II.H.2 Hydrogen Permeability and Integrity of Hydrogen Transfer Pipelines (New Project)

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Objectives

- Quantify hydrogen permeability and embrittlement of pipeline steels and their welds under high-pressure hydrogen exposure.
- Optimize the base metal and weld metal composition and microstructure to avoid excessive hydrogen permeation and increase service performance of hydrogen pipelines.
- Evaluate the possibility of using existing steel and welding industry standards and technology to achieve high-performance high-pressure hydrogen pipelines.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
- F. Transport Storage Costs

Approach

Hydrogen production and supply methodologies are critically important for a hydrogen based transportation infrastructure. Transportation of hydrogen from reforming plants to dispensers includes transfer through high-pressure pipelines posing the following challenges. (1) The inner surfaces of tubes are exposed to pure hydrogen at high pressures, whereas outer surfaces are exposed to atmospheric pressure with low partial pressure of hydrogen. This will lead to a flux of hydrogen (permeation) through the steel. (2) If the underlying microstructures in base metal and welded regions are very hard, and if residual stresses are present, the welded joints may exhibit hydrogen-induced cracking after extended service time.

The proposed research will leverage an extensive knowledge base that is available on hydrogen embrittlement phenomena and microstructure development in steels. With this knowledge, innovative process-material combinations will be derived for high-strength steel piping for high-pressure hydrogen transport. The research tasks to be completed in this multi-year project will focus on (a) hydrogen management, (b) weld stress management, (c) interface barrier design and (d) evaluation of base metal and weld metal microstructure and properties.

Hydrogen Management: The first phase of the research will address hydrogen solubility in steel. Hydrogen diffuses into steel in monatomic form [see Figure 1]. On entering the steel, the hydrogen may be (1) trapped at discrete sites (e.g., inclusions and grain/phase boundaries) or (2) present in diffusible form in the interstitial positions within the ferrite lattice. Hydrogen assisted cracking is mostly caused by diffusible hydrogen. In this research hydrogen

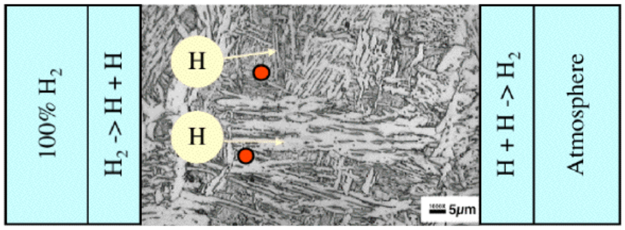

Figure 1. Schematic diagram illustrates the hydrogen transport from the interior of a steel pipe through the steel matrix and into the atmosphere. The hydrogen trapping sites (red circles) and microstructure (background image from a weld) need to be designed for welds with good integrity for hydrogen transport.

permeation through pipeline steel and weld material will be experimentally measured over different pressure ranges, and modeled mathematically. In addition, the microstructures and mechanical properties of these steels with and without hydrogen charging will be characterized.

Weld Stress Management: In the second phase of the project, attention will be focused on stresses that are present in the weld metal region. Recent in-situ transmission electron microscopy analyses have shown that diffusible hydrogen increases the velocity of dislocations, resulting in localized plasticity that ultimately leads to embrittlement. Thermal stress management in pipeline welds will be described using state-of-the-art thermo-mechanical-metallurgical models that consider the interactions between thermal fields, dynamic microstructure evolution, and the effects of temperature and microstructure on thermophysical and mechanical properties.

Interface Barrier Design: In the final phase of the work, attempts will be made to reduce the hydrogen concentration gradient by physically separating the steel and hydrogen-rich atmosphere. This approach is currently being used in oil pipelines to prevent the corrosion of the exterior surfaces of pipelines by coating them with epoxy resin. Similar approaches can be used to coat the interior of the pipelines to retard the permeation of hydrogen into the steel, thus reducing the concentration gradient and peak concentration. In addition, the effects of surface oxides on the hydrogen permeation through steel pipes will be considered.

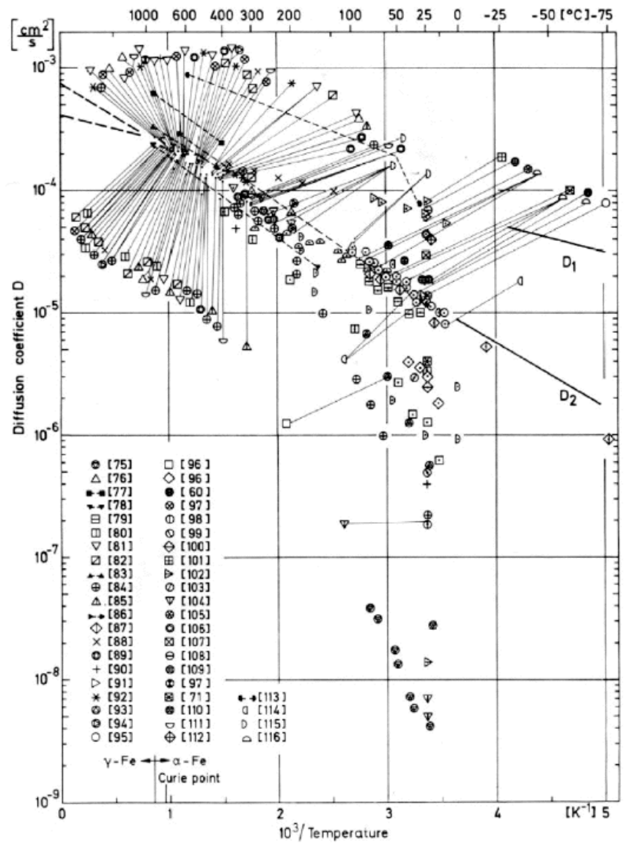

Figure 2. Variation of the measured diffusion coefficient with (1/Temperature) from literature sources showing a large variation in hydrogen diffusivity $1x10^{-9}$ to $1x10^{-4}$ cm^2s^{-1}) (25-100°C) in α-iron.

Evaluation of Welds and Base Material: The welds produced in this study will be compared with the performance of commercial line pipe steel. The evaluation will focus on microstructural characterization, hydrogen permeability, toughness (under both hydrogen charged and uncharged conditions in both heat-affected-zones and weld metal regions), and residual stress measurement.

Results

This research was initiated in March 2004. Since that time, an extensive literature review was performed on hydrogen permeation and embrittlement in pipeline steels. The review suggested large variations in hydrogen diffusivity ($1x10^{-9}$ to $1x10^{-4}$ cm^2s^{-1}) near room temperature, which could be related to steel composition, microstructure or surface conditions [see Figure 2].

Some preliminary work on Fe-C-Mn steel welds indicates the addition of aluminum to steel may reduce hydrogen permeability. The reasons for this are unknown. To confirm these observations and also to study the effects of composition and microstructure, two typical (X52 and X65) pipeline steels and a weld material that is known to reduce hydrogen permeability have been acquired for experimental investigation. In addition, a prototype high-pressure permeability testing apparatus has been designed and fabricated. Preliminary permeability testing up to 1000-psi inlet pressure will begin in August to September 2004. Preliminary evaluation of surface mechanical properties under different charging conditions will begin in August – September 2004.