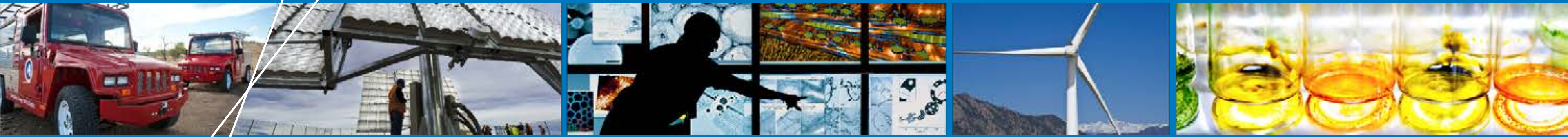
Component Standard Research and Development



2015 DOE Annual Merit Review
Hydrogen Safety Codes and Standards

Robert Burgess (PI), Matthew Post, Arlen Kostival, William Buttner, Carl Rivkin

National Renewable Energy Laboratory

June 09, 2015

Project ID # SCS002

Overview

TIMELINE

- Start date: 10/1/2014
- End date: 09/30/2015*

*Project continuation and direction determined annually by DOE

BARRIERS

2012 Multiyear RD&D Barriers

- ***A.*** Safety data and information: Limited access and availability
- ***C.*** Safety is not always treated as a continuous process
- ***F.*** Enabling national and international markets requires consistent RCS
- ***G.*** Insufficient technical data to revise standards
- ***H.*** Insufficient synchronization of national codes and 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

BUDGET

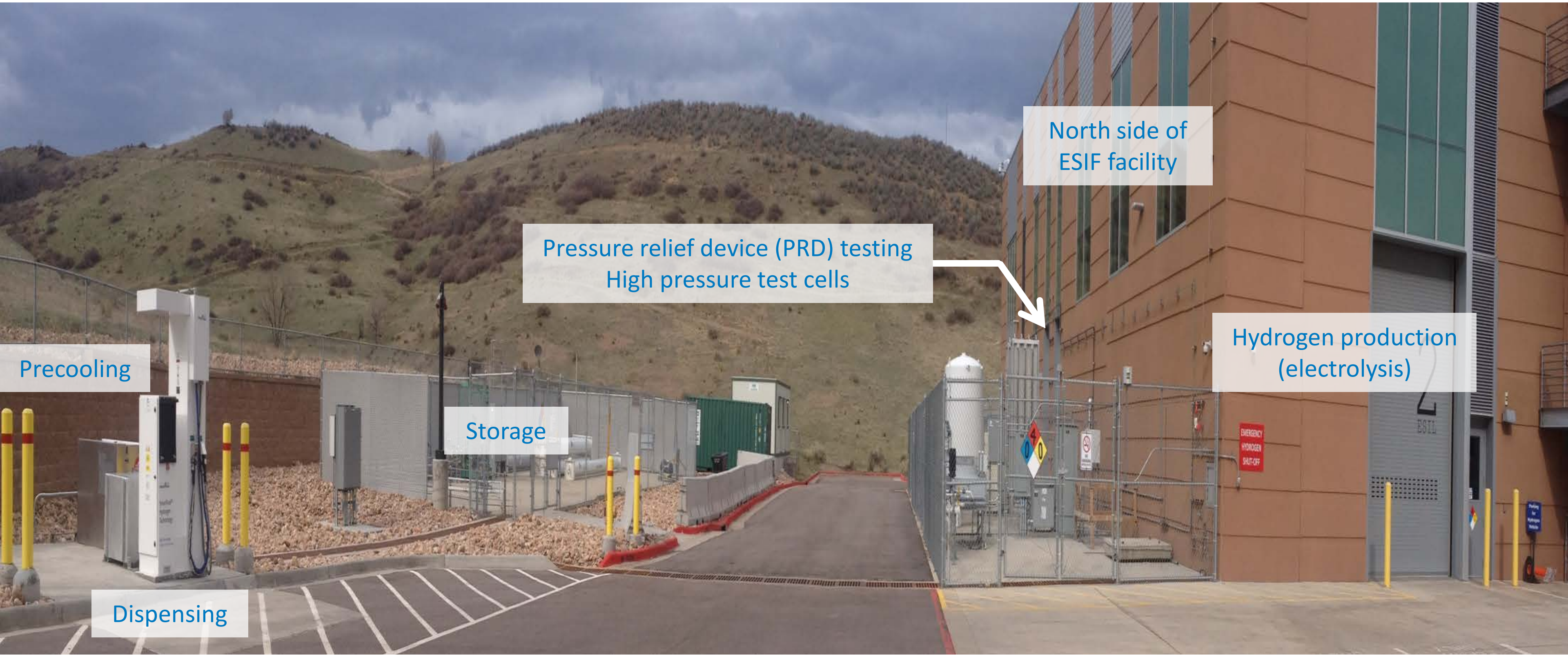
- Funding for FY14: **$250K**
- Planned FY15 funding: **$330K**
- Total DOE funds to date: **$580K**

PARTNERS

- Industry (component manufacturers, automotive original equipment manufacturers, station suppliers)
- Laboratories/universities (SNL, CDFA, PNNL, JRC, NHTSA, NIST, CSM, others)
- Codes and standards development organizations (SAE, CSA, ASME, ISO, UL, NFPA, IEC, GTR, ANSI, others)

Relevance: Integrated Component Testing at ESIF

Component testing at the Energy Systems Integration Facility (ESIF) integrated with a 70 MPa SAE J2601 hydrogen dispenser



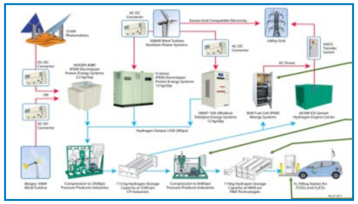
Successful deployment of hydrogen infrastructure will require components that are proven to meet existing safety standards

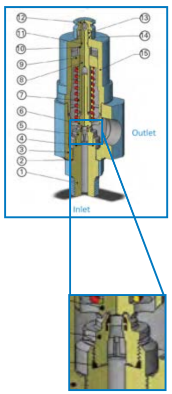
Component R&D Approach

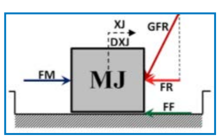
Approach	Barrier*
Work closely with codes and standards technical committees to develop test requirements with sound technical basis	G. Insufficient technical data to revise standards K. No consistent codification plan and process for synchronization of R&D and code development
Integrate DOE/NREL component test projects with Safety Codes and Standards program	C. Safety is not always treated as a continuous process
Support hydrogen manufacturers and system suppliers with safety/reliability analysis and testing that can facilitate pre-certification of components and systems	F. Enabling national and international markets requires consistent RCS J. Limited participation of business in the code development process
Publish technical reports for general use by stakeholders and NREL outreach activities	A. Safety data and information: Limited access and availability

