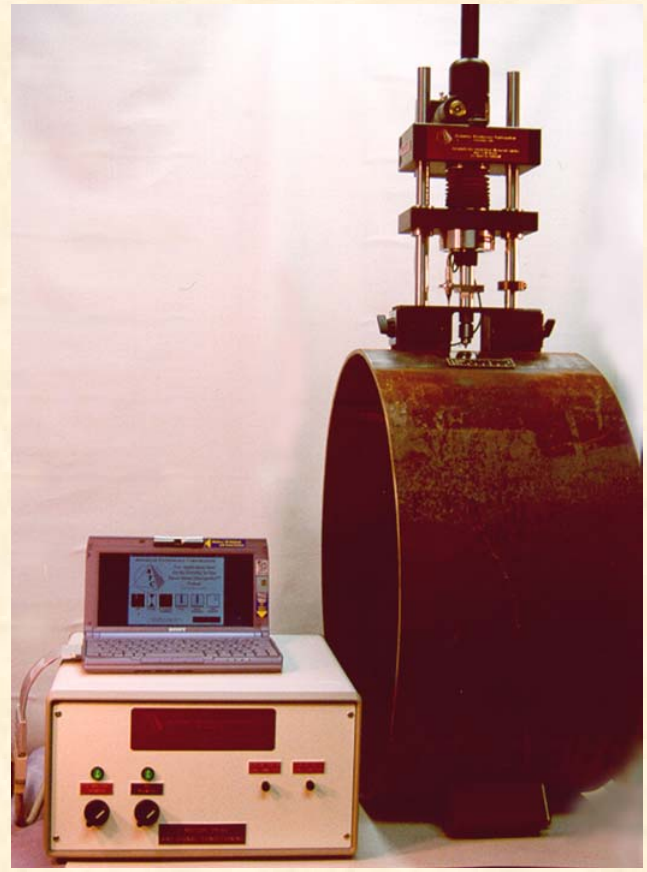
Task 1: Evaluate hydrogen embrittlement characteristics of existing commercial pipeline steels under high-pressure hydrogen

- Very little data is available on the effect of high pressure hydrogen on the mechanical properties and hydrogen embrittlement of pipeline steels
- Typical pipeline steel compositions will be down-selected
- Mechanical properties of these steels will be measured *in-situ* in high pressures of H_2 (up to 5000 psi) as a function of metallurgical variables such as heat treatments, grain size, and processing such as welding
- Automated Ball Indentation (ABI) test, a novel test method which can be used to characterize local mechanical properties, will be used to characterize the effect of long-term exposure to high pressure hydrogen on properties of fabricated pipes with and without weld joints
- Failed specimens will be characterized to understand the failure mode and compare with existing knowledge of failure modes
- Thermodynamic and kinetic modeling will be combined with microstructural characterization to understand the relationship between hydrogen embrittlement, alloy composition, and microstructure
- Best compositions will be down-selected for further work with barrier coatings

Systems for Mechanical Testing



System that will be reassembled at ORNL for mechanical testing at hydrogen pressures upto 5000 psi



In-situ testing of pipes is feasible with ATC's Automated Ball Indentation Testing System (ABI), SSM-M1000

