Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure

Kriston Brooks, PNNL (PM, Presenter)
Kyle Alvine, PNNL
Chris San Marchi, SNL
Nalini Menon, SNL
Alan Kruizenga, SNL
Amit Naskar, ORNL
Barton Smith, ORNL
Jong Keum, ORNL
Mike Veenstra, Ford

June 7, 2016
Overview

Timeline

- Project Start Date: October 2015
- Project End Date: September 2018
- % Completed: 14%

Budget

- Total Project Budget: $1800K
- Total Funds Spent (as of 3/31/16)
  - $82K (PNNL)
  - $129K (SNL)
  - $17K (ORNL)

Barriers

A. Safety Data and Information: Limited Access and Availability
G. Insufficient Technical Data to Revise Standards
J. Limited Participation of Business in the Code Development Process
K. No consistent codification plan and process for synchronization of R&D and Code Development

Partners

- SNL
- ORNL
- Ford Motor Company
## Project Objective

- Provide scientific and technical basis to enable full deployment of H₂ and fuel cell technologies by filling the critical knowledge gap for polymer performance in H₂ environments.

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Project Goal for this Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier J: Limited Participation of Business</td>
<td>Gather and assess stakeholder input for their challenges and materials and conditions of interest for H₂ compatibility.</td>
</tr>
<tr>
<td>Barrier G: Insufficient Technical Data</td>
<td>Develop three standard test protocols for evaluating polymer compatibility with high pressure H₂: (1) cycling tests, (2) in-situ tribology tests, and (3) neutron scattering.</td>
</tr>
<tr>
<td>A. Safety Data and Information: Limited Access and Availability</td>
<td>Develop an approach to disseminate test protocols and compatibility information to SDOs and support the deployment of H₂ infrastructure.</td>
</tr>
</tbody>
</table>
Overall Technical Approach: Reporting Period

**Task 1: Stakeholders’ Input**
- Materials of Interest
- Operating Conditions of Interest
- Challenges faced
- Test methods currently employed by them

(On-Going)

**Task 2: Test Methodology Development**
- Selection of relevant polymers
- Determining preliminary test parameters
- Conducting preliminary tests and establishing optimum conditions of operation

(On-Going)

**Task 3: Characterization of Polymers**
- Baseline properties before and after exposure to H₂

(Future Work)

**Task 4: Disseminate Information**
- Lay the groundwork and deliver preliminary data for a database
- Share results with stakeholders
- Feedback from them to improve/modify test methodologies
- Identify dissemination approaches: Technical Reference

(Future Work)
Approach
Task: 1 Gather and Assess Stakeholder Input
(BARRIER J: Limited Participation of Business)

Stakeholders (20 participants to date)
- System Users
  - Automotive, Aerospace, Stationary
- System Suppliers
  - Tanks, H₂ gas
- Component Manufacturers
  - Valves, Compressors
- Seal Producers
  - O-rings, seals, tubes, liners
- Polymer Manufacturers
- Consultants
  - CSA, ASME
  - Academia

Task 1: Stakeholders’ Input
- Materials of Interest
- Operating Conditions of Interest
- Challenges faced
- Test methods currently employed by them
Questions Asked for Stakeholders

- Challenges Related to H₂ Compatibility
  - What failure mechanisms or degradation have you observed or are concerned about?

- Operating Conditions of Interest
  - What operating conditions are you most concerned about for polymers in hydrogen service for your application (e.g. temperature extremes, pressure cycles)?

- Suggested Polymers
  - What polymers or applications are most needed for hydrogen compatibility of polymers?

- Availability of Compatibility Information
  - Is the compatibility information in the literature sufficient to meet your needs?
  - What tests do you use to evaluate hydrogen compatibility?

- Method of Collecting and Disseminating Information on Polymer Compatibility
  - What is the most valuable method to disseminate hydrogen compatibility for polymers information to your sector?
Challenges Related to H₂ Compatibility

- Rapid Pressure Transients
  - Explosive decompression, blistering, liner collapse
- Long Term Pressure Cycling
  - Fatigue, change in mechanical properties
- Wear and Abrasion changes from H₂ permeation in the material
  - O-ring and valve seat leakage
- Dimensional and Mechanical Properties changes
  - O-ring and valve seat leakage

Some Stakeholder Challenges may be Unrelated to H₂ Compatibility

- Temperature effects associated with sub-ambient and cryogenic temperatures
- Impurities in the hydrogen impacting fuel cell use
Accomplishments

