# Pipeline Working Group Support and Off-Board Hydrogen Storage Development

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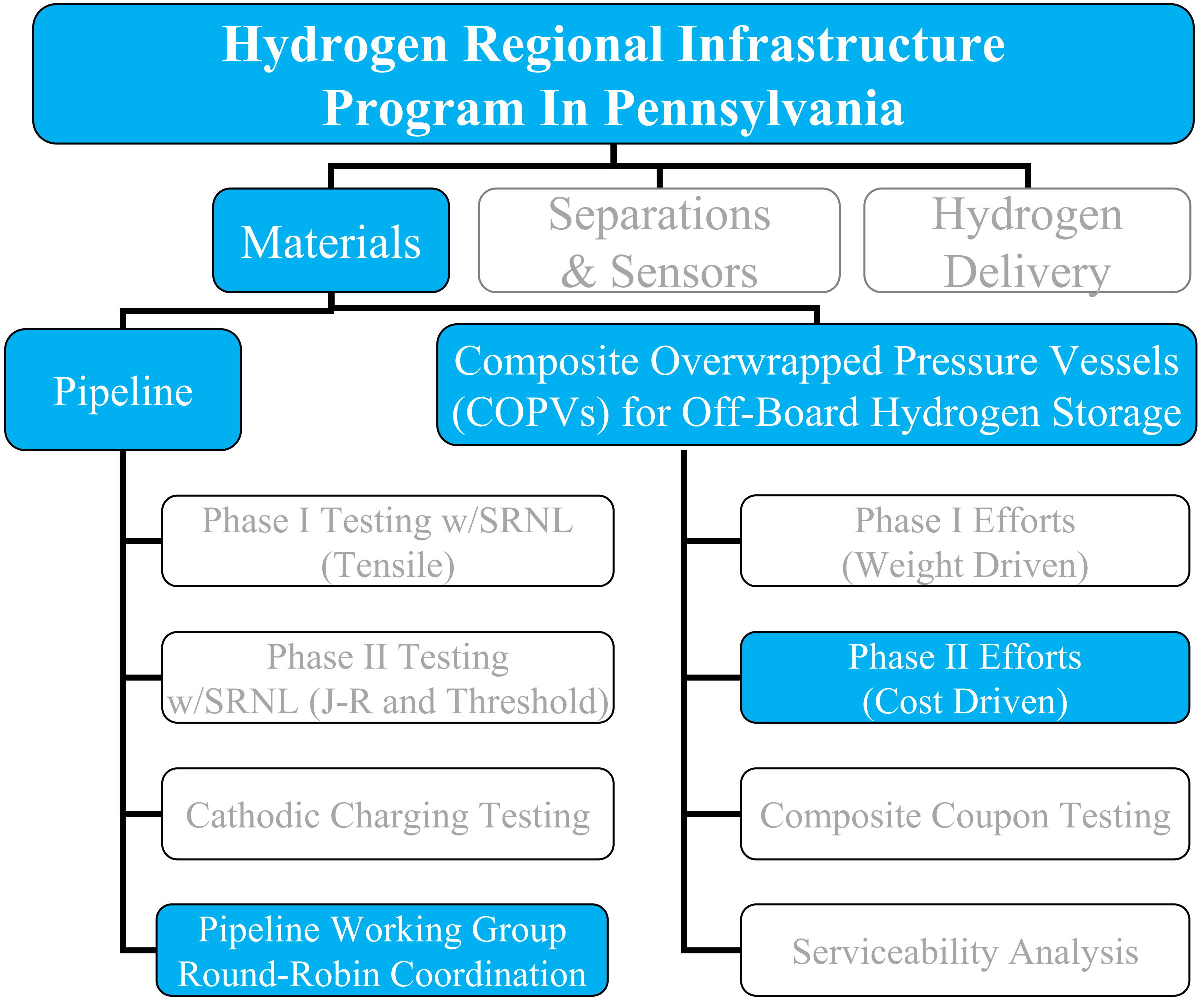
# Program Structure & Poster Organization

- The Hydrogen Regional Infrastructure Program in Pennsylvania consists of three tasks
- The materials task consists of pipeline and COPV subtasks
- At DOE's request, this poster focuses only on Pipeline Working Group (PWG) and Phase II COPV efforts



