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Forklift Storage Tank R&D: Timely, Critical, Exemplary

August 14, 2012

DOE EERE Fuel Cell Technologies Program Webinar

Daniel E. Dedrick and Chris San Marchi
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Webinar Objectives

- Provide an overview of Sandia and our Hydrogen Program
- Describe how FC forklifts provided an opportunity to validate the effectiveness of EERE investments in Safety, Codes & Standards
- Describe how Sandia and its partners approached the challenge of H_2 assisted fatigue
- Describe some of the critical experimental results
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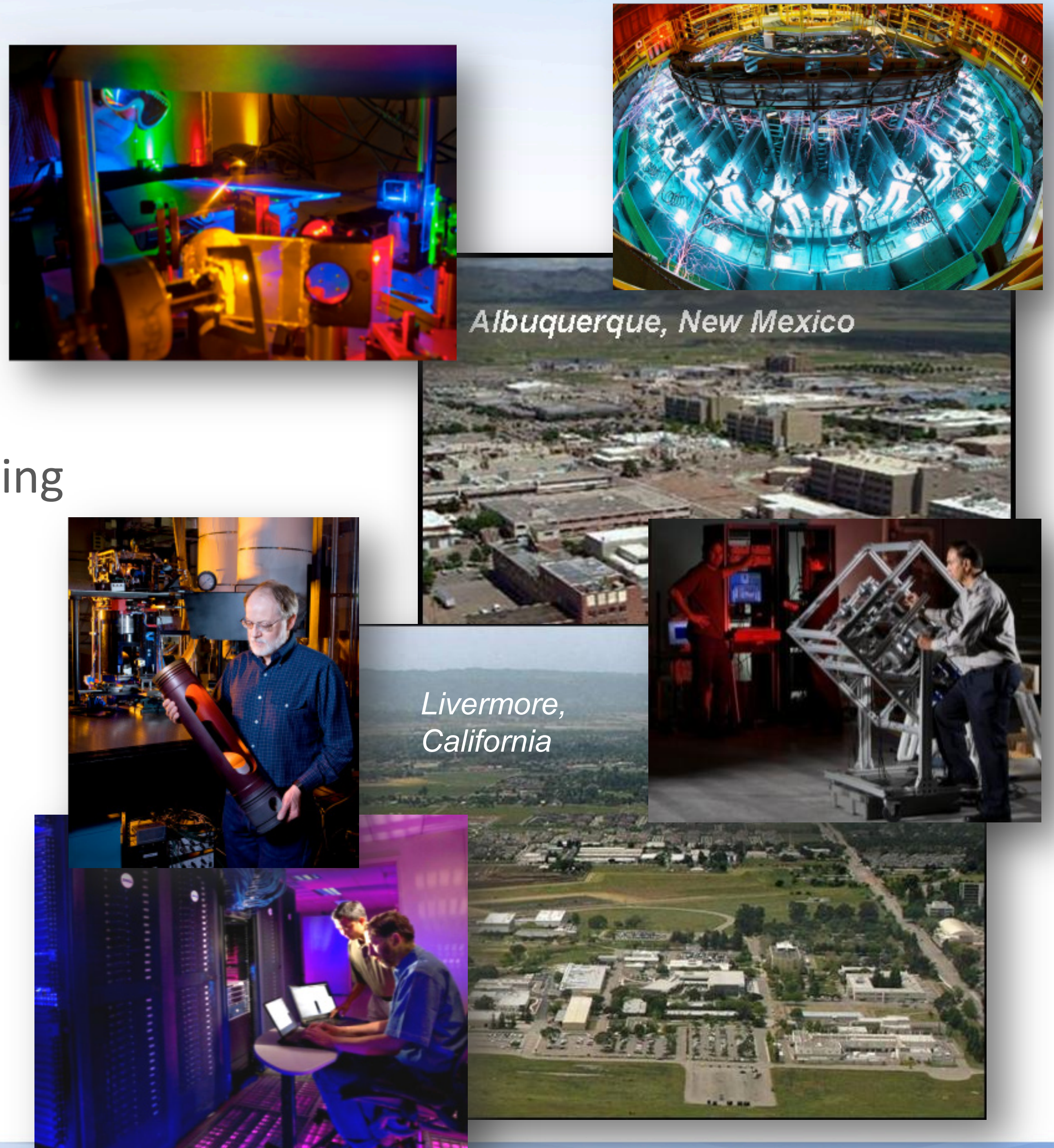
Sandia National Laboratories
"Exceptional service in the national interest"

- Largest national lab
  - ~10,000 employees
  - ~$2.3 B/yr
- Missions
  - Energy and climate
  - Nuclear security engineering
  - Defense systems
  - Homeland security
- Locations
  - Albuquerque
  - Livermore
  - Also Nevada, Hawaii, DC



Sandia Hydrogen and Fuel Cells Program

Sandia's Hydrogen Program supports the President's all-of-the-above energy strategy, helping to diversify America's energy sector and reduce our dependence on foreign oil.

- Our focus
  - Removing technical barriers to deployment and enhancing public acceptance of vehicle, fueling, and power systems.
  - Providing pathways to de-carbonization of hydrogen fuel through RD&D in renewables integration, distributed generation, and energy storage RD&D.

Energy, Climate, and Infrastructure Security (ECIS) Transportation Energy
Bob Carling (Director) & Art Pontau (Deputy Director)

Guiding Principle:

We seek to enhance our premiere H_2 science and engineering capabilities to promote US innovation and competitiveness.

Enabler:

We emphasize partnerships with leading industry, labs, and academia through our Livermore Valley Open Campus REACH Initiative.