Task 1: Stakeholder Input

Take-away messages from stakeholder survey:

- Wide range of suggested polymers
- Conditions of Interest:
  - -40 to +85 degrees C
  - 1(atm.) to 880 bar (13,000 psi)
  - Cryogenic applications
- All agree that more testing is required
- Continued Discussions with Stakeholders

Thermoplastics of Interest:

- HDPE, PB-1, PA, PEEK, PP-R/PP-RCT, PEKK, PET, PEI, PVDF, PTFE, PCTFE

Elastomers of Interest:

- EPDM, NBR/HNBR, Viton, Levapren

Thermosetting polymers of Interest:

- Epoxy, PI, NBR, Polyurethane

Polymers in hydrogen service selected for test methodology development:

- Elastomers: Viton A, NBR
- Low Temperature Seal: PTFE
- Tank liner Material: HDPE
- Hose Material: Delrin (future)
Approach
Task 2: Test Methodology Development
(Barrier G: Insufficient Technical Data)

Tests Currently Being Developed:

a. Pacific Northwest National Laboratory
   Wear and tribology studies on polymers in H₂

b. Sandia National Laboratories
   Characterization studies (baseline)
   High pressure H₂ cycling of polymers

c. Oak Ridge National Laboratory
   Evaluation of H₂ exposed polymers
   with neutron and X-ray scattering methods

Task 2:
Test Methodology Development
- Selection of relevant polymers
- Determining preliminary test parameters
- Conducting preliminary tests and establishing optimum conditions of operation
PNNL is developing test methodologies for in-situ high pressure hydrogen tribology

- Application is valves and seals for infrastructure applications
- Damage and failure mechanisms are increased wear and leakage

**Current status – Tribometer is functional and active**

- Sample is reciprocating pin configuration
- In-situ testing with pure H₂ up to 4,000 psi done; 5,000 psi capable,
- Current system designed for room temperature – future upgrades may include sample heating or cooling
- Current measurement is frictional load

**Upgrade planned May 2016**

- Planned upgrade to machine will add vertical LVDT to measure wear track depth in-situ
- Requires modification of the tribometer and the autoclave
Accomplishments

Task 2a: Test Methodology Development: Tribology

In-situ H₂ Tribometer

Viton sample with wear track after hydrogen

Planned upgrade with vertical LVDT for in-situ wear track measurement
Task 2a: Test Methodology Development: Tribology

Accomplishments

**Capability to adjust the weight of the Tribometer**

- **Reciprocating linear motion**
  - Top: 202g 100 cycles
  - Middle: 614g 100 cycles
  - Bottom: 1037g 100 cycles

**Initial variation in load response much higher than after 100 cycles**

Preliminary Force Curves

Wear Tracks in Viton in H₂ Autoclave
Task 2a: Test Methodology Development: Tribology

Wear Track Comparison Between Air and Hydrogen for Various Weights

Preliminary Data Results:
No obvious difference at low weights, damage more prominent in H₂ at higher weights
Accomplishments

Task 2a: Test Methodology Development: Tribology

Viton Frictional Load Comparison: Weights vs. Number of Cycles

Preliminary Results:
We are still trying to understand the correct operational parameters needed for best results. (weight, pin size, etc.)
Preliminary experiment to investigate testing parameters of a high pressure hydrogen system for Polymers

- Four polymers selected based on components in hydrogen infrastructure - NBR, Viton A (seals, gaskets, O-rings), HDPE (tank liners), and PTFE (seals, gaskets, O-rings)
- Molded specimens (O-rings, gaskets) vs sheets; off-the-shelf grades
- Static isobaric (100 Mpa), and isothermal (25ºC) conditions of exposure
- Time of exposure: 1 week for saturation of 3 mm thick specimens of all polymer types (calculated based on DIFFUSE*)
- Characterization tests performed: DMTA, Compression set (elastomers only), Polymer volume change, TGA/DSC, tensile strength (thermoplastics only), Micro CT analysis before and after exposure

General trends observed:

- Polymer structure-property relationships explain trends in hydrogen environments.
- As expected, Viton A and Buna N (elastomers) showed greater H₂ effects than HDPE and PTFE (thermoplastics) within the scope of the experiment.
- With hydrogen exposure, elastomers exhibited:
  - a decrease in storage modulus
  - significant change in densities with recovery afterwards (swelling)
  - increased compression set (Viton A)
- Thermoplastics did not exhibit significant changes with hydrogen, except for mechanical properties:
  - Young’s Modulus 35% higher for PTFE and 15% higher for HDPE
  - HDPE exhibited cold-drawing (plastic deformation); PTFE failed in the elastic region.
Accomplishments