# Overview – Materials Task

## Timeline

- Start - September 1, 2004
- Finish - January 31, 2009
- 85% Complete

## Budget

- Total overall* project funding
  - DOE share - $5,917K
  - Contractor share - $1,491K
- Materials task funding**
  - FY05: $632,560
  - FY06: $249,506
- Funding received in FY07: $0
- Funding for FY08: $0

| Barriers | MYRDDP Reference |
|---|---|
| Hydrogen Embrittlement of Pipelines | 3.2.4.2 D |
| Gaseous Hydrogen Storage Costs<br>Storage Tank Materials and Costs | 3.2.4.2 F<br>3.2.4.2 G |

## Targets

- Aid PWG in obtaining critical pipeline mechanical test data in hydrogen
- COPV Cost efficiency: $500/kg (2010) and $300/kg (2015)
- COPV Volumetric efficiency: 0.030 kg/L (2010) and 0.035 kg/L (2015)

## Partners

- Pipeline Working Group, including:
  - Department of Energy
  - National Institute of Standards and Technology
  - Oak Ridge National Laboratory
  - Sandia National Laboratory
  - Savannah River National Laboratory
  - University of Illinois at Urbana-Champaign
- HyPerComp Engineering, Inc.
- American Society of Mechanical Engineers

* Including the materials, separation and sensors, and hydrogen delivery tasks
** This covers the entire materials task (outlined on previous slide), not just the items covered on this poster

# Objectives – Pipeline Working Group Support

Mission Statement – Pipeline Working Group (PWG)

- Develop hydrogen delivery technology that is safe, improved and cost effective

Objective Statement – Round Robin Testing (RRT)

- Verify that participating laboratories conform to the same test procedures for tensile testing of pipeline steels in hydrogen
  - Coordinate and report test outcomes
  - Develop understanding of any differences that arise in measured properties

CTC's Objectives

- Support tensile RRT as described on next slide
- Transition to fatigue testing round robin

# Approach – Pipeline Working Group Support

Communication

- Interface with other members of PWG via email, teleconference and semi-annual on-site meetings

Material Procurement and Specimen Preparation

- Lead pipeline material selection, procurement and inspection
  - Initial focus on tensile testing of X52 and X100 pipeline steels
- Coordinate and down-select specimen geometry that can be accommodated by all participating laboratories
- Facilitate machining, inspection, documentation and distribution of all relevant specimens
- Work with testing participants to define test matrix

Verification and Documentation

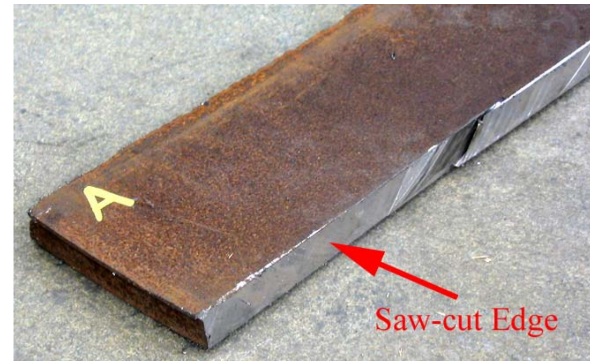
- Monitor testing at participating laboratories
- Document and report RRT results to PWG

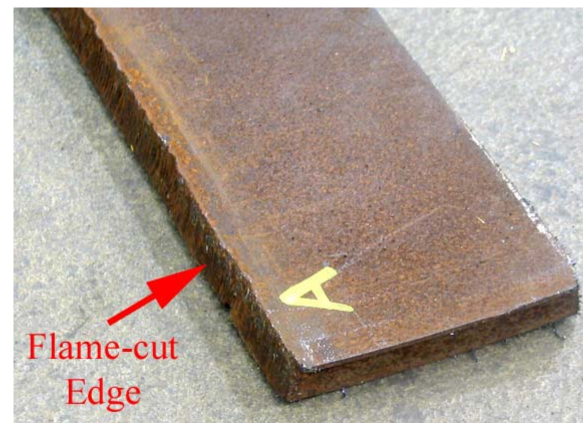
# Material Selection, Procurement and Inspection