Hydrogen Program
Daniel Dedrick

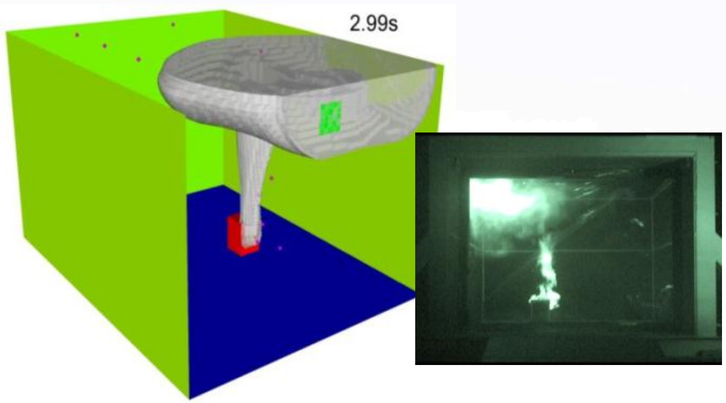
- **Project Manager** – *Marcina Moreno*
- **Business Development** – Ed Noma

- **Systems Analysis** – *Todd West*
- **Safety, C&S** – *Aaron Harris*
- **H_2 Structural Materials** – *Chris Moen*
  - Metals – *Brian Somerday*, *Chris San Marchi*
- **Renewable Production** – *Tony Martino*
  - Solar Thermochemical – *Tony McDaniel*
- **Fuel Cells** – *Tony Martino*
- **Storage** – *Daniel Dedrick (acting)*
  - Utility-scale Storage – *Anna Lord*
  - Storage materials – *Vitalie Stavila*
- **Systems Engineering** – *Aaron Harris*
  - Market Transformation – *Lennie Klebanoff*

R&D program for Safety, Codes and Standards

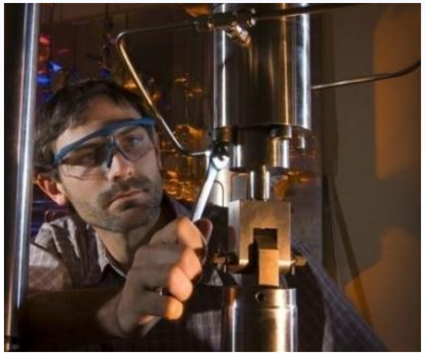
Enabling safe, efficient, and high-performing hydrogen technologies and systems

Hydrogen behavior



Simulation and experimental validation of release during indoor refueling

H_2 effects in materials, components, and systems



Mechanical load-frame used to characterize H_2 effects in materials

Online Technical Reference

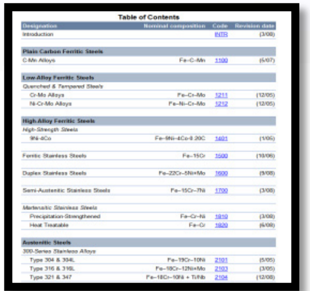


Table of Contents

Designation	Nominal composition	Code	Revision date
Introduction		INTR	(3/08)
Plain Carbon Ferritic Steels			
C-Mn Alloys	Fe–C–Mn	1100	(5/07)
Low-Alloy Ferritic Steels			
Quenched & Tempered Steels			
Cr-Mo Alloys	Fe–Cr–Mo	1211	(12/05)
Ni-Cr-Mo Alloys	Fe–Ni–Cr–Mo	1212	(12/05)
High-Alloy Ferritic Steels			
High-Strength Steels			
9Ni-4Co	Fe–9Ni–4Co–0.20C	1401	(1/05)
Ferritic Stainless Steels	Fe–15Cr	1500	(10/06)
Duplex Stainless Steels	Fe–22Cr–5Ni+Mo	1600	(5/08)
Semi-Austenitic Stainless Steels	Fe–15Cr–7Ni	1700	(3/08)
Martensitic Stainless Steels			
Precipitation-Strengthened	Fe–Cr–Ni	1810	(3/08)
Heat Treatable	Fe–Cr	1820	(6/08)
Austenitic Steels			
300-Series Stainless Alloys			
Type 304 & 304L	Fe–19Cr–10Ni	2101	(5/05)
Type 316 & 316L	Fe–18Cr–12Ni+Mo	2103	(3/05)
Type 321 & 347	Fe–18Cr–10Ni + Ti/Nb	2104	(12/08)

http://www.sandia.gov/matlsTechRef/

Quantitative Risk Assessments

Quantitative Risk Assessment helps establish requirements for hydrogen installations

C&S development support

NFPA · CSA · SAE · UL · ISO · ICC INTERNATIONAL CODE COUNCIL · ASME SETTING THE STANDARD

Regulations Codes and Standards Advocacy

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Sandia's objectives for materials R&D in Safety, Codes & Standards

- Enable *market transformation* by providing critical data for standards and technology development
  - Create materials reference guide ("Technical Reference") and identify material property data gaps
  - Execute materials testing to meet immediate needs for data in standards and technology development
  - Improve efficiency and reliability of materials test methods in standards

- Participate directly in standards development
  - Design and safety qualification standards for components
    - SAE J2579, CSA HPIT1, ASME Article KD-10
  - Materials testing standards
    - CSA CHMC1

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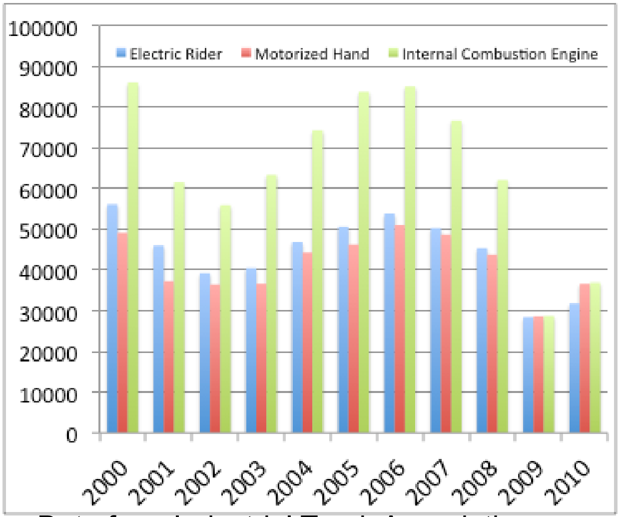
Fuel cell forklifts – a market transformed with ARRA funding as a catalyst