* Barriers are based on 2012 DOE MYRD&D SCS Section 3.7.5

Component R&D Approach: Test Hierarchy

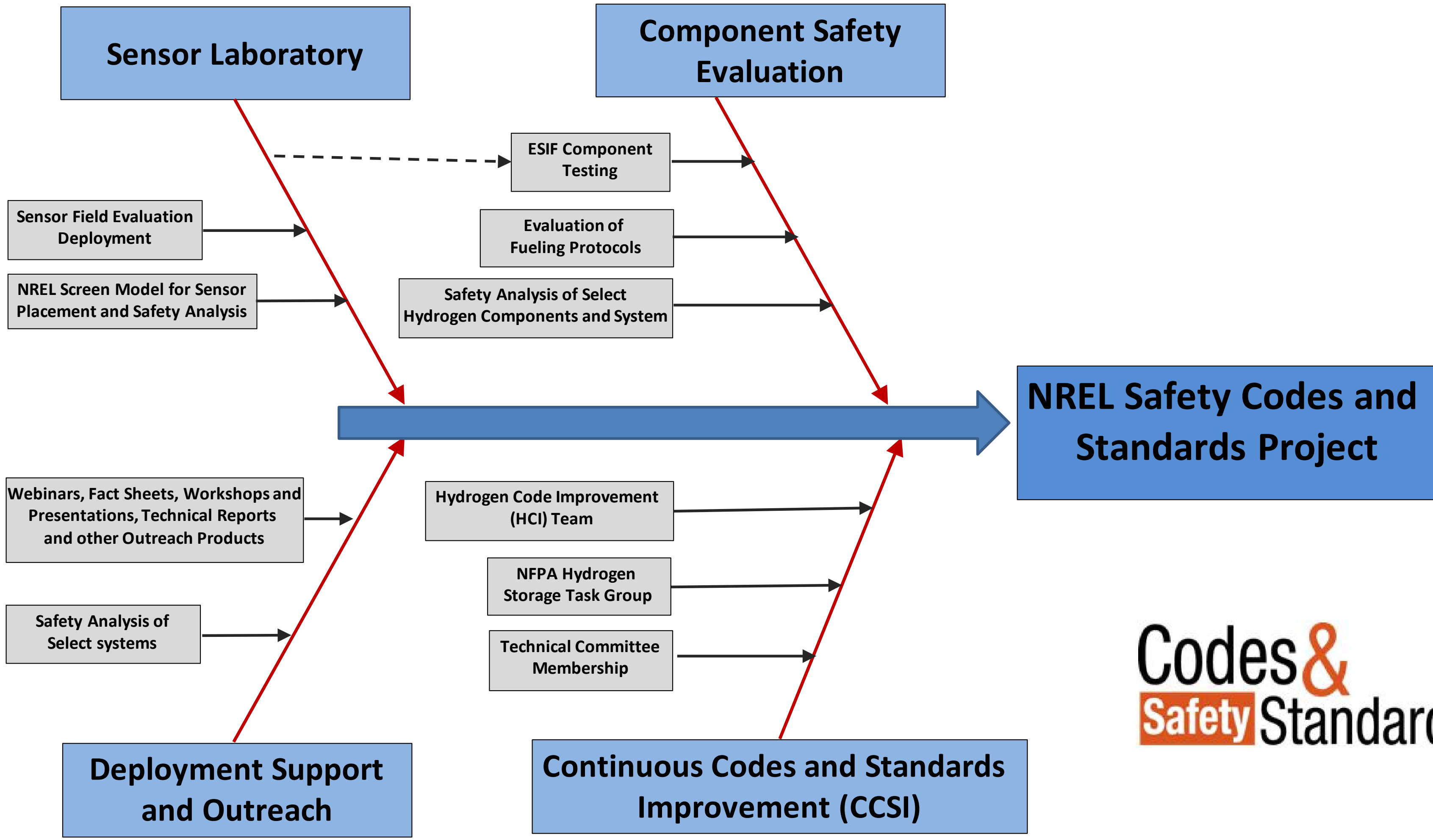






	Description	Advantages	Limitations
System Level Field Testing	Data from hydrogen demonstration and other installations including NREL Technology Validation and NREL Wind-to-Hydrogen data	• Large statistical sample size • Actual stresses	• Data fidelity limits • Limited controls on stresses
Component Level Laboratory Testing	Reliability and accelerated life testing at the component level (including production and development hardware)	• Actual hardware • Laboratory control of stresses	• Costly multiple sample run • Proprietary issues • Difficult to measure degradation
Sub-Component Laboratory Testing	Reliability and accelerated life testing at the sub-component level (such as check valves used in hydrogen compressors)	• Actual hardware • Laboratory control of stresses • Less costly than full component testing	• Costly multiple sample run • Proprietary issues • Difficult to measure degradation
Mechanical Element Testing	Fundamental testing of mechanical element root cause failure modes caused by friction, wear, stress, fatigue, and other mechanisms.	• Test design flexibility • Statistical sampling • Root cause isolation • Data can be easily shared	• Scaling to component level may be difficult • Special apparatus

Approach:
NREL Safety Codes and Standards Project Structure



Codes & Safety Standards

Approach:
Relief Valve Failure Mode Test Plan

- **Replicate known failure under controlled laboratory conditions**
- **Use valves that are "designed to fail" (use of high strength material under tensile loading)**
    - Example: NREL funded testing of glass wrapped COPV to show performance based test is capable of failing cylinder known to fail when exposed to acid
- **Phase I test: Laboratory control of stressors that include pressure loading and temperature cycling**
- **Phase II test (if needed to produce failure): Additional stressors include pressure cycling, humidity, vibration, and induced flaws**