Task 2b: Test Methodology Development: High Pressure Hydrogen Exposure

ELASTOMERS IN HYDROGEN

Viton A and Buna N swelling evident from comparing before hydrogen (bottom row) and after hydrogen exposure (top row)

<table>
<thead>
<tr>
<th>Polymer</th>
<th>% Volume Change/gram upon Hydrogen Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Immediately</td>
</tr>
<tr>
<td>Buna N</td>
<td>57.2%</td>
</tr>
<tr>
<td>Viton A</td>
<td>69.0%</td>
</tr>
</tbody>
</table>

Compression Set: Different responses to hydrogen for Viton A and Buna N

(1/8” thick sheets, Round 1 H₂ exposure removed after 7 days, compression set measured on 3 specimens under 75% compression at 110°C for 21 hours, recover 38 min)
Accomplishments

Task 2b: Test Methodology Development: High Pressure Hydrogen Exposure

Fillers can cause hydrogen effects in polymers

Rare void around filler particles

Many voids around filler particles after hydrogen

Micro-CT of Viton A before and after hydrogen: Voids seen around filler particles
Accomplishments

Task 2b: Test Methodology Development: High Pressure Hydrogen Exposure

Void like defects

Micro CT of Buna N before and after Hydrogen exposure

No void encapsulation of filler particles, no new defects after hydrogen in Buna N
Accomplishments

**Task 2b: Test Methodology Development: High Pressure Hydrogen Exposure**

**THERMOPLASTICS IN HYDROGEN**

Thermoplastics are less impacted by high pressure H₂ soak than elastomers: little impact on Yield Stress and Strength, Swelling, and DMTA properties. Young's Modulus is increased.

<table>
<thead>
<tr>
<th>Polymer properties</th>
<th>Before Hydrogen exposure</th>
<th>After Hydrogen exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tg (°C) (Tan Delta peak)</td>
<td>Storage Modulus (MPa)</td>
<td>Tg (°C) (Tan Delta peak)</td>
</tr>
<tr>
<td>HDPE</td>
<td>-110</td>
<td>848±7</td>
</tr>
<tr>
<td>PTFE</td>
<td>34, 137*</td>
<td>431±12</td>
</tr>
</tbody>
</table>

* PTFE shows two Tₙs because of possible separation of components

**PTFE Stress Strain Results**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Young’s Modulus MPa</th>
<th>Yield Stress MPa</th>
<th>Strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. No H₂ Soak</td>
<td>493</td>
<td>8.8</td>
<td>24.4</td>
</tr>
<tr>
<td>Ave. With H₂ Soak</td>
<td>667</td>
<td>9.1</td>
<td>25.4</td>
</tr>
</tbody>
</table>

**HDPE Stress Strain Results**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Young’s Modulus MPa</th>
<th>Yield Stress MPa</th>
<th>Strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. No H₂ Soak</td>
<td>863</td>
<td>20.3</td>
<td>24.0</td>
</tr>
<tr>
<td>Ave. With H₂ Soak</td>
<td>990</td>
<td>22.3</td>
<td>25.8</td>
</tr>
</tbody>
</table>
Deliverables (present-end of FY 16)

- Basic design of a high pressure manifold is ready and necessary steps to build are in progress at SNL’s Hydrogen Materials Laboratory

- Based on stakeholder meetings:
  - Finalize “most desirable” polymer selection
  - Identify potential suppliers, different grades
  - Selection of test parameters mimicking actual operating conditions

Proposed additions for FY 17

- Addition of an environmental test chamber to pressure manifold capable of operating between -40°C and 100°C to study pressure and temperature effects in hydrogen
Objective

- Use neutron and x-ray scattering to investigate molecular dynamics of hydrogen solvated polymers and additive-modified polymer composites
- Understand effect of temperature and high-pressure H₂ at the interface of crystalline and amorphous regions within semi-crystalline polymers, at the interface of solvated hydrogen and the polymer matrix, and the loaded additive and the matrix
- Identify microscopic properties critical to polymer performance, and predict failure modes
Task 2c: Test Methodology Development: Neutron and X Ray Scattering

- Ex situ (U)SANS provides information about final pore structure after sample treatment.

- In situ (U)SANS provides real-time information during solvation, compression, swelling and depressurization processes.
  - Determines pore-size distribution in a polymer structure.