- Through ARRA funding, there were over >500 FC-forklifts deployed*
  - Combined 1 million hours of runtime
- Today, there are over 3500 additional FC forklifts installed or planned *with no DOE funding*
  - Combined 6.5 million hours of run time**
- Industry innovation led the deployment of FC forklifts
  - Enabling bridging funding (ARRA)
  - Technologies deployed "without all the answers"

Number of forklifts shipped from US factories per year indicates room for significant growth:



Data from Industrial Truck Association
https://www.indtrk.org/marketing.asp

*US DOE EERE FCT program source ** Plug Power data

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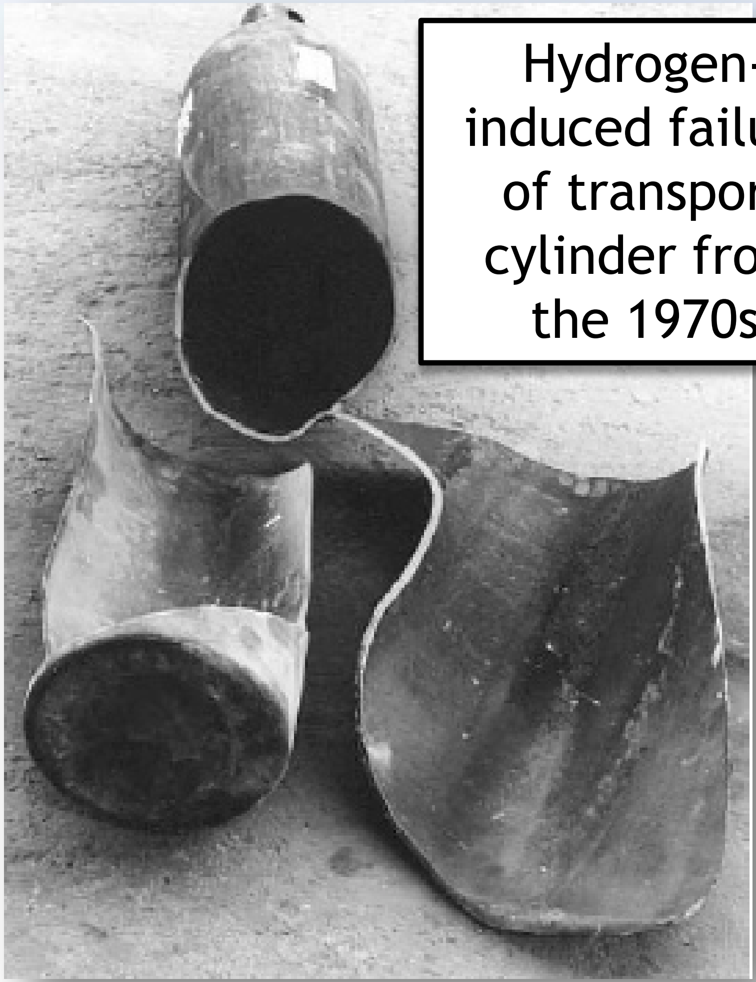
The challenge: the cycle-life of steel storage tanks uncertain

- DOT-spec low-alloy steel tanks allow for:
  - Low cost
  - Appropriate weight
  - Accelerated filling

- Fracture and fatigue resistance of steels is degraded by exposure to H_2

- Forklifts represent an expanded design space beyond engineering experience
  - >10,000 refueling cycles are anticipated for hydrogen-powered industrial trucks*
  - Tanks must "leak-before-burst"

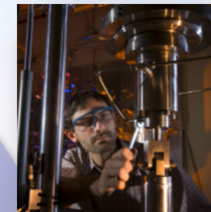


Hydrogen-induced failure of transport cylinder from the 1970s

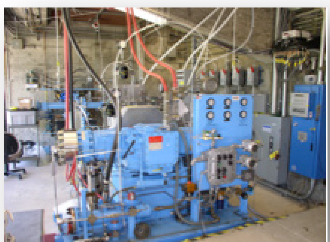
Ref.: *Barthélémy, 1st ESSHS, 2006*

*HPIT1 working group

A healthy S,C&S program was critical to the timely and appropriate response to challenges

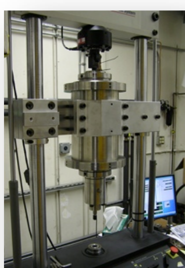


People
(SNL and Partners)

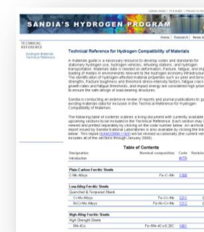


Unique Tools
(labs, diagnostics, software)

Communication infrastructure
(HIPOC, Safety Panel, working groups)



Technical Reference



U.S. DEPARTMENT OF ENERGY
NNSA
Energy Efficiency & Renewable Energy

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The Program supports three critical communication and coordination entities

Entity	Critical Role	DOE Contribution
Ad-hoc industry groups (eg. HIPOC)	**Ask critical questions: How will H_2 embrittlement impact cycle-life? Will tanks "leak-before burst"?**	**Provide world's leading experts in H_2 effects in materials**
Regulations, C&S development committees	**Assemble and promote CSA HPIT1, CHMC1, SAE, ASME, UN GTR committees**	**Measure properties, developed models and validated understanding**
Safety Panel	**Provide forum for discussion of forklift installations**	**Promulgate learning with site visits and online resources**