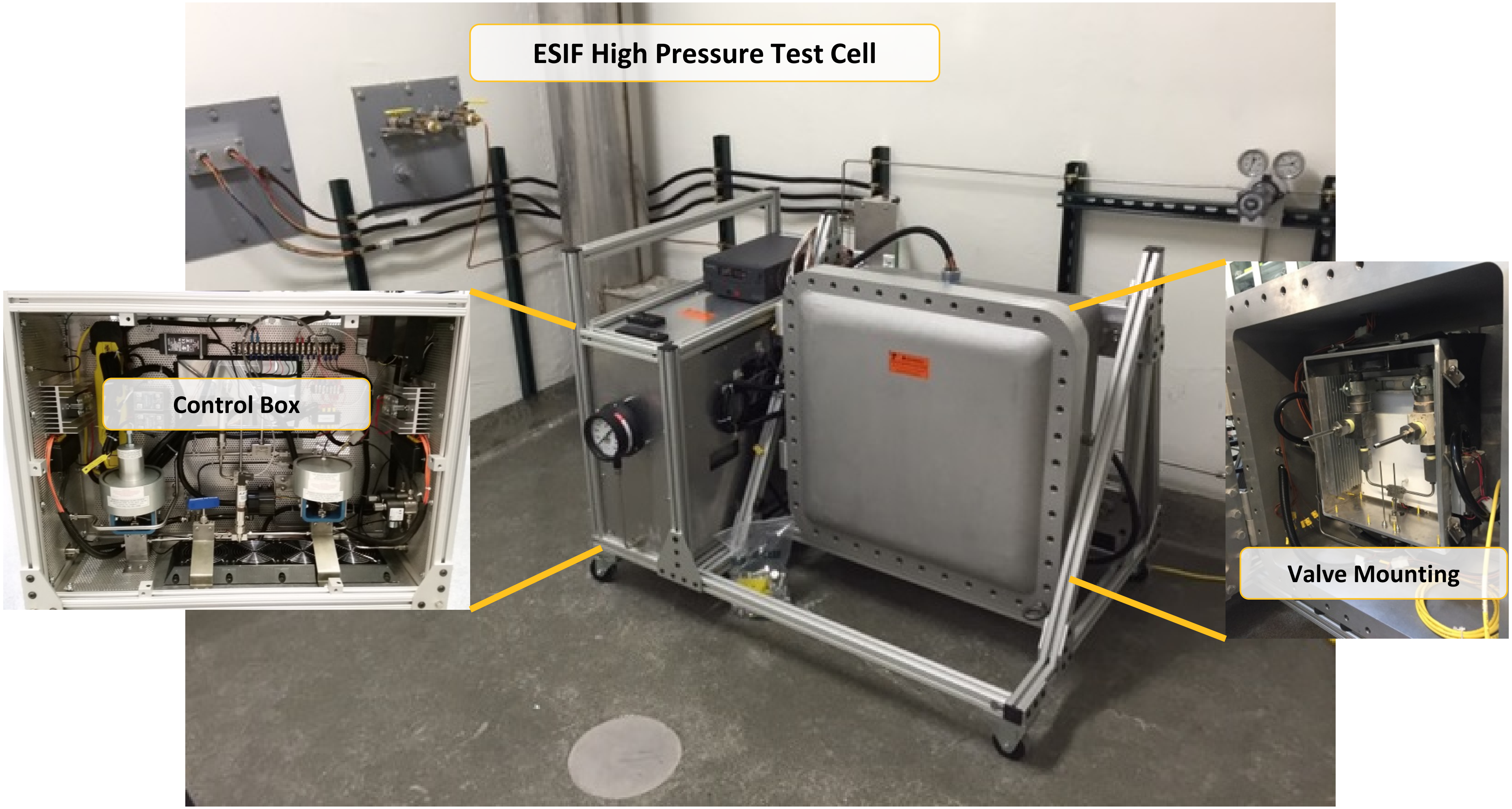
Accomplishments and Progress: Relief Valve Testing

- Qualitative ALT (Accelerated Life Testing) testing to duplicate known field failure under controlled laboratory conditions
- Accelerated stresses of temperature and pressure in hydrogen environment
- Leak detection to identify point of failure

Relief valve apparatus
installed in ESIF high pressure test bay

Relief valve programmable logic controller (PLC) control box

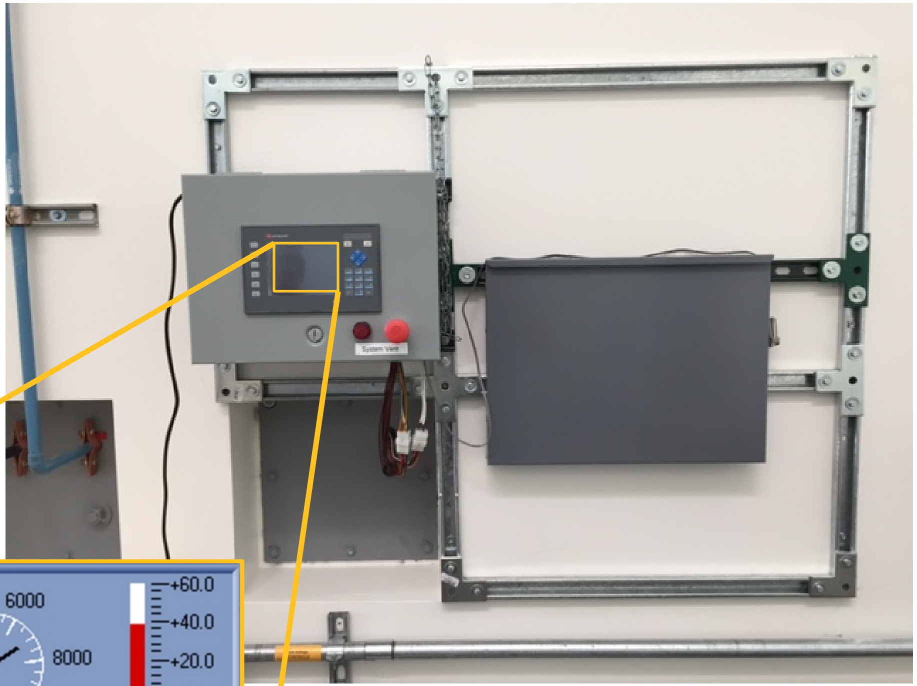
Accomplishments and Progress: Test Device Installation



ESIF high pressure test cell allows for safe operation of hydrogen systems, designed for end of life component testing

Accomplishments and Progress:
Energy Systems Integration Laboratory Control Room

- **Unitronics PLC for automation control and data acquisition**
- **Real time data is viewed on touch screen**
  - Test setup
  - System resets
  - Safety alarms
  - Monitor data