- Use in situ neutron reflectometry (NR) provides real-time information during solvation, compression, swelling and depressurization processes.
  - Determines pore-size distribution along the vertical direction of a polymer film.
  - Discover morphology of the polymer crystal and amorphous regions.
  - Determine local solvation of the polymer matrix.
  - Examine effect of high-pressure hydrogen on interface between the loaded additive and the matrix.
Task 2c: Test Methodology Development: Neutron and X Ray Scattering

Sandia National Laboratories has provided high pressure-cycled polymers samples for scattering studies

Selected thermoplastics (PTFE, HDPE) and elastomers (FKM, NBR)

WAXD Patterns of HDPE Before and After H₂ Cycle

- Different intensity ratios of orthorhombic (110) and (200) HDPE diffraction peaks suggest that applied high pressure H₂ induced lamellar rotation along the in-plane direction.
- No martensitic deformation peak (monoclinic peak) was observed implying that no crystal deformation. Only crystal rotation.
Task 3: Characterization of Polymers

Characterize polymers selected based on stakeholder input and preliminary test methodology development

- Large variations in materials properties for a given polymer purchased from different suppliers
- Establish baseline performance of select polymers in H₂ environment
- Understand the impact of thermal history, processing aids, additives such as fillers etc. of polymers on H₂ compatibility

<table>
<thead>
<tr>
<th>Thermal Techniques</th>
<th>Purpose</th>
<th>Spectroscopy Techniques</th>
<th>Purpose</th>
<th>Rheological Techniques</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSC</td>
<td>Glass transition (Tg), melt temperature (Tm), percent crystallinity, aging, hardness, mechanical properties</td>
<td>FT-IR</td>
<td>chemical structure, molecular characterization, degree of crystallinity</td>
<td>Rotary vane</td>
<td>filler loading and cure kinetics</td>
</tr>
<tr>
<td>DTA</td>
<td></td>
<td>Raman</td>
<td></td>
<td>Cone and Plate</td>
<td></td>
</tr>
<tr>
<td>TMA</td>
<td></td>
<td>UV/VIS/NIR</td>
<td></td>
<td>Parallel Plate</td>
<td></td>
</tr>
<tr>
<td>DMA</td>
<td></td>
<td>XRD</td>
<td></td>
<td>Twin Screw</td>
<td></td>
</tr>
<tr>
<td>Dilatometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Collaborative Activities

<table>
<thead>
<tr>
<th>Partner</th>
<th>Project Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE</td>
<td>Sponsorship, steering</td>
</tr>
<tr>
<td>PNNL</td>
<td>Project Lead, Polymer Characterization, Wear and Tribological Studies, Mechanical Properties and Moderate Pressure</td>
</tr>
<tr>
<td>SNL</td>
<td>Exposure Pressure Cycling studies, Mechanical Properties and High Pressure, Develop Technical Reference Documentation and Database</td>
</tr>
<tr>
<td>ORNL</td>
<td>Neutron and x-ray scattering studies</td>
</tr>
<tr>
<td>Ford</td>
<td>Subcontracted Participant and Consultant, Represent OEM Perspective</td>
</tr>
<tr>
<td>Air Liquide Parker</td>
<td>Stakeholder Participant and Consultant</td>
</tr>
</tbody>
</table>
Remaining Challenges and Barriers

- Large gaps exist in knowledge base for performance and degradation of polymers in hydrogen environments
- A wide range of polymeric materials for components, operating conditions and applications exist in the hydrogen infrastructure
- Large variations in material properties of a single polymeric material from suppliers is common
- Standardized tests to identify polymer compatibility have not been developed
- There is a tremendous need to develop methods for the dissemination of information on the hydrogen compatibility of polymers and standardized tests developed on this program to stakeholders and SDOs
Proposed Future Work

Remainder of FY16

- Develop test procedure and conditions for tribological tests and high pressure cycling tests
  - Gather preliminary information about scoping study materials
- Evaluate hydrogen surface affects using neutron scattering and XRD
  - Publication of comparative porosity data on SNL/PNNL polymer specimens using SAXS, WAXS and ex situ small angle neutron scattering data
- Identify and characterize 3-5 materials to be used in future tests
  - Use results of stakeholder evaluation and preliminary tests to identify materials
  - Characterize baseline initial polymers for molecular weight, Tg, Tm, degree of crystallinity, thermal history
- Develop the framework for an initial database of compatibility results
  - Approach may be similar to that done for metallic materials compatibility

Next Year (FY17)

- Refine test procedure and conditions for characterized materials
  - Produce statistically meaningful results that can be compiled in database
- Expand the range of temperatures, pressures or cycling rates
# Project Summary

## Relevance
Information will fill critical knowledge gap for polymer performance in H₂ environments by developing standard test protocols for key applications and disseminating both the test methods and results to the H₂ infrastructure stakeholders.