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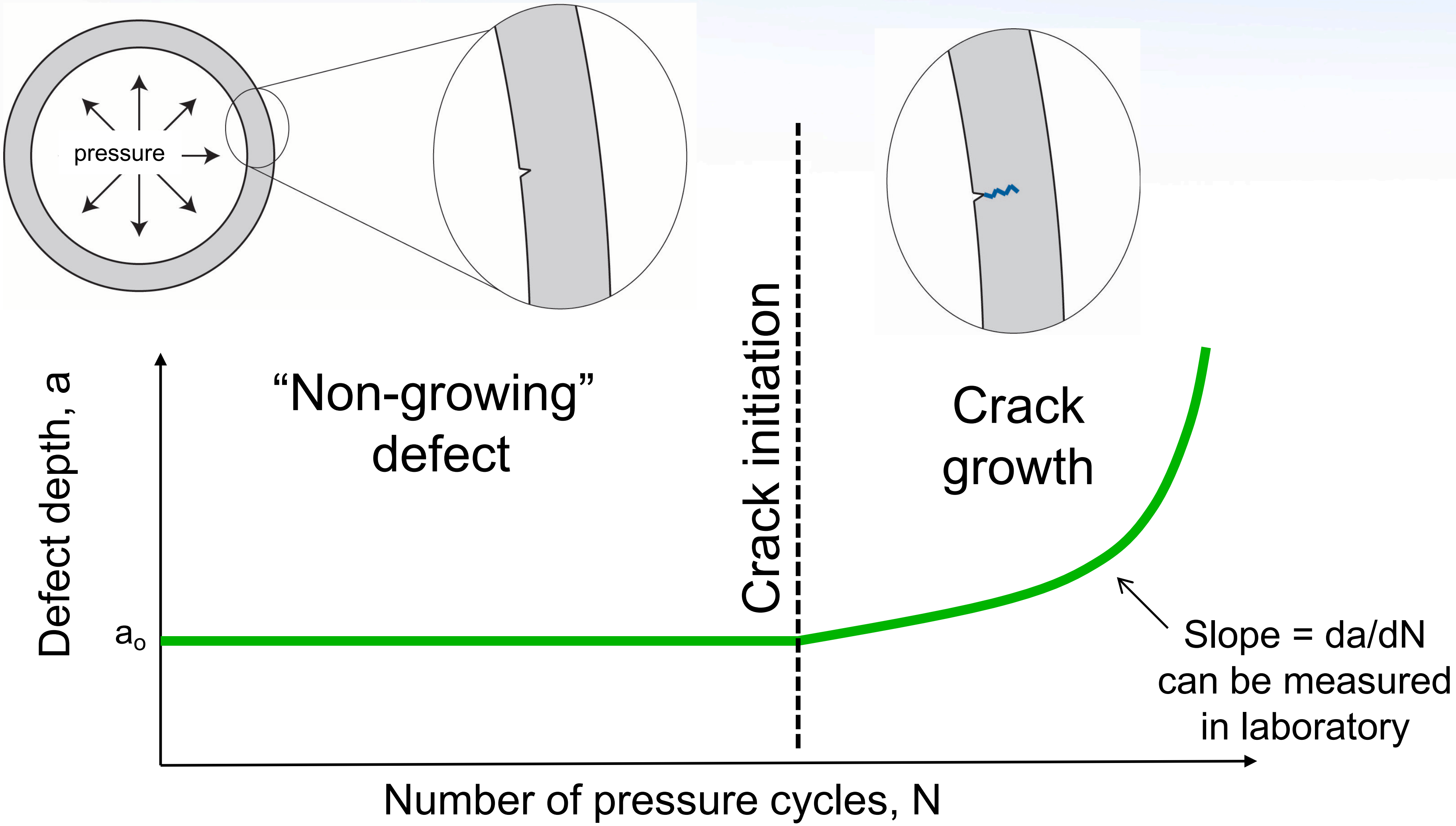
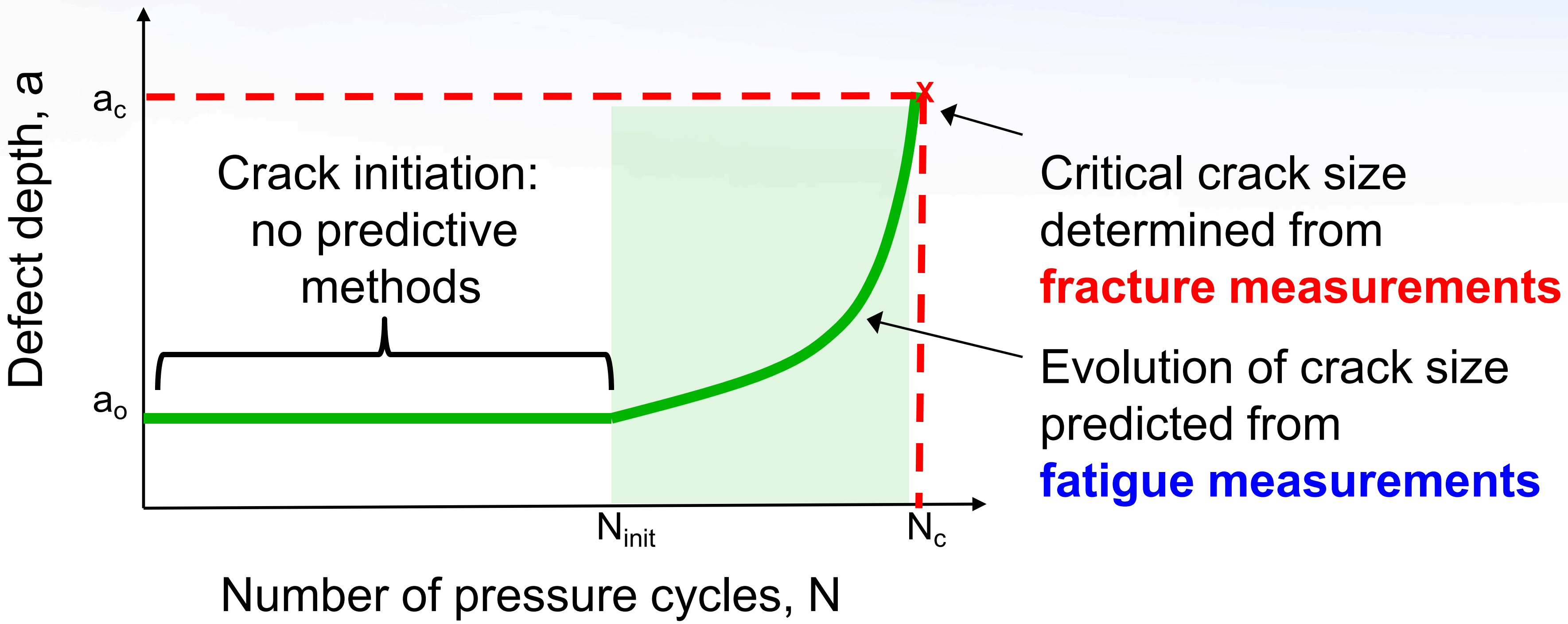
Fatigue life depends on crack initiation and crack growth