## API 5L X52 Steel


Approximately 40′ of 12.75″ OD, 0.5″ thick, electric resistance welded (ERW) X52 pipeline was procured from Oregon Steel Mill’s Tubular Camrose facility in Alberta, Canada

## API 5L X100 Steel

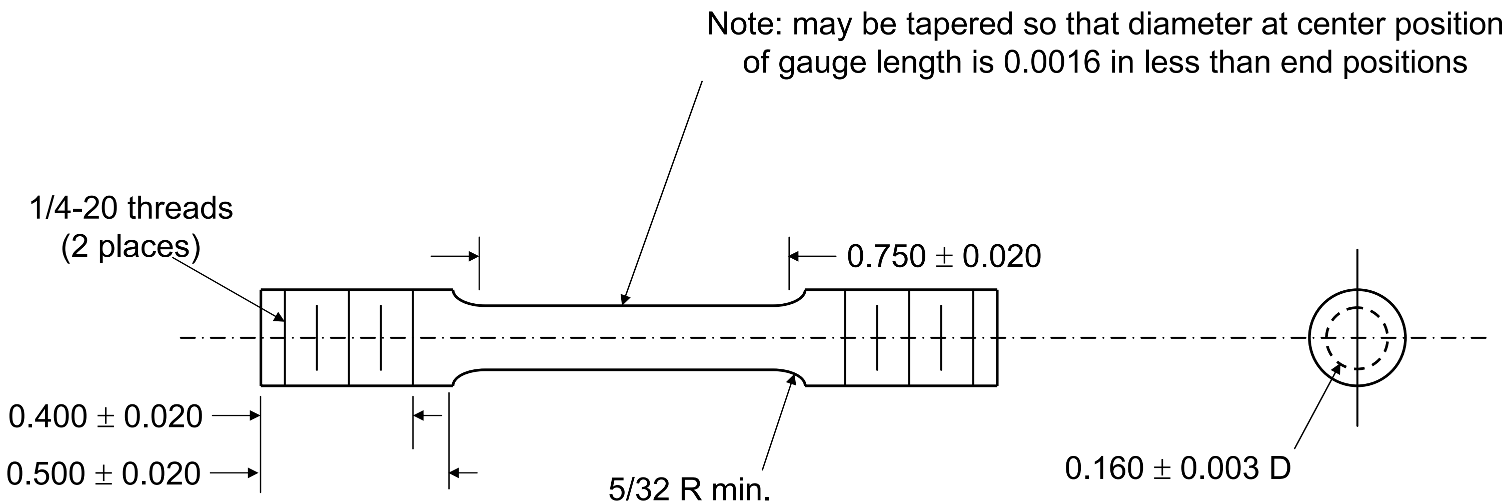



A strip of material measuring approximately 6′ long and 4″ wide was supplied from a 30-36″ diameter X100 pipe by NIST-Boulder

# Down-Selected Tensile Specimen Geometry

- A sub-sized, cylindrical geometry conforming to ASTM E-8 was selected as a common specimen for each lab to test

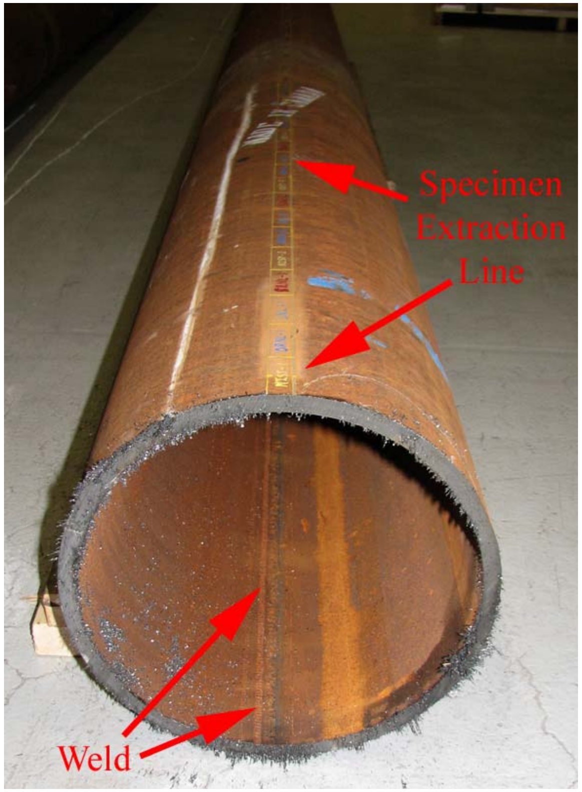



All dimensions are in inches.
Maximum RMS surface roughness = 8 microinches

Drawing courtesy of Brian Somerday (SNL)