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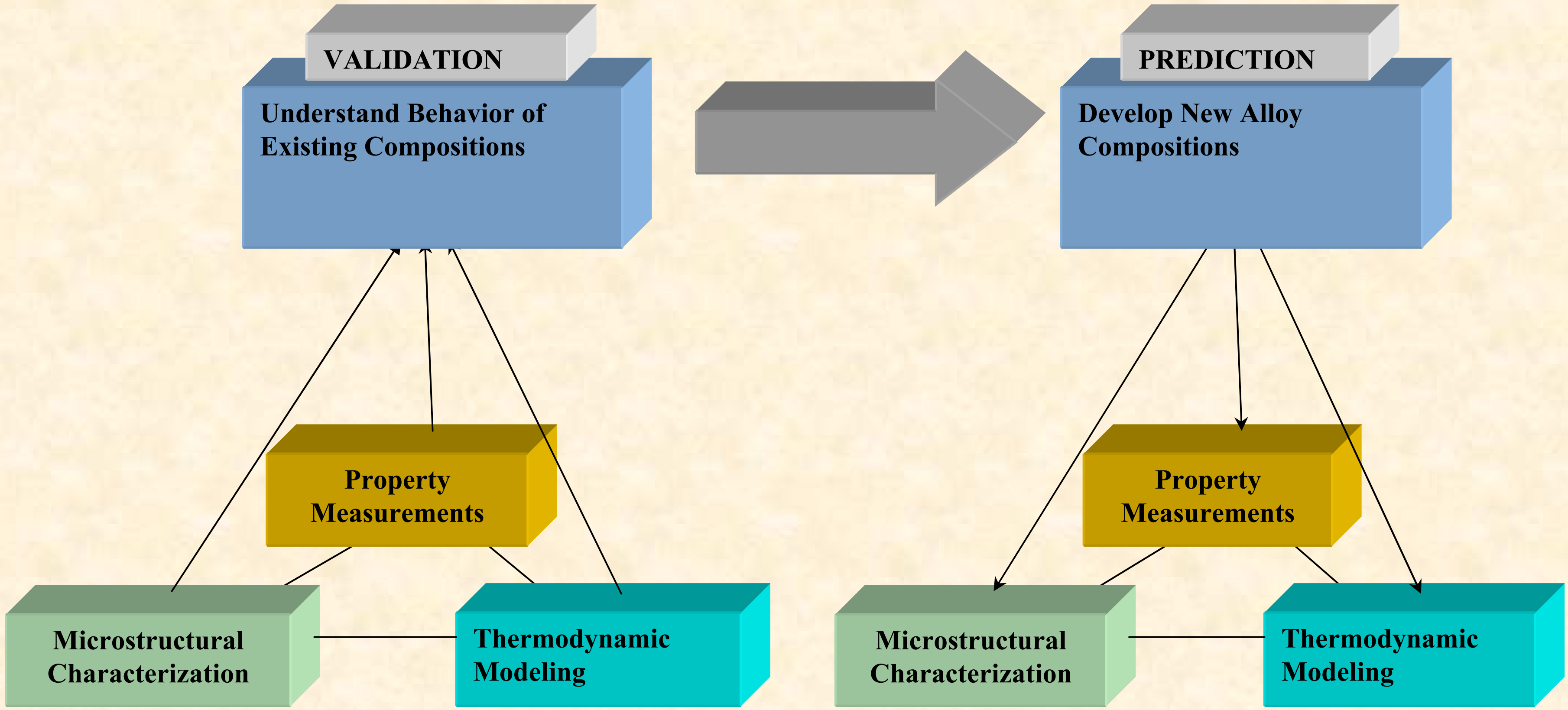
Details of Approach-Task 2

Task 2: Develop and/or identify alternate alloys and evaluate hydrogen embrittlement:

- Certain microstructures in steels are known to be more resistant to hydrogen embrittlement (for example, quenched and tempered martensite is preferred over untempered bainite or untempered martensite)
- Literature also shows that certain alloying element additions would be beneficial for hydrogen embrittlement resistance while others would be detrimental
- Trends in composition-microstructure-hydrogen embrittlement relationships will be developed using previously available data and from Task 1
- Modeling studies performed at the University of Illinois will also aid in the development of this relationship
- Computational thermodynamic and kinetic modeling techniques will be used to search composition space for desired microstructures
- New alloy compositions will be identified and small heats of alloys will be prepared
- Hydrogen embrittlement in these alloys will be evaluated using rapid screening tests and high pressure testing
- Based on results of mechanical tests, refinement of steel compositions will be carried out and one best composition will be down-selected
- A similar approach has been successfully used at ORNL in designing new alloys for high temperature applications