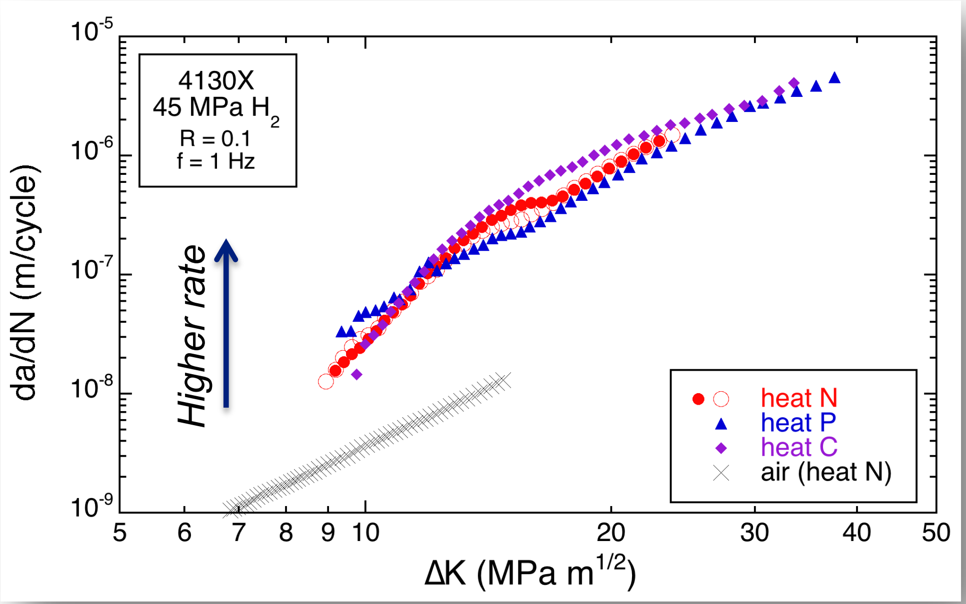
Fatigue life qualification by fracture mechanics does not account for initiation



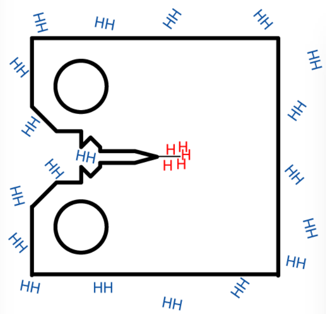
- Implicit assumption:
  cracks "initiate" at first cycle, i.e. $N_{init} = 0$
  GAP ⇒ is crack initiation important?

Fatigue crack growth is accelerated in gaseous hydrogen

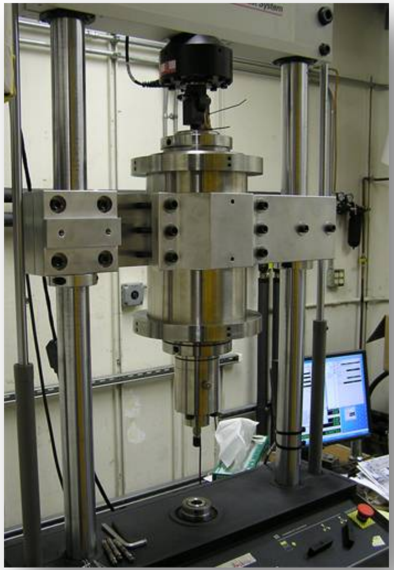
- Fatigue crack growth rates measured in gaseous hydrogen at pressure of 45 MPa and compared to measurements in air
- 3 heats of 4130X steel from pressure vessels



Coupon



Test rig



Ref: San Marchi et al., ICHS4, San Francisco CA 2011.

- Cycle-life can be predicted from this data
  ASME BPVC VIII.3 KD-10 specific to hydrogen tanks (based on KD-4)