# Tensile Specimen Preparation – X52

- Material for forty-eight (48) tensile specimens was removed from a single, longitudinal line along the X52 pipe.
- Single extraction line used to minimize the variation in residual stress (which is a function of circumferential location).
- Selected extraction line ("6 o'clock" position) was directly opposite the weld line ("12 o'clock" position).
- Blanks were shipped to Westmoreland Mechanical Testing & Research, Inc. (WMT&R) for specimen preparation.





# Tensile Specimen Preparation – X100


- All flame cut edges were avoided
- Specimens were arranged in rows of thirteen, such that each column included one specimen for each of the four testing labs
- The specimen blanks were shipped to WMT&R as a single piece

# Tensile Test Matrix

| Test Lab | Extraction Location | Test Atmosphere | Test Pressure (psi) | Test Temperature (°F) | # Specimens |
|---|---|---|---|---|---|
| NIST-B | Base metal opposite weld | Air | 14.7 (i.e., 1 atm) | RT | 3 |
| | | Helium | TBD (same as H2) | RT | 3 |
| | | Hydrogen | TBD (same as He) | RT | 3 |
| | | TBD - Spare specimens | | | 3 |
| ORNL | Base metal opposite weld | Air | 14.7 (i.e., 1 atm) | RT | 3 |
| | | Helium | TBD (same as H2) | RT | 3 |
| | | Hydrogen | TBD (same as He) | RT | 3 |
| | | TBD - Spare specimens | | | 3 |
| SNL | Base metal opposite weld | Air | 14.7 (i.e., 1 atm) | RT | 3 |
| | | Helium | TBD (same as H2) | RT | 3 |
| | | Hydrogen | TBD (same as He) | RT | 3 |
| | | TBD - Spare specimens | | | 3 |
| NIST-G | Base metal opposite weld | Will use cathodic charging to introduce hydrogen to the specimens. Exact conditions TBD. | | | 9 |
| NIST-B = NIST facility in Boulder, CO, which will test via high-pressure hydrogen gas<br>NIST-G = NIST facility in Gaithersburg, MD, which will test via cathodic hydrogen charging | | | | | |

- Same test matrix will be used for both X52 and X100 specimens

# RRT Schedule

| Activity | Date | Complete? |
|---|---|---|
| **Meetings** | | |
| RRT specifics discussed at PWG meeting in Boulder, CO | 22 July 2007 | Y |
| Further PWG discussion in Aiken, SC | 26 September 2007 | Y |
| Pipeline Working Group Meeting in Livermore, CA | 20-21 February 2008 | Y |
| 2008 DOE MERIT Review | Week of 9 June 2008 | N |
| 2008 International Hydrogen Conference | Week of 8 September 2008 | N |
| **Material Procurement** | | |
| Identification of pipeline suppliers & inventory | September/October 2007 | Y |
| X52 ordered from Oregon Steel Mill | 29 October 2007 | Y |
| X52 received at *CTC* | 14 November 2007 | Y |
| X100 received at *CTC* | 11 December 2007 | Y |
| **Specimen Layout and Machining** | | |
| Machining quotations received from vendors | 19 November 2007 | Y |
| Purchase order issued to WMT&R | 21 December 2007 | Y |
| Tensile specimen blanks labeled and removed | 11-31 December 2007 | Y |
| Tensile specimen machining at WMT&R | January – February 2008 | Y |
| Tensile specimens received at *CTC* | 8 February 2008 | Y |
| Confirmation of tensile specimen geometry & surface roughness (Note: surface roughness of specimens were not originally within specification, which required subsequent touch-up and final surface roughness verification) | 11 February 2008 – 14 March 2008 | Y |
| Tensile specimens mailed to laboratories | 27 March 2008 | Y |
| **Testing** | | |
| Tensile testing | April 2008 to September 2008 | N |
| **Misc PWG Communications** | | |
| *CTC* update document emailed to PWG | 7 January 2008 | Y |
| Monthly PWG Teleconferences | 14 February 2008/monthly | N |

