Project ID: **ta004**

# Continuous Fiber Composite Electrofusion Coupler

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# Overview

- **Timeline and Budget**
  - Project Start Date: 12/1/15
  - Project End Date: 4/30/19
  - Total Project Budget: $1,876,865
    - Total Recipient Share: $376,865
    - Total Federal Share: $1,500,000
    - SRNL Share: $525,000
    - Total DOE Funds Spent*: $950,533
      - *As of 01/31/2019

| Technical Targets | |
|---|---|
| Transmission Pressure (bar) | 100 |
| $H_2$ Leakage | < 5x10e-4 cm3 $H_2$/s |
| Lifetime (years) | 50 |

- **Barriers addressed**
  - D: High As-Installed Cost of Pipelines

- **Partners**
  - *DOE*: Project Sponsor
  - *SRNL*: Project Partner
  - *NOV*: Project Partner
  - *Automated Dynamics, part of Trelleborg Group*: Project Lead

# Relevance

- **3-Year Project Objective**: Design and Validate pipe coupler for FRP Hydrogen Delivery for **yet to be installed pipes**, without use of elastomeric seals

  **ASME B31.12 Code Committee (Hydrogen Piping and Pipelines) concerned that existing seal components (i.e. O-rings or other elastomeric seals) will require maintenance in underground service.**

  - 350 bar Burst, < 5x10e-4 $cm^3$ $H_2$/s Leak Rate, 50 year life

- **Current Year Objective, April 2018 – April 2019**
  - Pass Milestone for Fatigue Failure Criteria (fail pipe before coupler)

- **Past Year's Impact**
  - Finalized Coupler Design to allow low-maintenance composite $H_2$ pipelines.

# Approach

EF = Electrofusion

## Enable FRP for Hydrogen Delivery

- Problem with existing steel pipe solution is corrosion
- Problem with existing O-ring based seals on FRP is O-ring maintenance
- Develop Pipe Coupling Technology through <u>unique combination of existing market solutions</u>
  - Metal end fittings for FRP (but *without O*-rings)
  - Electrofusion Couplers (but for *high* pressure pipe)
  - Thermoset FRP with HDPE liner (but with *thermoplastic* EF coupling)
- Work based on previous SRNL and NOV's DOE-funded project.
- **<u>2018 Work focused on slight design modifications to design to pass fatigue test</u>**

| Technical Goal | Result | |
|---|---|---|
| Leak Rate < 5x10e-4 $cm^3$ He/s | PASSED: 10e-6 $cm^3$ He/s | 50x > than needed |
| Burst Pressure > 350 bar | PASSED: 364 bar | On par with goal |
| Fatigue: Pipe bursts before coupler bursts<br>Initial estimates is 10,000 cycles | Max reached is 8,500 cycles | 10x > than previous trial 1 year ago |



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# Approach

## Milestones and Percent Completion

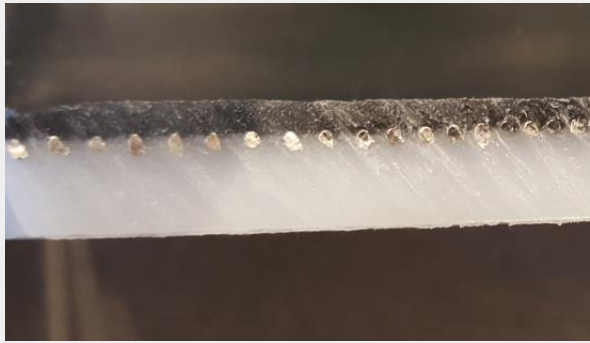
| 2019 Goal | Date | Prototype must show 1) leakage rate less than 5 x $10^{4}$ $cm^3$ He/s, 2) hydrostatic standards set by ASTM D2992 at 1,500psi ( 100bar), an R ratio of 0.1 and pipe must burst before joint bursts. | % Achieved |
|---|---|---|---|
| Pass Fatigue Test | 12/31/18 | Test Coupler by hydrostatic standards set by ASTM D2992 at 1,500psi (~100bar), an R ratio of 0.1. Pipe must burst before joint bursts. | 85% |
| Fatigue to Failure, Burst, Leak, Tests (Go/No-go) | 3/4/19 | Fatigue test at R=0.1, 1,500psi, run on coupler and pipe. Pipe must fail before coupler. Burst Test must pass 350 bar (5,076psi). Leakage rate less than 5 x 10-4 $cm^3$ $H_2$/s, (Initial tests done with He vs $H_2$ / practical safety vs value) | 67% |
| Create Manufacturing and Quality Plan | 3/30/19 | Complete Manufacturing and Quality Plan. | 75% |
| Final Design Report | 4/30/19 | Write final report | 50% |

# Accomplishments: Redesign = 10x past fatigue performance

- Fundamental Problem
  - Weakening of small amount of plastic acting as leak barrier, during fatigue test.
- Solution
  - Ensure bond area is clean
  - Ensure fusion process is reliable, robust, repeatable
  - Remove non-essential materials from design that cause potential failures.
  - Modified electrofusion machine to achieve necessary power to fuse.