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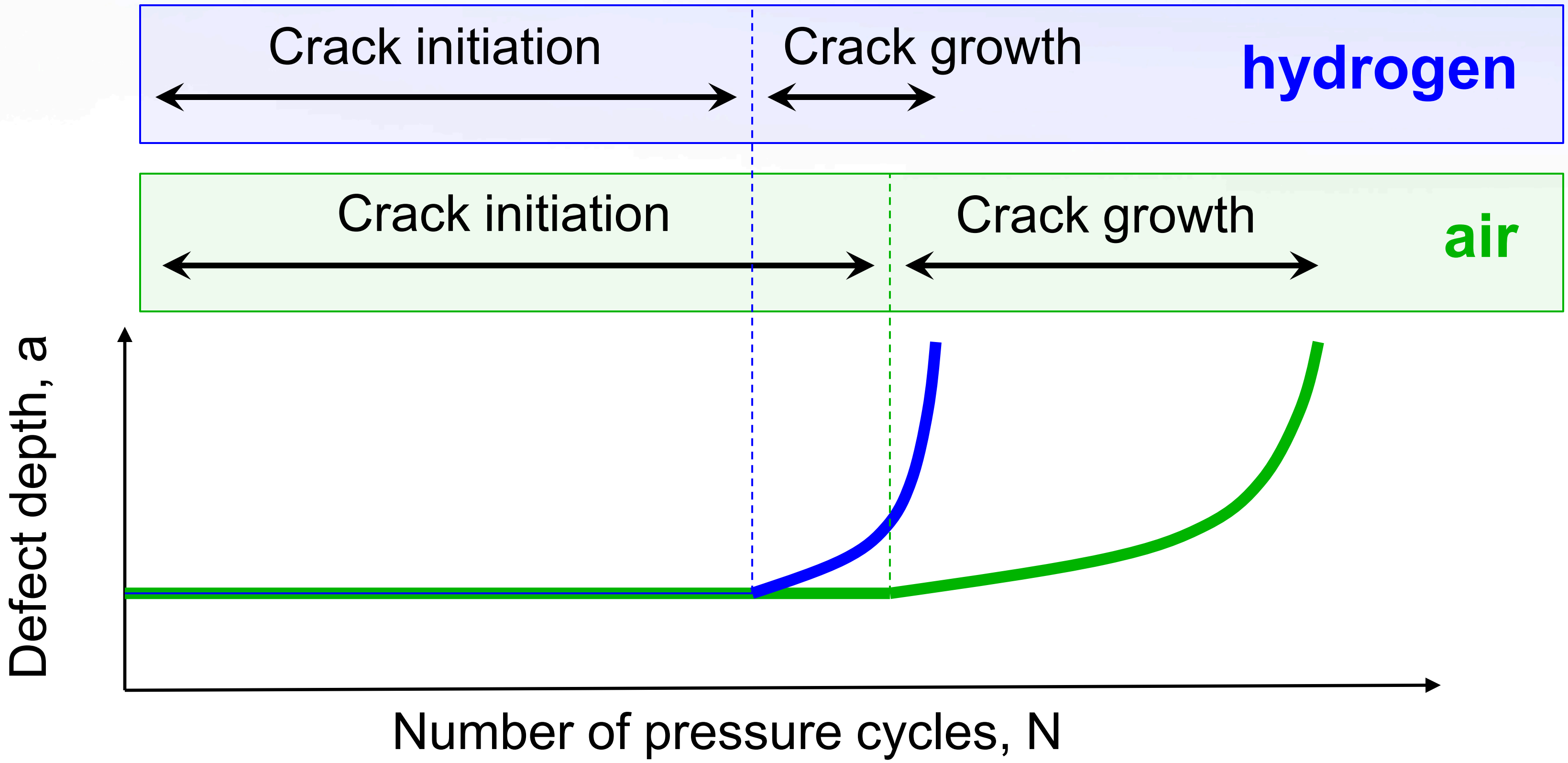
Designing for crack growth only in H_2 can be very conservative

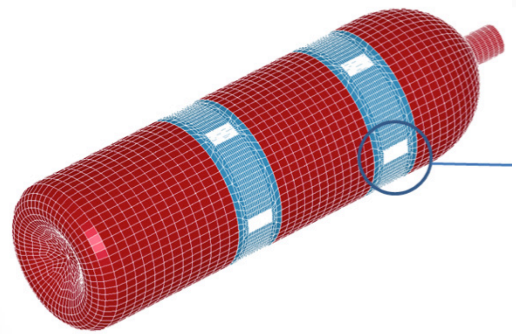


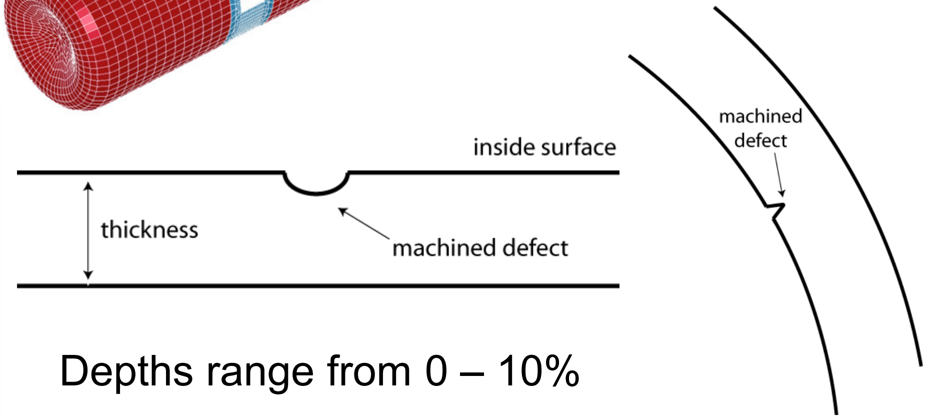
Crack growth methods predict cycle-life in hydrogen as low as a few thousand pressure cycles for tank geometries of interest

Tanks acquired from OEM partners and modified to accelerate R&D

NUVERA FUEL CELLS · NORRIS CYLINDER · plugpower

Engineered defects used to initiate failures





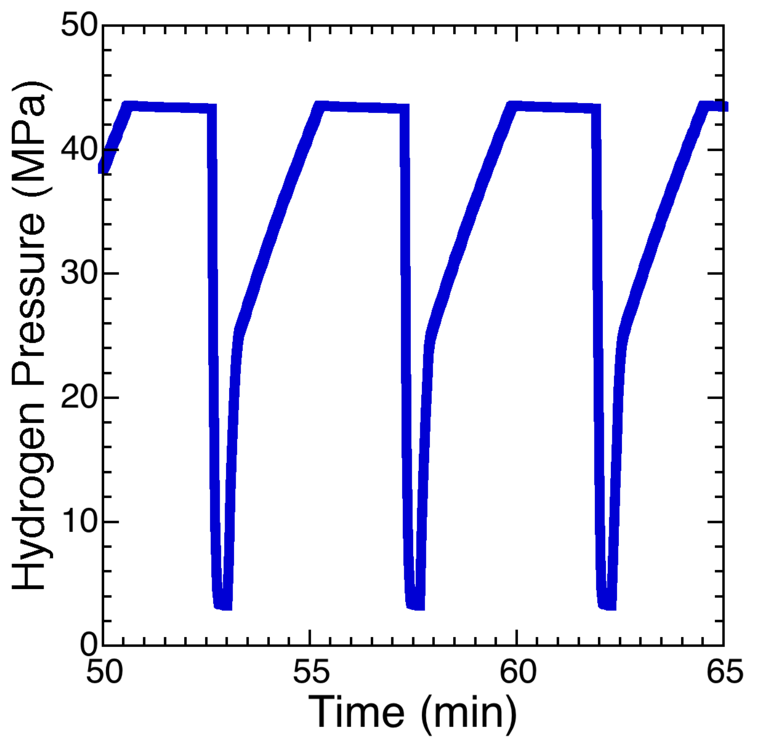
Depths range from 0 – 10%

Allows for investigation of crack growth and initiation in real tanks - critical for understanding cycle-life