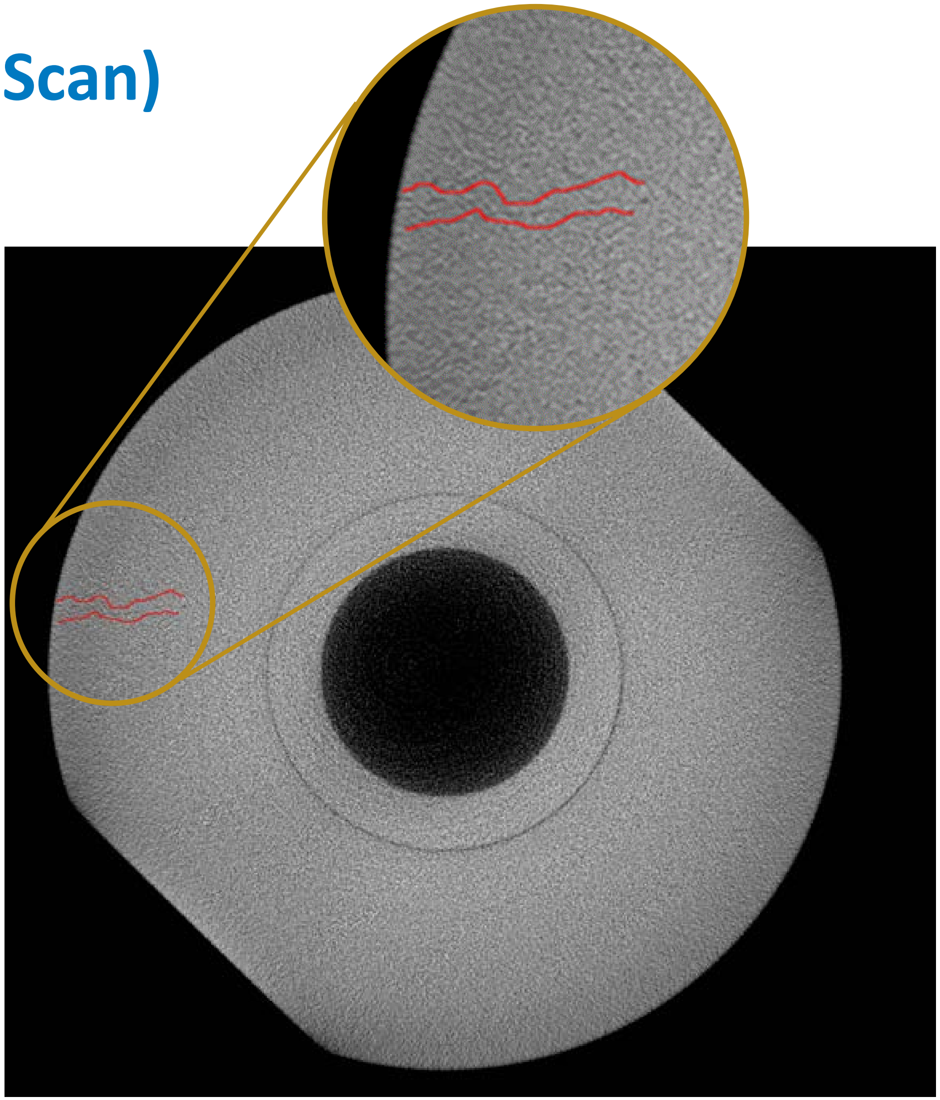


Automated PLC control and operation allows for unattended 24 hour operation of component accelerated life testing

Accomplishments and Progress: Nozzle Non-Destructive Inspection/Evaluation

Computed Tomography (CT Scan)

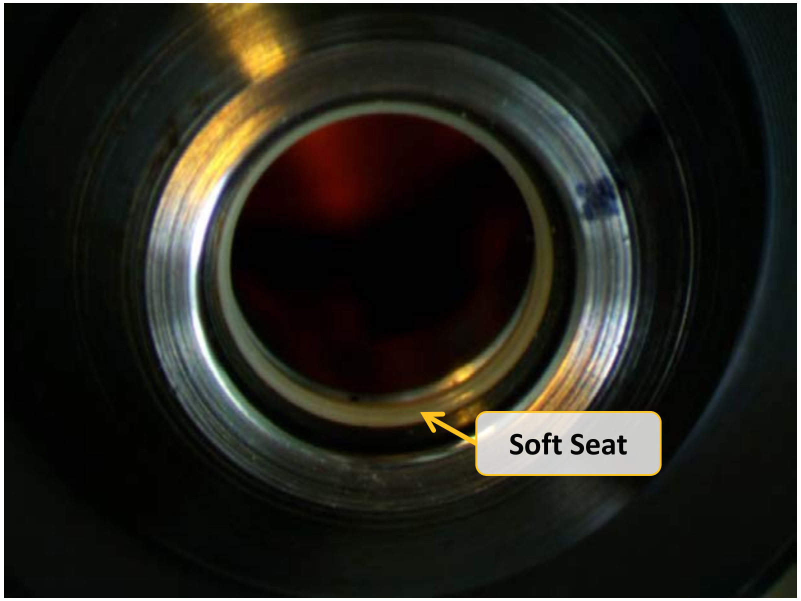
- X-Ray technique capable of detecting subsurface flaws and inclusions
- Top view images taken at intervals of .02 mm, defect is visible over ten image slices
- Defect is detected on 440C relief valve nozzle S/N 586381 after three-year operation in hydrogen service at NREL's Wind-to-Hydrogen demonstration facility



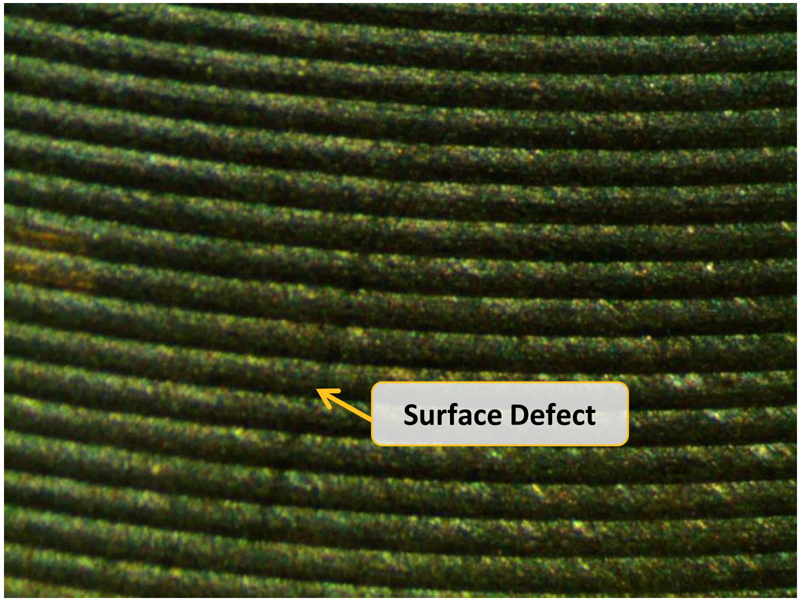
S/N 586381, slice 98, 8.5659 mm (Nikon Metrology Inc.)