All steps necessary to allow low cost as-installed composite pipelines - coupler must achieve necessary fatigue performance!

# Accomplishments: Design



- Reduced wire diameter
  - Allows ease of assembly → repeatable results
  - Required modified electrofusion coupler
- Fatigue Performance Improvement
  - Did not reach full fatigue goal of 10,000 cycles (8,500 cycles failure at coupler)

Inherent challenge in coupling a restrained sealing mechanism (electrofusion bond) to axially-induced strain from pressure cycles. Fundamental need to avoid underground maintenance on O-rings should be reevaluated and underlying assumptions challenged.

# Accomplishments: Reference FEA vs Testing

## ADC Coupling Fatigue Analysis

HDPE Fatigue Behavior Considerations

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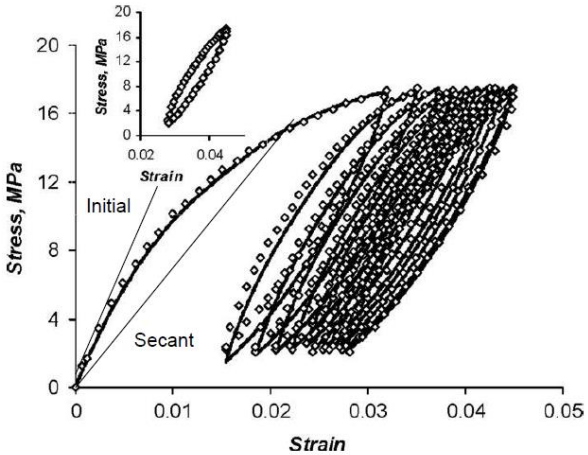
Under controlled stress loading the plastic deformation within the specimen accumulates.




Stress Controlled Plastic Deformation

K. Hizoum et. al, "Coupling of Nanocavitation With Cyclic Deformation Behavior of High-Density Polyethylene Below the Yield Point", J. Eng. Mater. Tech. 133, 030901, 2011.

The HDPE modulus used in the analysis is the initial modulus. A secant modulus may be more representative of the nonlinear behavior and lower the stresses.

The HDPE will likely see a strain controlled cyclic load due to the relative stiffness of the metal and composite components. This will lower the stress within the HDPE each cycle.

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# Accomplishments: Reference FEA vs Testing

## ADC Coupling Fatigue Analysis

HDPE Strain Amplitude

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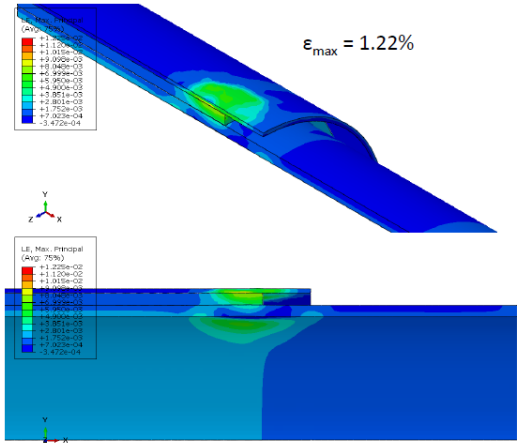
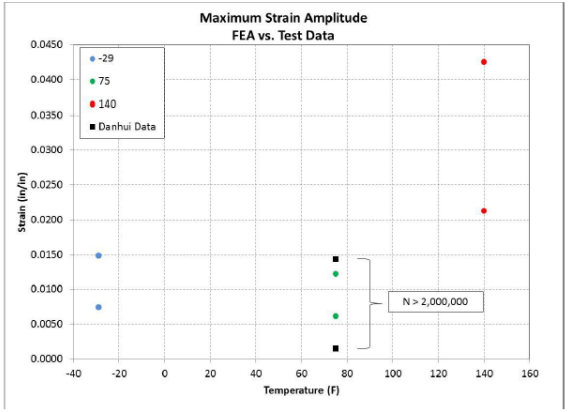
Max Principal Strain
70 F




At room temperature, the HDPE fatigue strain in the electrode port is within the bounds from literature. This suggests the HDPE has a life greater than N = 2,000,000. At 140 F the HPDE is 1/4 the stiffness leading to 4 x the strain.