A Generalized Scheme for the Rapid Development of New Alloys



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Details of Approach-Task 3

- **Task 3: Develop coatings to minimize dissolution and penetration of hydrogen**
  - Laboratory 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
  - This work will evaluate the effectiveness of coatings from three industrial partners: Cerablak™ from Advaced Thin Films (oxides), multi-component oxides with rare earths from C^3, and glass coatings from Schott North America
  - Coating chemistries and processes to deposit coatings on steel substrates (including techniques appropriate for *in-situ* deposition in the field) will be developed
  - Quality, integrity of coatings, adhesion to the substrate, microstructure of coatings and that of substrates, wear characteristics, and barrier properties of coatings will be characterized
  - Chemistries of coatings, and deposition processes will be modified to optimize required properties and two best coating compositions will be down-selected for Task 4

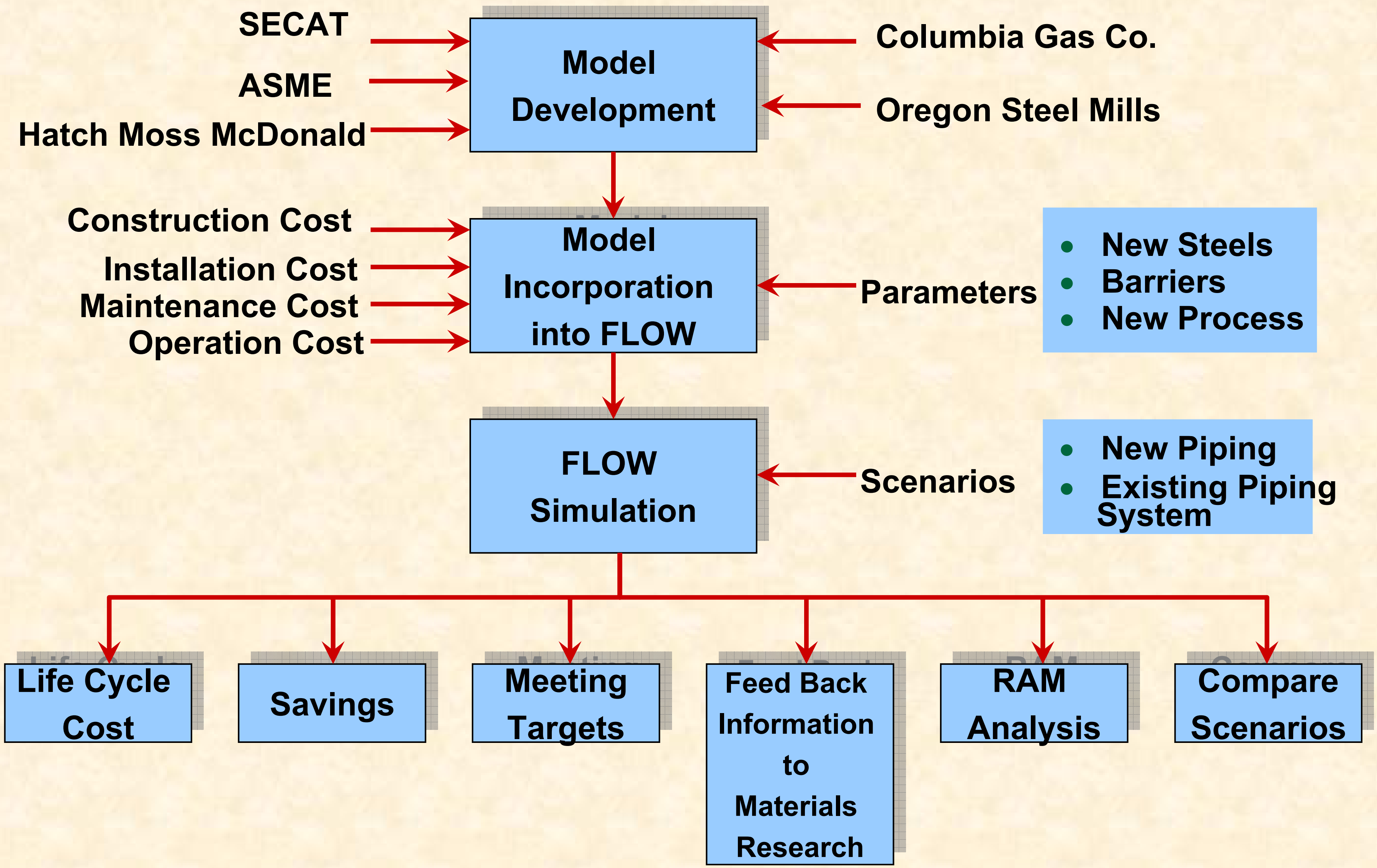
Details of Approach-Task 4

- **Task 4: Evaluate the hydrogen embrittlement in alloys coated with selected coatings**
  - Down-selected coatings will be deposited on selected steel substrates, pipes, and weld joints
  - Short-term effect of coatings on hydrogen embrittlement will be evaluated using *in-situ* mechanical testing in high pressure hydrogen
  - Long-term barrier properties and effectiveness of coatings in minimizing hydrogen embrittlement will also be characterized using Automated Ball Indentation tests on pipes, and welds
  - Microstructural characterization will be carried out to study the effect of coatings on failure mechanisms
  - Effect of procedures such as pigging on coating effectiveness will also be evaluated
  - Promising coating-substrate combinations will be identified for further development and cost analysis