## Approach
- Obtain input from H₂ infrastructure stakeholders
- Characterize the materials to be tested
- Develop appropriate test protocols
- Provide dissemination tools to share results

## Technical Accomplishments and Progress
- Gathered information from Stakeholders on materials and conditions of interest
- Preliminary results of tribology and high pressure soak testing demonstrate impact of hydrogen
- Preparing for pressure cycling and neutron scattering tests

## Collaborations
- PNNL/SNL/ORNL/Ford Team with Stakeholder Input

## Proposed Future Research
- Continue to refine and develop of test methods
- Expand temperature, pressure and cycling range
- Develop approach to disseminating information collected

May 5, 2016
Contacts

Pacific Northwest National Laboratory
Kriston P Brooks  📞: 509-372-4343  📧: kriston.brooks@pnnl.gov
Kyle Alvine      📞: 509-372-4475  📧: Kyle.Alvine@pnnl.gov

Sandia National Laboratories
Nalini Menon     📞: 925-294-4872  📧: ncmemon@sandia.gov

Oak Ridge National Laboratory
Amit Naskar      📞: 865-574-0309  📧: naskar@ornl.gov
Barton Smith     📞: 865-574-2196  📧: smithdb@ornl.gov

Ford Motor Company
Mike Veenstra    📞: 313-322-3148  📧: mveenstra@ford.com
Questions?
Response to previous year’s reviewers’ comments

- This project was not reviewed last year.
Technology Transfer Activities

► Stakeholders
  ■ Maintain contact with survey participants
  ■ Present and publish results

► Code and Standards Committees
  ■ Share approach to information dissemination with Committee members

► Industrial Collaborators (e.g. Ford)
  ■ Maintain dialog with Collaborators to discuss pathways for qualification and technology transfer
Polymer Permeability
Coefficient X $10^{-9}$
(mol.H$_2$/m.s.MPa)

Diffusion
Coefficient
X $10^{-10}$
(m$^2$/s)

Solubility
coefficient
(mol.H$_2$/m$^3$.MPa)

| Polymer | Permeability Coefficient X $10^{-9}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>0.82</td>
</tr>
<tr>
<td>PTFE</td>
<td>3.2</td>
</tr>
<tr>
<td>Buna N</td>
<td>5.0</td>
</tr>
<tr>
<td>Viton A</td>
<td>3.5</td>
</tr>
</tbody>
</table>

| Polymer | Diffusion Coefficient X $10^{-10}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>1.9</td>
</tr>
<tr>
<td>PTFE</td>
<td>-</td>
</tr>
<tr>
<td>Buna N</td>
<td>4.3</td>
</tr>
<tr>
<td>Viton A</td>
<td>1.9</td>
</tr>
</tbody>
</table>

| Polymer | Solubility coefficient
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>4.3</td>
</tr>
<tr>
<td>PTFE</td>
<td>-</td>
</tr>
<tr>
<td>Buna N</td>
<td>11.4</td>
</tr>
<tr>
<td>Viton A</td>
<td>19</td>
</tr>
</tbody>
</table>

Task 2b: Test Methodology Development, High Pressure Hydrogen Exposure

Permeability and related information on polymers

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Tg (°C) (Tan Delta peak)</th>
<th>Storage Modulus (MPa)</th>
<th>Tg (°C) (Tan Delta peak)</th>
<th>Storage Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buna N</td>
<td>-32</td>
<td>34.0±2</td>
<td>-31</td>
<td>19.9±3.7</td>
</tr>
<tr>
<td>Viton A</td>
<td>-2</td>
<td>10.7±0.5</td>
<td>-3</td>
<td>5.4±1.4</td>
</tr>
</tbody>
</table>

TGA percent mass loss for Buna N and Viton A before and after hydrogen exposure
(Method 30°-200°C, 2°C/min, Ar 40.0 ml/min.)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Buna N</th>
<th>Viton A</th>
</tr>
</thead>
<tbody>
<tr>
<td>No hydrogen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediately after exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48 hours later</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>