# Summary – Pipeline Working Group Support

- X52 and X100 pipeline materials were obtained
- A labeling convention was developed to track tensile specimens
- *CTC* removed tensile specimen blanks from the X52 and X100 feedstocks
- WMT&R machined the tensile specimens
- After confirming their geometry and surface roughness, *CTC* shipped the tensile specimens to each laboratory

# Future Work – Pipeline Working Group Support

- *CTC* will monitor the RRT activities at each lab and report the cumulative results
- *CTC* will machine fatigue specimens in support of the next planned PWG activity

# Objectives – Composite Overwrapped Pressure Vessels (COPVs) for Off-Board Hydrogen Storage

Technical Targets

- Produce and test cost-efficient prototype vessel for off-board hydrogen storage, with the following goals:
  1. Cost efficiency: \$/kg $H_2$ stored
     - \$500/kg (2010) and \$300/kg (2015)
  2. Volumetric efficiency: kg $H_2$/L of storage volume
     - 0.030 kg/L (2010) and 0.035 kg/L (2015)
  3. Weight efficiency*: mass $H_2$ stored at service pressure/ mass of COPV
     - 6 % (2010) and 9 % (2015)

Implications

- Reducing the cost of COPVs will aid in meeting overall refueling station and similar off-board storage infrastructure cost targets

* Not a specific goal for off-board hydrogen storage; listed for information only.

# Approach – COPVs for Off-Board Hydrogen Storage

COPV Design

- Leverage lessons learned during Phase I (weight-driven) COPV design effort for Phase II (cost-driven) design effort
- Develop and execute a computer program to explore the effects raw materials, tank geometry and pressure have on storage tank purchased capital cost, volumetric efficiency and weight efficiency
- Assess the cost and volumetric capacity of the COPV design

COPV Production

- Produce prototype, Type II COPVs

Evaluate Prototypes

- Burst test four prototype COPVs
- Cycle fatigue test four prototype COPVs
- Drop (i.e., damage) and then cycle fatigue test four prototype COPVS

# Background – Prior COPV Work

- Previous year's efforts ("Phase I") focused on weight reduction with Type III* (aluminum-lined) COPV
  - 7.75 liter water volume aluminum liner; 10,000 psi design pressure
  - Hoop and helical wrapped with carbon fiber
  - Designed to fail in sidewall

Mass $H_2$/Mass COPV (tank only) = 5.88%
Kg $H_2$/L COPV volume = 0.0391
\$/kg $H_2$ = \$4,249

  - Additional results presented in
    - "Project # PDP-19: Hydrogen Regional Infrastructure Program in Pennsylvania", 2007 DOE Annual Merit Review
    - "Meeting the DOE's Goals for Compressed Hydrogen Gas in Off-Board Tank Storage", Olson and Klug, NHA Annual Hydrogen Conference 2007

* COPV Type III: composite-reinforced cylinder with metal liner to provide permeation barrier; normally termed full-wrapped.

# Type II* COPV Design

- Cost reduction was primary goal of this phase
- Liner options for prototypes limited due to small quantities required, limited budget and short-term schedule
- Best available option was high-strength chromium molybdenum (34CrM04) steel SCUBA tank
  - Made by FABER (Italy)
  - Two "dog-bone" specimens cut from a liner

| Yield Strength | UTS | Elongation | Reduction of Area |
|---|---|---|---|
| 122.8 ksi | 141.1 ksi | 14 % | 51 % |

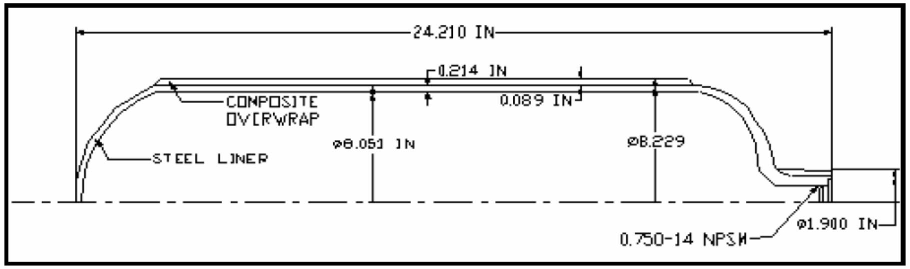
Performance of liner in hydrogen is currently unknown, but high strength suggests embrittlement concerns. For scale-up, a more suitable alloy should be selected and incorporated in overall COPV design.