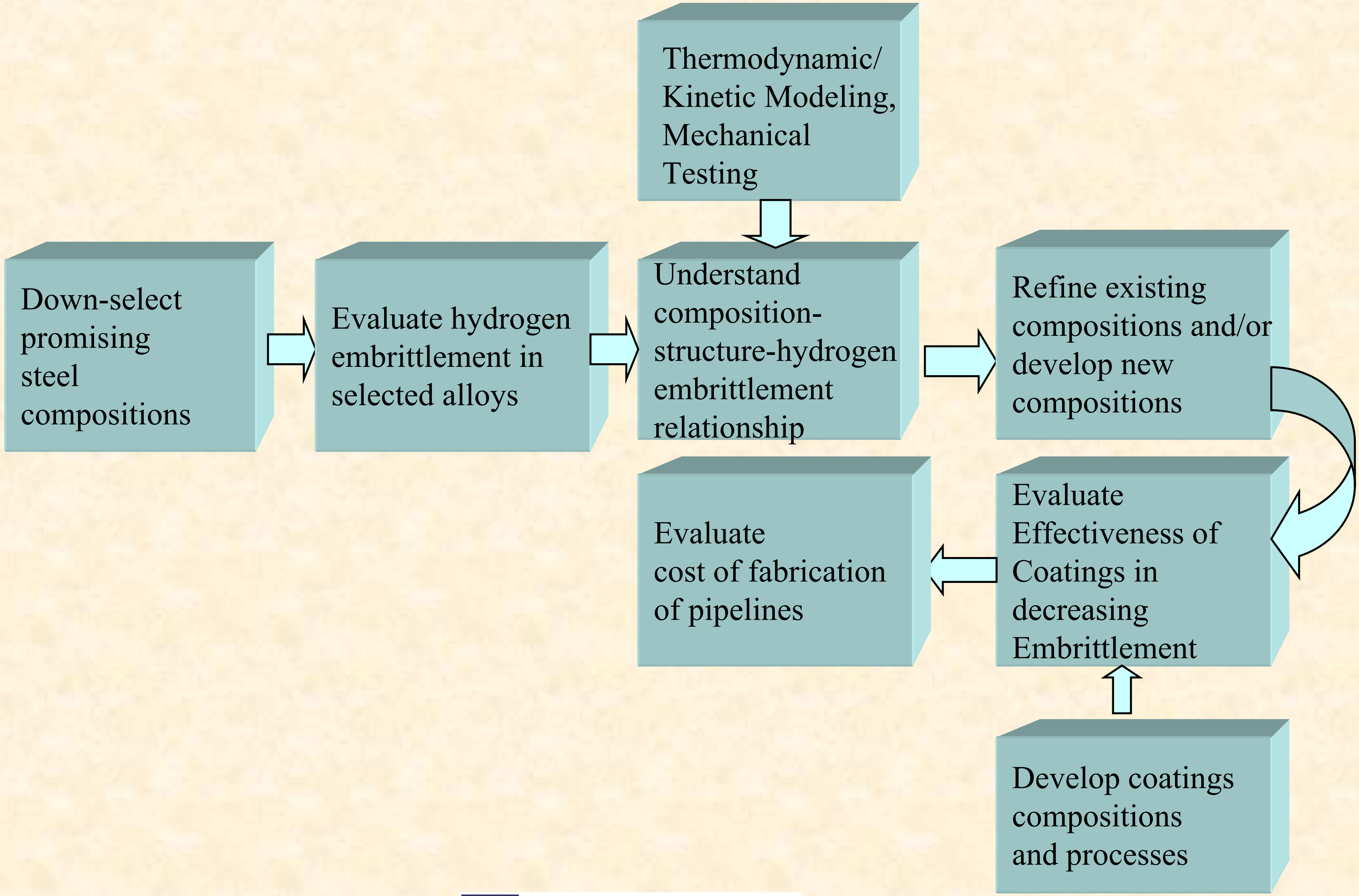
Details of Approach-Task 5

- **Task 5: Perform financial analyses and assist in the incorporation of knowledge into codes and standards**:
  - The cost of a typical pipeline installation includes many components such as that of materials, construction, inspection, engineering survey, right of way permits, and overhead costs; cost of ownership also includes the cost of maintenance over the lifetime of the pipeline
  - As part of this project, with the help of industrial partners and an ORNL developed financial analysis model-COST, we will analyze the current cost components of pipeline construction and maintenance, analyze potential savings that could be feasible, and methods to achieve cost reductions
  - Cost analysis will be updated as the additional cost of newly developed technologies become available and the different possible scenarios for reduction in costs of construction and maintenance will be reevaluated
  - Work will be coordinated with the H2A analysis being carried out as part of the DOE hydrogen program
  - The results of this analysis will be used to re-focus the project if and as appropriate vs. the goal, objectives, and targets for the DOE hydrogen Delivery Multi-Year R&D Plan

Steps in Financial Analysis



Schematic of Overall Approach



Roles of Project Partners

IMPROVED MATERIALS TO ENABLE HIGH-PRESSURE DELIVERY OF HYDROGEN