Accomplishments and Progress: Relief Valve Nozzle Inspection

- Relief valve has been in service for three years and shows evidence of operational and/or installation wear
- Documented condition of nozzle at start of accelerated life cycle testing



Relief valve nozzle S/N 586381 (NREL photo)



Relief valve nozzle S/N 586381 (NREL photo)

Accomplishments and Progress: Experimental Operation Conditions

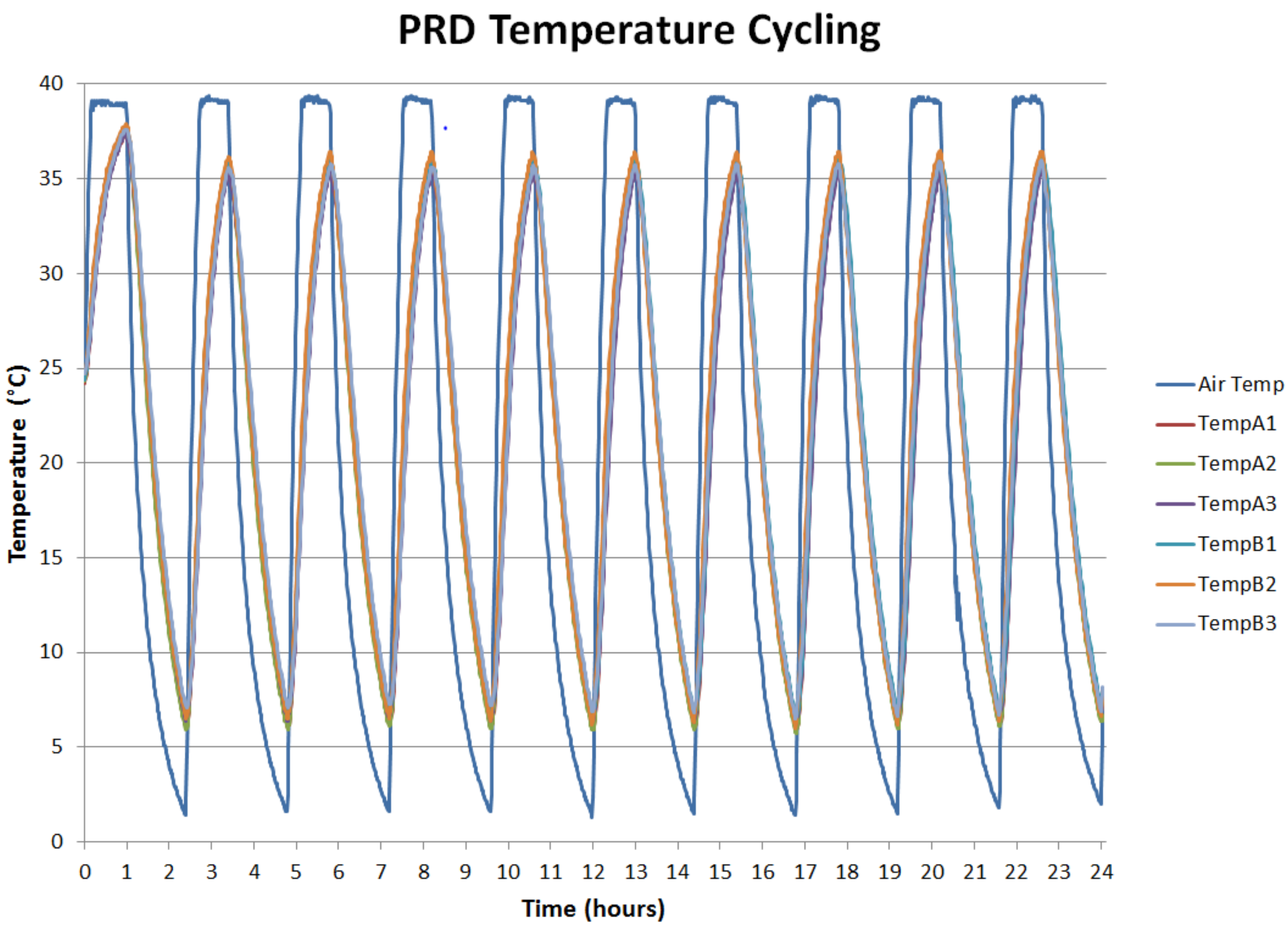
Temperature:

- Control temperature to simulate extremes over an annual cycle to mimic accelerated service conditions
  - 0°C ≤ T ≤ 39°C design
  - Actual 6°C to 36°C determined from thermal inertia of valve body
- Ramp/soak to temperature set point
  - Hold for ≈1 hour
  - Change set point, repeat
- 10 cycles per day
  - Acceleration ratio of 10:1

Pressure:

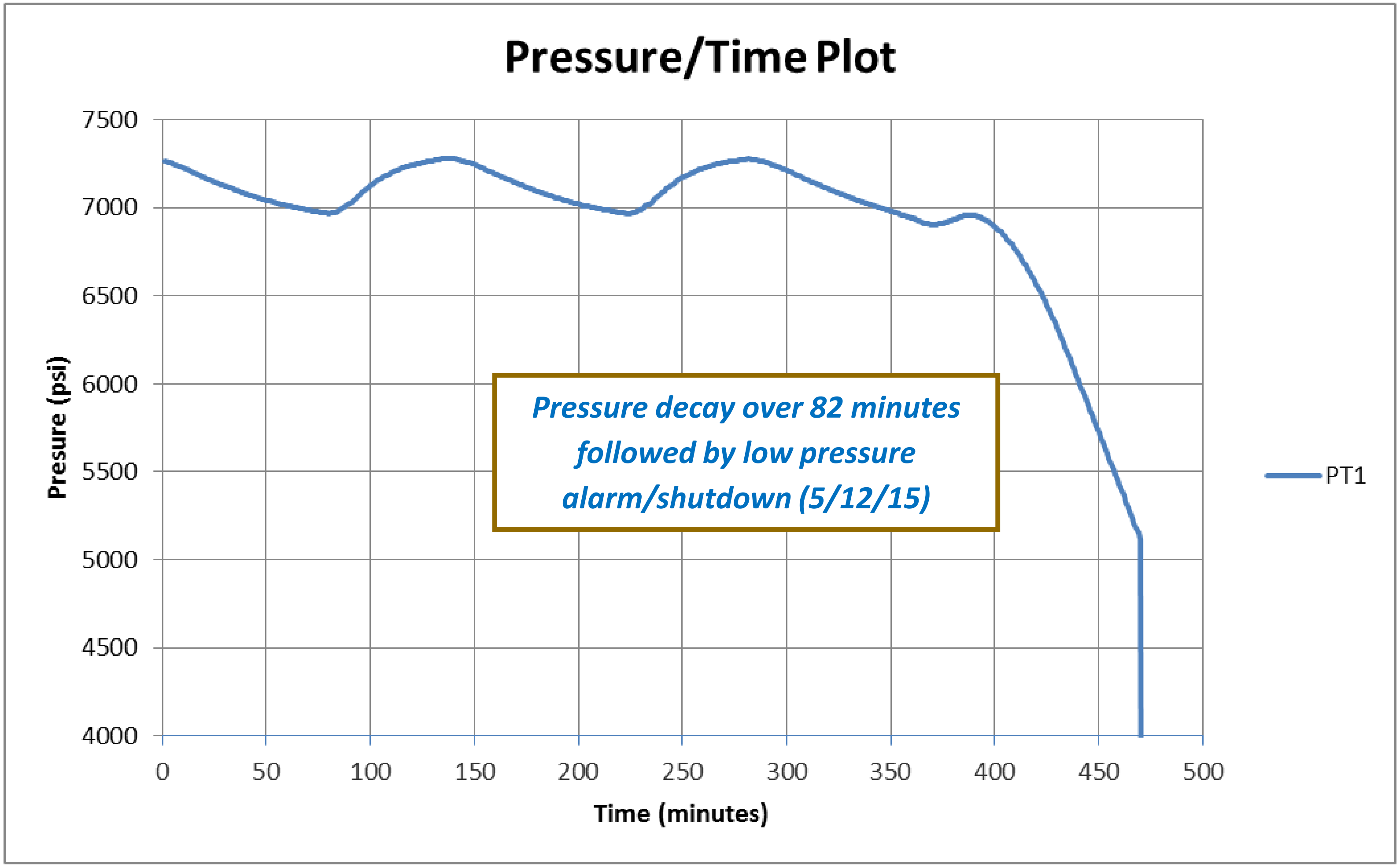
- Initial fill to 7,000 psi
  - Relief valve set point – 8,000 psi
  - Slow leak rate due to valve cracking occurs near 7,500 psi, pressure stabilizes near 7,200 psi
- Leak testing with helium
  - System leaks identified and repaired. Pressure hold for 12 hour period