Accelerated pressure cycle designed with partners, SDOs

Relevant for 350 bar gaseous hydrogen fuel system

- Nominal pressure of 35 MPa
- Allow 25% over-pressure during rapid filling
- Minimum system pressure of ~3 MPa



Pressure cycle for testing

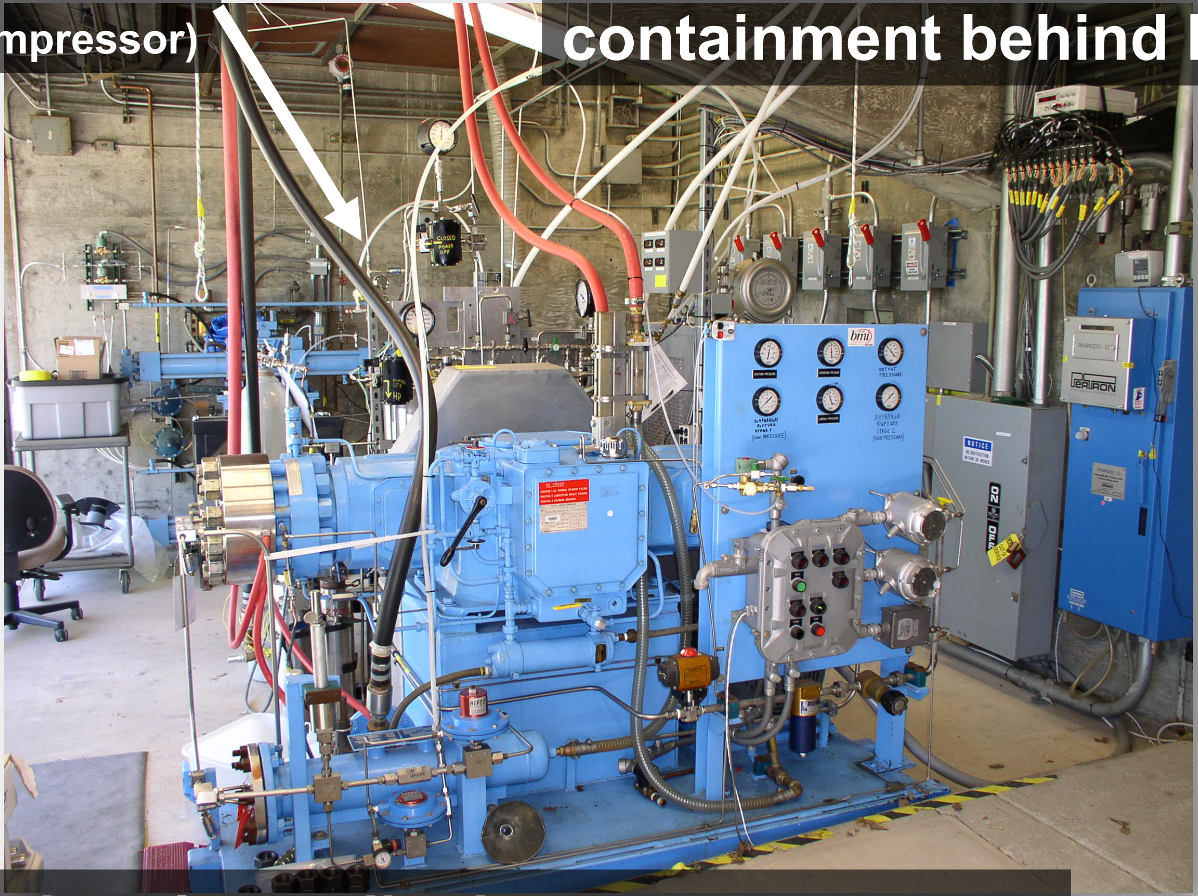
- maximum P = 43.5 MPa
- 2-minute hold at maximum P
- rapid depressurization to 3 MPa
- 30-second hold at minimum P
- pressurization time ~ 2 min

4 to 5 minute cycle time
(~300 cycles per day)

Closed-loop system developed for pressure-cycling 10 tanks simultaneously

Accumulators
(behind compressor)