U. S. Pipeline Company

Oregon Steel Mills

Pipeline lifetime prediction model

University of Illinois

Financial Analysis, Codes and Standards

- Financial analysis: "FLOW" (SECAT, ORNL)
- Codes and Standards (ASME Standards and Technologies)
- Implementation (SECAT, Columbia Gas)

Coatings Development

- Cerablak™: ATFI
- Rare earth oxide:C3
- Glass Coatings: SCHOTT NA

Materials Characterization

- Mechanical testing in high-pressure H_2 (ORNL)
- Automated Ball Indentation (ORNL & ATC)
- Microstructural studies (SECAT,
- ORNL)

Alloy and Weld Filler Development

- Thermodynamic and kinetic modeling
- Experimental alloy preparation (ORNL)

Fundamental Studies- University of Illinois

University Project: Hydrogen Embrittlement of Pipeline Steels: Causes and Remediation

- H_2 embrittlement and failure mechanisms
- Microstructure effect on hydrogen embrittlement
- First principles study of alloying element additions
- Surface chemistry and physics

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Technical Accomplishments/ Progress/Results

- Project Kick-off meeting conducted March 15-16 at Lexington, KY
  - Near-term activities were outlined
  - Internal milestones for individual project team-members were defined
  - Contract details and agreement for intellectual properties were discussed

Future Work-FY2005

Remainder of FY 2005 (subject to availability of funding)