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# Accomplishments: Reference FEA vs Testing

## ADC Coupling Fatigue Analysis

Summary & Results

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The composite pipe shows small negative margins in the transition region. The pipe is still supported by the coupling in this area. The fatigue strength envelope was computed based on R = 0.1 test data making the analysis conservative.

The E-glass/HDPE layer of the coupling has negative margins for the cold condition. This layer is back by steel and therefore the inplane failure of this layer should not compromise the fatigue life of the part.

The HDPE components show positive margins for the 75 F and 140 F temperature conditions. At -29 F, the HDPE shows fatigue failure in all regions. This is not a concern if the cold condition is the temperature of the environment and not the temperature of the H2 gas.

MR&D believes the HDPE in the electrode port will come to a stress-strain equilibrium, where the stress is below the referenced fatigue strengths (2125 ksi) and the elongation is below the reference fatigue strain (200%).

Modifications to the electrode port have been provided to improve the HDPE fatigue margins. These modifications will also mitigate any creep issues that may occur in the electrode port region during hydrostatic testing (ASTM 2992 Procedure B).

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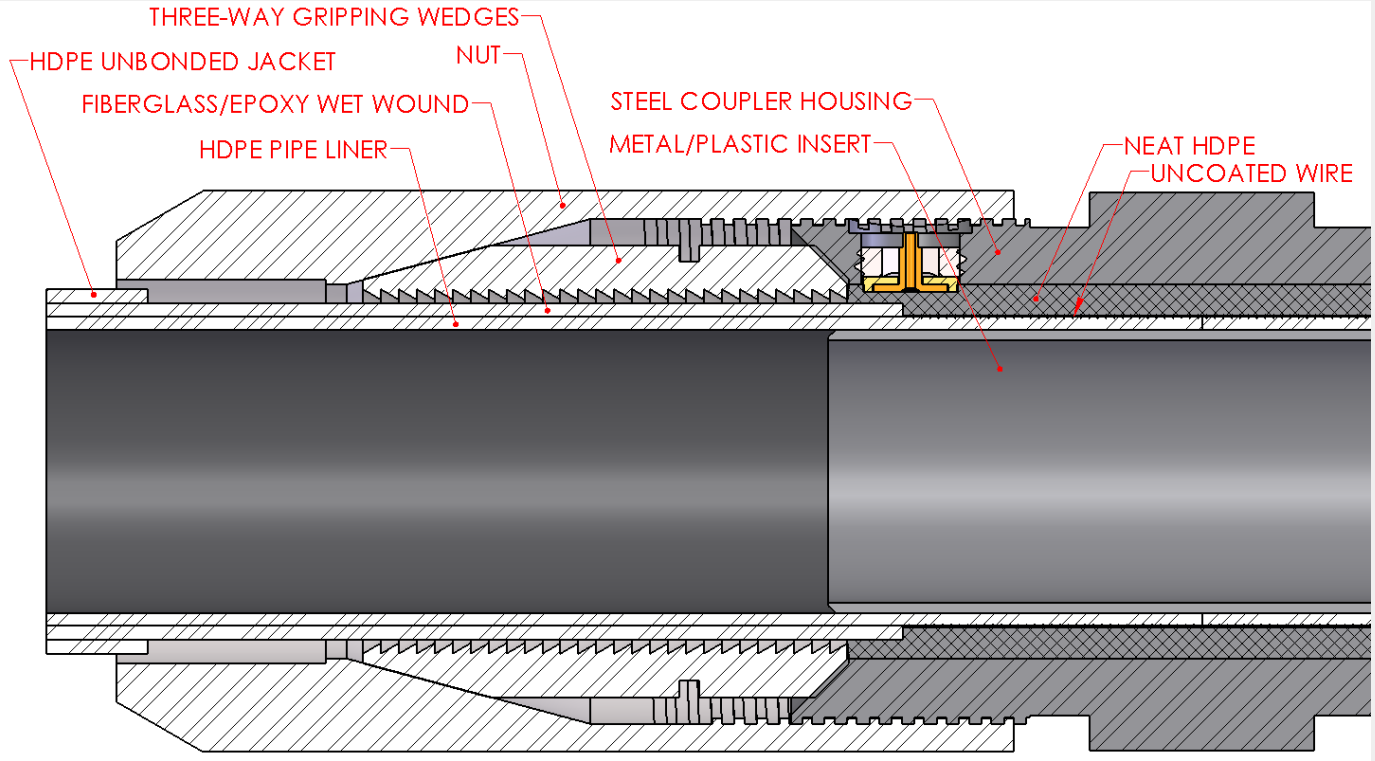
# Accomplishments: Reference FEA vs Testing

- Improvement from last fatigue test failure at 900 cycles
  - Part failed at 8,500 cycles.
  - Non-straight pipe likely induced significant eccentricities for higher bending stress.
  - Awaiting failed sample for analysis.