* COPV Type II: composite-reinforced cylinder with load-sharing metal liner; normally termed hoop-wrapped.

# Type II COPV Design (continued)

- Fiber: commercial grade Toray T700 12K (carbon fiber)
- Resin: Epon 828 (epoxy resin)
- COPV Design Details:
  - Volume: 15 L
  - Mass: 17.95 kg
  - Service Pressure: 6,700 psi




- A total of 14 Type II COPVs were produced
  - 4 each were hydrostatically burst tested, fatigue cycle tested and fatigue cycle tested after impact
  - 2 were held in reserve

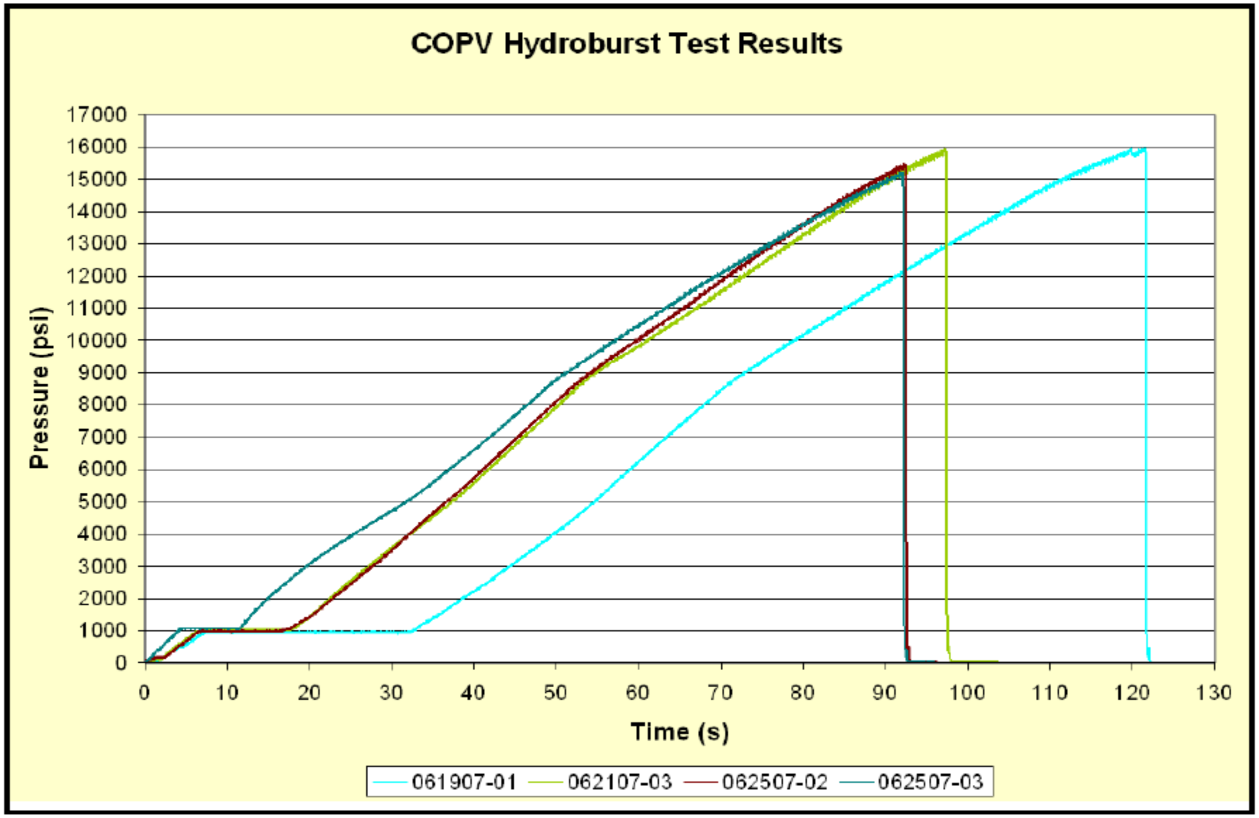
$/kg $H_2$ = $642
kg $H_2$/L COPV volume = 0.0292
Mass $H_2$/Mass COPV = 2.46%