Accomplishments and Progress: Accelerated Life Cycle Test



Automated PLC temperature control provides repeatable and reproducible operation over the planned temperature extremes

Accomplishments and Progress: Relief Valve Reliability



Upset condition encountered after 1200 cycles. Leak was detected in vent line. After depressurization and restart, valve was able to reseat and temperature cycle testing continued.

Accomplishments and Progress: NREL Facility Relief Valve Failure

- A relief valve at the NREL Wind-to-Hydrogen facility failed under normal use
- Failure was detected by local hydrogen detection alarm; the failed valve did not create any additional damage or injury
- An estimated 50 kg hydrogen was released based on pressure differential between start pressure and pressure at which the remaining tanks were isolated
- Root cause determination is pending facility shutdown when valve can be safely removed from service

Accomplishments and Progress: Component Outreach

- **NREL Component Webinar February 4, 2015**
  - Provide educational information on hydrogen component issues to industry stakeholders
  - Establish new collaborations with component suppliers
  - Solicit input on gaps and future direction during Q&A session

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Hydrogen Component Webinar

Informational Webinar:
Hydrogen Component R&D to Enable FCEV Technologies
Supporting Development and Deployment of Hydrogen Infrastructure

Join us Wednesday February 4th 11-12am Mountain Standard Time (1-2pm EST, 10-11am PST)

Presented by: Carl Rivkin, Chris Ainscough, Robert Burgess, William Buttner and Michael Peters, Huyen Dinh, National Renewable Energy Laboratory (NREL) Fuel Cell Technology Program

About this Webinar
NREL is supporting hydrogen infrastructure deployment through hydrogen component R&D. These DOE funded component projects support the goals of H_2USA member organizations. NREL's role is to provide R&D support to hydrogen technologies and is coordinating this effort with Sandia National Laboratory through the H_2FIRST collaborative agreement. These component projects are aimed at improving the safety, reliability and operating costs of hydrogen systems by working closely with industry partners. Collaboration with other key stakeholders provides feedback to help direct the research efforts. Presentations will be followed by a question and answer period.

Join this webinar to learn about
- Factors in design selection for hydrogen systems
- Pressure relief valve failure mode investigation
- Hydrogen safety sensor evaluations
- Dispenser metering support
- 70 MPa hydrogen dispenser hose reliability testing
- Future work

Who Should Attend
- Component manufacturers
- Fuel cell manufacturers
- Hydrogen system end users & integrators
- Interested stakeholders

Accomplishments and Progress: Metrology Collaboration

- **Metrology information exchange meeting held January 14, 2015, at NREL**
- **U.S. representation from DOE, NREL, NIST**
- **Japan representation from AIST, HySUT, Tatsuno, Iwatani**
- **Sharing of lessons learned from station metrology efforts in United States and Japan**
- **Outcome**
  - Metrology methods
  - Flow standards development
  - Future joint test projects

Picture of NREL, NIST, DOE, and NEDO project members at the January 14, 2015, joint meeting held at NREL. From left to right: Mr. Komiyama (HySUT), Dr. Otaki (Tatsuno), Mr. Ito (Iwatani), Mr. Osawa (Tatsuno), Mr. Kaneko (HySUT), Dr. Rivkin (NREL), Dr. Morioka (AIST), Dr. Burgess (NREL), Dr. James (DOE), Dr. Buttner (NREL), and Dr. Pope (NIST).

Accomplishments and Progress: Component Open House

- **NREL held a Hydrogen Component Open House May 28–29, 2015, to:**
  - Provide educational information on hydrogen component issues to industry stakeholders
  - Establish new collaborations with component suppliers
  - Solicit input on gaps and future direction during Q&A session

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Hydrogen Component Open House

Hydrogen Component Open House: Hydrogen Component R&D to Enable FCEV Technologies

Supporting Development and Deployment of Hydrogen Infrastructure

Save the dates and reserve a seat- there will be limited space available so reserve early. This open house includes lab tours and opportunity for extensive discussion/exploration of potential collaboration

May 28 & 29, 2015
Thursday May 28th 1pm-5pm Mountain Standard Time &
Friday May 29th 9am-3pm Mountain Standard Time

Presented by: NREL Hydrogen Component Researchers, National Renewable Energy Laboratory (NREL) Fuel Cell Technology Program

About this Open House
NREL is supporting hydrogen infrastructure deployment through hydrogen component R&D. These DOE funded component projects support the goals of H_2USA member organizations. NREL's role is to provide R&D support to hydrogen technologies and is coordinating this effort with Sandia National Laboratory through the H_2FIRST collaborative agreement. These component projects are aimed at improving the safety, reliability and operating costs of hydrogen systems by working closely with industry partners. Collaboration with key stakeholders provides feedback to help direct the research efforts.