To date: awaiting sample for destructive test evaluation on material to determine failure mode and compare with FEA.

# Accomplishments: For reference - existing design



# Progress: Response to last year's comments

- **How is design relevant to non-PE liners? Would PP liner work with this tech?**
  - This design could be adapted to any melt-processable thermoplastic liner including polypropylene, PA, PEEK, and others.
- **A steel insert could be cheaper than composite.**
  - Yes that is a good option. Original design considered hydrogen embrittlement, but this has been noted by DOE as not a concern. Overall, this detail is very small and any structurally rigid form will suffice.
- **What technical gaps exist?**
  - Installation details is the next step toward commercialization (pipe cutting, pipe joining, in-field fusion. Commercial solutions exist for each but would need to be slightly adapted).
  - Resolving fatigue performance. Further FEA is an option. Revisiting fundamental assumption on unfavorable underground maintenance is good too. Alternative materials and designs may allow elastomeric seals, backup seals to reach 50 year goal.

# Progress: Testing

## Fatigue Test

- ASTM D2992
- Prototype Fatigue Criteria: < 5x10e-4 $cm^3$ **He**/s
- Fatigue to Failure Criteria: < 5x10e-4 $cm^3$ $\mathbf{H_2}$/s
- Room Temperature
- Min/Max pressure 150 / 1,500 psi (R Value = 0.1)
- Vary R ration to extrapolate performance into millions of cycles

# Collaborations

| | |
|---|---|
| SRNL™ SAVANNAH RIVER NATIONAL LABORATORY | Project Partner (Federal Lab)<br>Test Expertise<br>Past Coupler Expertise<br>ASME Code Expertise |
| NOV Fiber Glass Systems | Project Partner (Industry)<br>Commercialization Value<br>In-field Expertise |
| AUTOMATED DYNAMICS® PART OF TRELLEBORG GROUP | Project Lead (Prime)<br>Composite Design and Automated Manufacturing |



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# Challenges & Barriers: Pass Fatigue Test Criteria

- Failure criteria in test: pipe fails before coupler. Expected >10K cycles for first fatigue failure criteria.
  - Pipe failure means any leak causing steady state pressure drop
  - Evidence in test is stepwise change in pressure measured in system

- Passing this test is critical in achieving 50 year service life

# Challenges & Barriers: Pass Fatigue Test Milestone

- Use of curved pipe in manufacturing is a significant challenge
  - Straight pipe (i.e. not previously spooled) was not possible for this program
- Assembly
  - Extreme precision required (differences <0.002” diameter) for quality fits.

# **Proposed Future Work:** FY19 and After

- **March/April 2019**
  - Another burst test at SRNL
  - Summarize and reports on existing project
  - Finalize commercialization plan
- **Commercialization**
  - Current Project: TRL 4
  - Future: TRL 4 to TRL 9
    - In-field processes: pipe cut, join, and fusion (general technologies exist, need to modify for existing design). This would be the next step required toward commercialization.
    - Buy-in and funding from fueling station(s) and pipe supplier(s) needed to advance TRL.
- **Cost Evaluation**
  - Overall cost of FRP solution is driven by cost of pipe, proprietary to NOV. Outside scope of this project.
  - Coupler will cost <$300 Total: <$20 for custom molded EF Coupler component, <$250 for machined components.

**Any proposed future work is subject to change based on funding levels.**

# Technology Transfer Activities

- Patent Application Finalized/Submitted October 2018
- Future commercialization plans include proposing idea to pipe suppliers and re-fueling stations.

# Summary

- Challenge is rigorous to seal against fatigue stress for millions of cycles.
- Commercialization and cost of FRP H2 lines is largely a function of FRP cost. Coupler is a necessary detail.
- Need to revisit fundamental assumption on cost/risk/reward on avoiding maintenance on underground pipe couplers
  - O-rings degradation is a concern
  - Alternative O-ring materials may be of interest (available or yet to exist), allowing de-coupling of sealing with axial-induced loading.

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