All hydrogen storage tanks were manufactured by HEI at their Brigham City, UT facility

# Burst Testing

- COPVs were filled with water and pressurized at manually controlled rate until failure

| COPV Serial Number | Burst Pressure (psi) |
|---|---|
| 061907-01 | 15,955 |
| 062107-03 | 15,944 |
| 062507-02 | 15,468 |
| 062507-03 | 15,193 |
| | |
| Mean Burst Pressure | 15,640 |
| Standard Deviation | 374.6 |
| Coefficient of Variation | 2.40% |



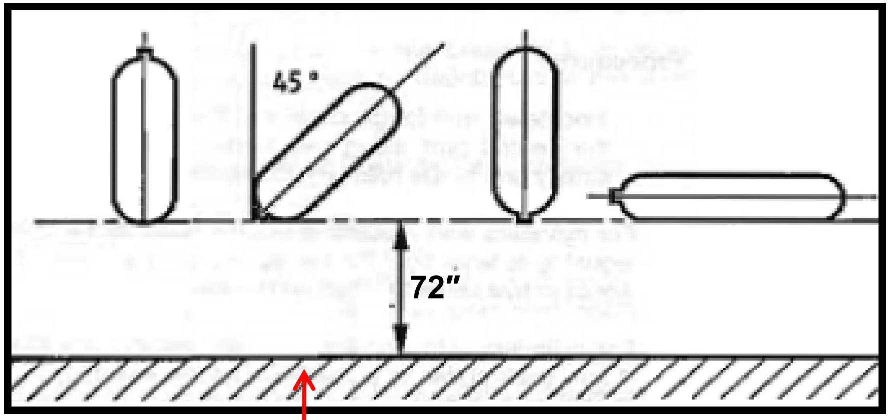

# Fatigue Testing

- COPV pressurized to 8,375 psi (1.25 x Service Pressure), depressurized to approximately 0 psi, repressurized, etc.
- Cycling continued until failure; all cycle test failures occurred by fatigue crack in liner, followed by leakage
- Test medium was a water/glycol mix to mitigate corrosion


| COPV Serial number | Cycles |
|---|---|
| 062107-05 | 11,799 |
| 062507-01 | 5,174 |
| 062607-05 | 9,600 |
| 062607-06 | 9,642 |
| | |
| Mean Cycles Achieved | 9,054 |
| Standard Deviation | 2782.9 |
| Coefficient of Variation | 30.74% |

# Post-Drop Fatigue Testing

- Each of four COPVs was dropped at various vertical, horizontal and offset angles
  - Cylinders were dropped 72 inches onto concrete
- After dropping, each COPV was subsequently fatigue tested using previously described procedure




| COPV Serial number | Cycles after Drop |
|---|---|
| 062107-01 | 8,223 |
| 062507-04 | 6,532 |
| 062607-04 | 8,831 |
| 062607-07 | 7,335 |
| | |
| Mean Cycles Achieved | 7,730 |
| Standard Deviation | 1007.7 |
| Coefficient of Variation | 13.04% |

# Summary – COPV for Off-Board Hydrogen Storage

- Prior (Phase I) effort focused on weight reduction
- Current (Phase II) effort focused on cost reduction
- 15 L, Type II COPV was designed and built
  - Chrome-molybdenum steel SCUBA tank liner
  - Toray T700 12K carbon fiber
  - Epon 828 resin
- Prototypes approached cost and volume efficiency targets
  - $/kg $H_2$ = $642; (DOE 2010 target = $500/kg )
  - kg $H_2$/L COPV volume = 0.0292; (DOE 2010 target = 0.030 kg/L)
- 4 COPVs each subjected to burst, cycle and post-drop cycle testing
  - Mean burst pressure = 15,640 psi
  - Mean fatigue = 9,054 cycles @ 8,375 psi
  - Mean post-drop fatigue = 7,730 cycles @ 8,375 psi

# Future Work – COPV for Off-Board Hydrogen Storage

- Future efforts are not currently funded, but should:
- Demonstrate scaled-up COPV
- Include optimized liners (alloy, wall thickness, dome thickness, etc.)