Open House Structure

- May 28 1-5pm Short presentation on NREL hydrogen component and system research
- May 29 9am-12pm Lab tours/ discussion
- May 29 12pm -3pm Feedback on NREL research activities and discussion of collaborations and future project work

Attend this open house to learn about

- Potential R & D collaborations with NREL
- Factors in design selection for hydrogen systems
- Pressure relief valve failure mode investigation
- Hydrogen safety sensor evaluations
- Dispenser metering support
- 70 MPa hydrogen dispenser hose reliability testing
- Future work/collaborations

NREL Component Collaborations

- Codes and standards development organizations – SAE, CSA, ASME, ISO, UL, NFPA, IEC, GTR, ANSI, others
- Laboratories/universities – SNL, CDFA, PNNL, JRC, NHTSA, NIST, CSM, others
- Collaboration across DOE subprograms including Technology Validation program for systems-level safety/reliability integration
- Work on GTR validation testing for incorporation into Federal Motor Vehicle Safety Standards (FMVSS)

Technology Transfer Activities

- **NREL's ESIF laboratory is a designated User Facility**
  - Developing work for others opportunities to further DOE/NREL activities is being pursued through outreach activities such as the NREL Hydrogen Component Open House
  - Examples include the work NREL completed for the California Department of Food and Agriculture (CDFA) Division of Measurement Standards (DMS)

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **"It appears that the capability (relief valve testing) is designed around the testing campaign at hand, leading to restricted temperature and pressure range of operation (0°C ≤ T ≤ 39°C, 48 MPa). The project team is planning to upgrade the facility to 70MPa, but there was no mention of upgrading the temperature range."**
  - Response: NREL has capability within the ESIF laboratory for testing to higher pressures with systems rated to 105 MPa. This covers the range of 70 MPa component testing needs for existing and future projects. Utilizing these relief valves with a set pressure of 8,000 psi (55 MPa) will provide a better understanding of performance-based standards designed to fail a part with a known failure mode in hydrogen service. The temperature range being tested is designed around actual extremes of environmental conditions at the location that produced a known failure. Higher temperature ranges can be included in future testing. NREL has capability for testing at −40°C to temperatures well above 40°C.
- **"A serious gap is not yet being addressed, and that is one of metering... There are several technology gaps 1) a fueling station mass flow rate meter that meets HB44 under a J2601 fill, 2) a mass flow rate device to qualify this meter, 3) a facility to qualify the master meter."**
  - Response: NREL is working with flow meter stakeholders to better understand these gaps and to provide support to flow meter manufacturers. NREL hosted a hydrogen metrology information exchange and is working on securing resources to conduct metrology testing on available flow meters to provide a baseline of performance that can be used as a basis for further development. NREL is also working with NIST on this effort to utilize NIST's metrology expertise and flow meter testing facilities.

Proposed Future Work

- **FY15 future work priorities**
  - Continue pressure relief valve testing – including potential for additional stresses (pressure cycles, notched parts)
  - Perform dispenser flow meter testing to provide baseline meter performance
  - Conduct master meter testing in high pressure hydrogen in collaboration with NIST flow measurement division
  - Collaborate with test laboratories to help enable NRTL/manufacturer component certification efforts
  - Perform accelerated life testing of receptacle wear and nozzle durability
  - Test low temperature sealing and publish best practices

Nozzle/Receptacle Testing (Future Work)

Design Features

- **Linear actuators**
- **Compact design**
- **Pressure hold and leak check**
- **Nozzle batch testing**
- **Stressors**
  - Velocity
  - Alignment
  - Angular offset

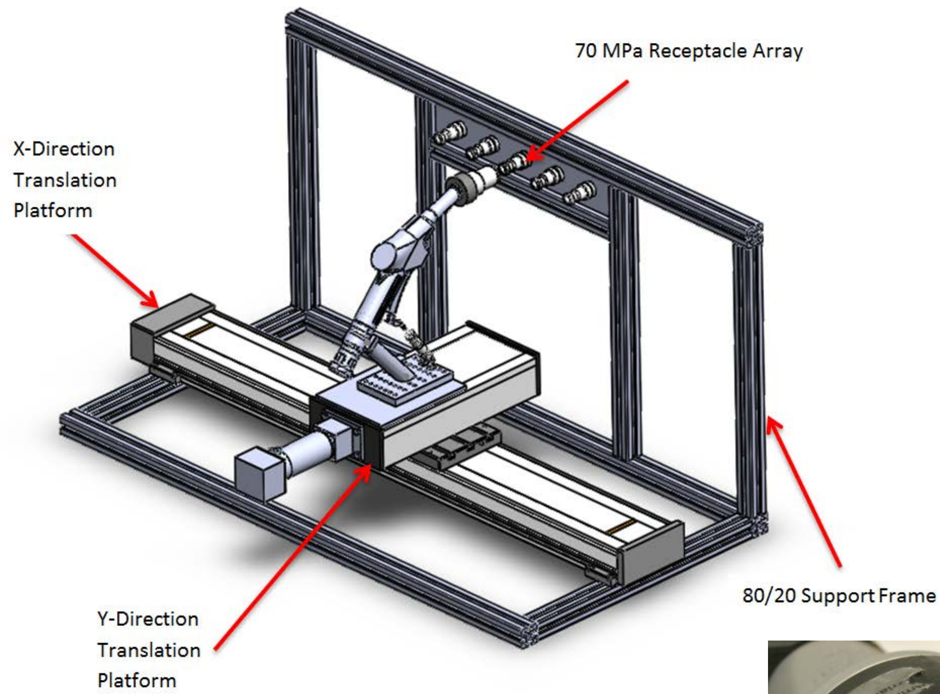


Figure 1. Nozzle/Receptacle Mechanical Testing Platform

70 MPa hydrogen dispenser nozzle (NREL photo)

Summary

Relevance: Safe deployment of hydrogen fuel cell technologies is dependent on components that are proven to perform safely and reliably as measured against new safety and performance standards.

Approach: NREL will work with manufacturers, installers, and NREL's Technology Validation program to prioritize gaps, then work toward closing those gaps by conducting hydrogen component R&D and performance validation.

Accomplishments and Progress: NREL is leveraging component R&D accomplishments, having provided a sound technical basis for new hydrogen codes and standards, and is now operating under a new multi-year plan to conduct root cause analysis and R&D testing to improve safety and reliability of hydrogen system components.

Collaborations: Collaboration with codes and standards technical committees, component manufacturers, industrial partners, and hydrogen fuel cell application experts has been a key part of NREL's success in advancing component program objectives.

Proposed Future Work: NREL will continue to work with codes and standards technical committees to identify R&D gaps and to utilize the ESIF laboratories to conduct basic engineering R&D aimed at closing technology gaps.

Technical Back-Up Slides

440C Material Certificate

07-02-'08 16:42 FROM- T-277 P014/022 F-088

MelCK

Acciaierie Valbruna S.p.A.