- **Steels**
  - Survey compositions of pipeline steels and other steel compositions for applicability in pipeline construction
  - Identify a screening test to rapidly evaluate hydrogen embrittlement characteristics of steels of interest
  - With the use of screening tests and industrial input, down-select four steel compositions for further detailed study of hydrogen embrittlement characteristics under high pressure H_2 (FY 2005 milestone)
  - Initiate microstructural characterization, thermodynamic, and kinetic modeling
  - Initiate permeability testing of selected steel compositions in high pressure hydrogen atmosphere
  - Start assembly of equipment for *in-situ* mechanical testing of materials under high hydrogen pressures along with setting up associated safety measures and controls at ORNL
  - Prepare preliminary design of chamber to perform *in-situ* mechanical testing in high pressure hydrogen using Automated Ball Indentation (ABI)

Future Work –FY2005 (cont'd)

- **Remainder of FY 2005 (subject to availability of funding)**
- **Coatings**:
  - Identify processing needs for deposition of coatings on steel substrates (temperature and time of curing, wetting characteristics etc) and deposit coatings
  - Characterize coatings with particular reference to their adhesion with the substrate, integrity (free from pinholes, cracks etc), and the substrate for structural changes due to the deposition process

- **Financial Analysis**:
  - Obtain from industrial partners, data on the magnitude of the individual components of costs related to pipeline construction and maintenance
  - Develop a preliminary model for the pipeline cost function using FLOW for evaluating sensitivity, and uncertainty
  - Coordinate information collection and model development with the H2A effort

Future work –FY 2006

- **FY2006 (subject to level and availability of funding)**:
- **Steels**
  - Complete assembly of equipment for *in-situ* mechanical testing of materials in high hydrogen pressures along with setting up associated safety measures and controls at ORNL
  - Complete fabrication and installation of chamber to perform *in-situ* mechanical testing using Automated Ball Indentation (ABI) at ATC
  - Complete measurement of mechanical properties and hydrogen embrittlement characteristics of down-selected steels using traditional mechanical testing and ABI tests
  - Complete thermodynamic, and kinetic modeling of initial down-selected steel compositions
  - Complete microstructural characterization of down-selected steels before and after exposure to hydrogen to understand the effect of microstructure on embrittlement

Future Work-FY 2006 (Cont'd)

- **Coatings:**
  – Barrier properties of the coatings will be characterized using permeability testing
  – Coating compositions and/or depositions processes will be modified based on the results of physical, mechanical, and barrier property testing
  – Coatings with new compositions will be deposited and tested

- **Financial Analysis**:
  – Finalize cost model for steel pipelines
  – Analyze various scenarios using FLOW software and evaluate sensitivities to various parameters in the cost function
  – Derive potential avenues for achieving cost savings from the analyses of various scenarios
  – Identify research priorities based on analyses of potential cost savings
  – Update cost functions as new information on developed technologies become available and reevaluate scenarios

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

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Publications and Presentations

None at the present time

Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

FLAMMABILITY/EXPLOSIVITY

- Hydrogen has a very wide range of flammability/explosivity and hence is a hazard to people and equipment
- Special precautions shall be taken to prevent hydrogen/oxygen mixtures in this range

Hydrogen Safety

Our approach to deal with this hazard is: Take steps to prevent the presence of a flammable mixture of hydrogen and air/oxygen during operation AND startup/shutdown

- Safe system startup will involve initial purging, then introduction of hydrogen into the fully inert system
- Safe shutdown requires removal of hydrogen from the system by an inert gas purge (for both normal shut down and emergency shut down)
- The system size will be minimized to reduce the available hazardous (hydrogen) energy
- System integrity will focus on ensuring no potential leakage of hydrogen from the system and no air into the system
- Safe system design at ORNL will be done by a team including an experienced engineer as well as a Certified Safety Professional and will be reviewed and approved by ORNL Fire Protection Engineers. Similar procedures will be followed at other partner's sites
- **Relevant Standards**: OSHA (29 CFR 1910.101, 102, 103, 104, 105, 253 and 29 CFR 1926.350, 352), DOT (49 CFR 106, 107, 110, 171-180, 397, Hazardous Materials), ASME B31.3, ASME BPVC (Sections I, II, IV, V, VI, VII, VIII, IX, and X), NFPA 45, NFPA 50A, NFPA 54, NFPA 55, NFPA 101, NFPA Pamphlet G-5-1991)