CERTIFICATO DI COLLAUDO
ABNAHMEPRUEFZEUGNIS
INSPECTION CERTIFICATE
CERTIFICAT DE RECEPTION
EN 10204 (2005) , 3.1

JB Stock 7486

36100 VICENZA (Italia) - Viale della scienza, 25 z.i.
Stab.: 39100 BOLZANO (Italia) - Via A. Volta, 4

Cliente: VALBRUNA STAINLESS INC.
2400 TAYLOR STREET WEST
USA-FORT WAYNE, IN 46801-USA

Avviso di Spedizione: D-BZ08002705

Certificato nr: MEST824992/2008/

Conferma ordine nr: EI07008243

Ordine nr: 21238 01-36671 CASTLE

Marchio di Fabbrica:

Produttore: STABILIMENTO DI BOLZANO

Oggetto Prove: Polished Annealed Peeled

Tipo di Elaborazione: E+AOD

Punzone del Collaudatore:

CASTLE METALS CORP.
DATE RCVD 7/2/08
IAC 15059
APPROVED BY AH

91-172002
N26
PO 48914
3/12/09

Specifiche:
3440-02 35 440C A
AMS 5383 C S44004 A

AISI 440C
ASTM A276 2006 S44004 A

AMS 5880 J S44004 A

Qualità: T-440C / S44004 - IAC # 15059

Punzonatura: 440C

Marca: CMXC

Pos. nr.	Oggetto	Dimensioni - In	Tolleranze	Lunghezza - Ft	Colata	Pezzi	Peso - LB	Lotto nr.
0010	Round	1,1250	484-08B	12 / 13	421421		4.332	723404650

Sono state soddisfatte tutte le condizioni richieste

Controllo antimescolanza: OK

Controllo visivo e dimensionale: soddisfa le esigenze:

TEST	Provetta	°F		Snervamento Rp 0,2% ksi	Snervamento	Resistenza Rm ksi	Allungamento %		Strizione RA %		Resilienza		Durezza HB
Valori richiesti		min		-	-	-	-	-	-	-	-		255
		max											
A	12,50	68	L	68		119		15		21			263

Sample quenched - Hardenability

Quenching 1877 °F AIR 50 °

TEST	Provetta	°F		Snervamento	Snervamento	Resistenza	Allungamento	Strizione	Resilienza	Durezza HRc
Valori richiesti		min		-	-	-	-	-	-	58,0
		max								
B	12,50	68	L							60,4

Sample quenched - Hardenability

Quenching 1900 °F OIL 50 °

TEST	Provetta	°F		Snervamento	Snervamento	Resistenza	Allungamento	Strizione	Resilienza	Durezza HRc
Valori richiesti		min		-	-	-	-	-	-	58,0
		max								
C	12,50	68								60,1

Grain size for ASTM E112 : 8

Bolzano,06/05/08 — Il collaudatore di stabilimento / der Werkssachverständiger / Works Inspector / L' agent d'usine — M.Rizzotto — Pagina - 1 di 2

07-02-'08 16:42 FROM- T-277 P015/022 F-088

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Produttore: STABILIMENTO DI BOLZANO

Oggetto Prove: Polished Annealed Peeled

Tipo di Elaborazione: E+AOD

Punzone del Collaudatore:

Analisi chimica

Colata	C %	Si %	Mn %	Cr %	Mo %	Cu %	Ni %	P %	S %
min / max	min 0,95 max 1,20	1,00	1,00	16,00 18,00	0,40 0,65	0,50	0,75	0,040	0,030
421421	1,02	0,68	0,64	16,04	0,47	0,15	0,60	0,022	0,001

Macroetch test: ok.
Decarburation free.
Material is DFARS Compliant

Tab N.ro 1 Inclusion Rating	A	B	C	D
Thin	1,5	1,5	1,5	1,5
Heavy	1,0	1,0	1,5	1,0

Melted and manufactured in Italy. No welding or weld repair. Material free from Mercury or radio-activity contamination

91-172002
N26
PO 48913
2/12/09

Bolzano,06/05/08 — Il collaudatore di stabilimento / der Werkssachverständiger / Works Inspector / L' agent d'usine — M.Rizzotto — Pagina - 2 di 2

ESIF Component Test Utilization

Energy Systems Integration Facility

Electricity Laboratories

1. Power Systems Integration
2. Smart Power
3. Energy Storage
4. Electrical Characterization
5. Energy Systems Integration

Thermal Laboratories

6. Thermal Systems
7. Thermal Storage Materials
8. Optical Characterization and Thermal Systems

Fuel Laboratories

9. Energy Systems Fabrication
10. Manufacturing
11. Materials Characterization
12. Electrochemical
13. Energy Systems Sensor
14. Fuel Cell Development
15. High-Pressure Testing

Data, Analysis, and Visualization

16. ESIF Control Room
17. Visualization Room
18. Secure Data Center
19. High Performance Computing

- Component Testing Laboratory Capability within ESIF

Component R&D Summary

- Work with codes and standards technical committees on revision efforts as these technical documents are vetted through early market system operation
- Identify root cause safety/reliability issues by utilizing statistical data provided through NREL Technology Validation activities
- Conduct component safety analysis and testing
- Develop user facility capabilities in NREL ESIF building

ESIF – Energy Systems Integration Facility
NREL laboratory facility, includes sensor lab, high pressure test lab, characterization lab, system integration lab, secure data room, and high performance computing.

ESIF Component Test Utilization

Work Scope

	Energy Systems Integration Laboratory	Material Characterization Laboratory	Energy Systems Sensor Laboratory	High Pressure Testing Laboratory	NFCTEC Technology Validation	High Performance Computing
4.1 Compressor Reliability	x	x		x		x
4.2.Material of Construction in Hydrogen	x	x	x	x		
4.3.Hose Reliability	x	x	x	x	x	
4.4.Flow Meter Accuracy	x			x		
4.5.Low Temperature Sealing	x	x	x	x	x	
4.6.Technology Validation Study					x	x
4.7.Receptacle Wear and Nozzle Durability	x	x	x	x		
4.8.Temperature Activated Pressure Relief Device	x	x	x	x		
4.9. Certification & Listing of Components	x		x	x		
4.10.Localized Fire Scenarios	x	x				x
4.11.COPV Production and Reliability	x	x		x		x
4.12.Hydrogen Safety Sensor Performance	x	x	x	x		x

Acronyms and Abbreviations

AIST: National Institute of Advanced Industrial Science and Technology

ANSI: American National Standards Institute

ASME: American Society of Mechanical Engineers

CDFA: California Department of Food and Agriculture

COPV: Composite Overwrapped Pressure Vessel

CSA: Canadian Standards Association

CSM: Colorado School of Mines

GTR: Global Technical Regulations

HySUT: The Research Association of Hydrogen Supply/Utilization Technology

IEC: International Electrotechnical Commission

ISO: International Organization for Standardization

JRC: Joint Research Centre

NEDO: New Energy and Industrial Technology Development Organization

NFPA: National Fire Protection Association

NHTSA: National Highway Traffic Safety Administration

NRTL: Nationally Recognized Testing Laboratories

NIST: National Institute of Standards and Technology

PLC : Programmable Logic Controller

PNNL: Pacific Northwest National Laboratory

SAE: Society of Automotive Engineers

SNL: Sandia National Laboratories