Tanks in secondary containment behind blast door



High-volume diaphragm compressor

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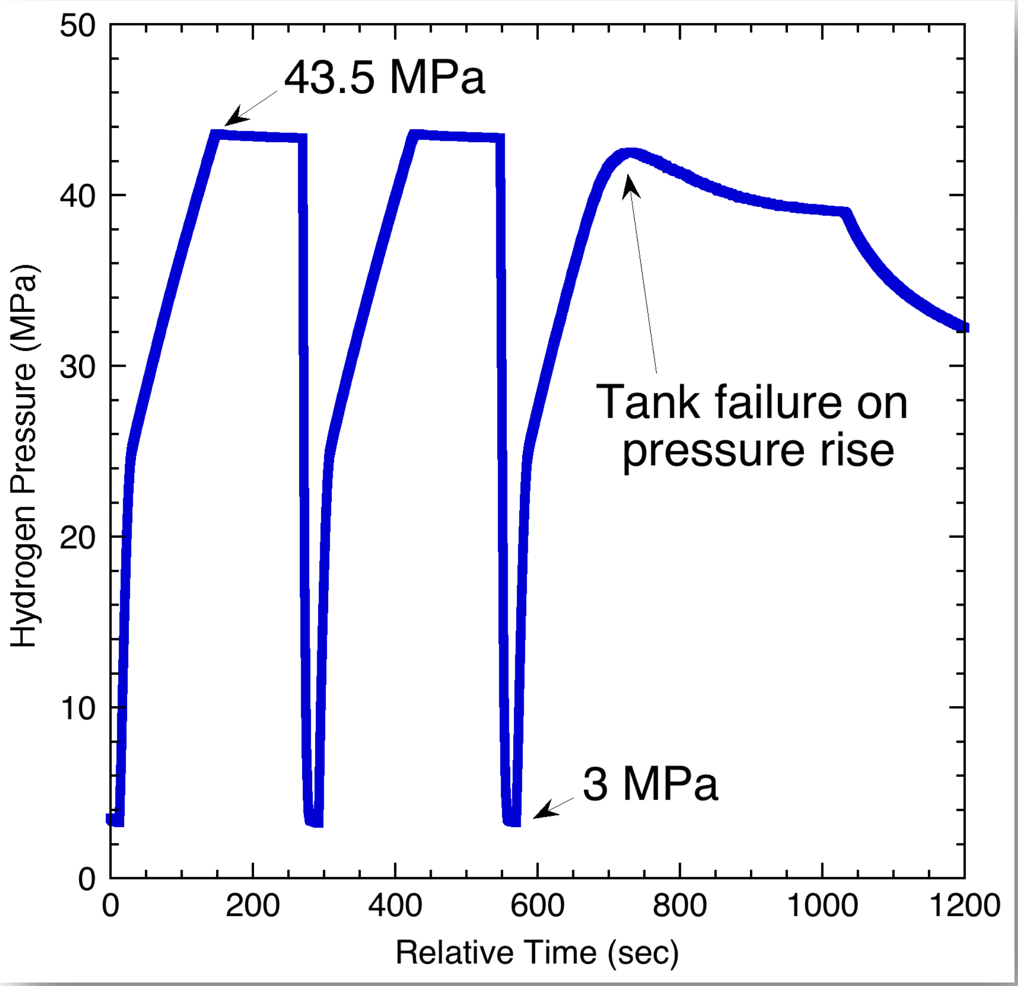
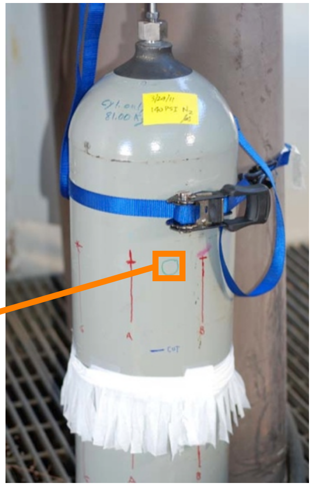
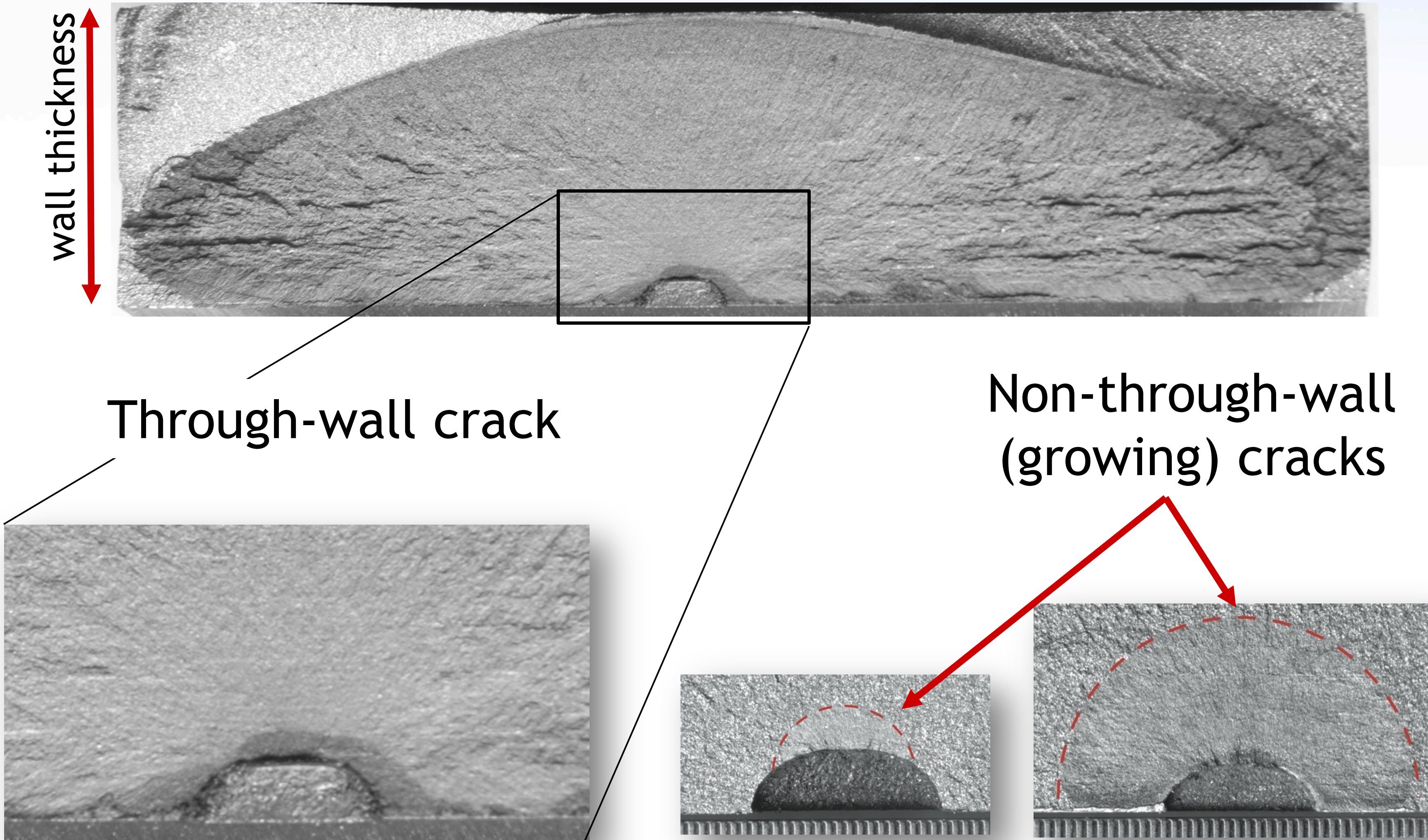
Key learning: all observed failures are leak-before-burst



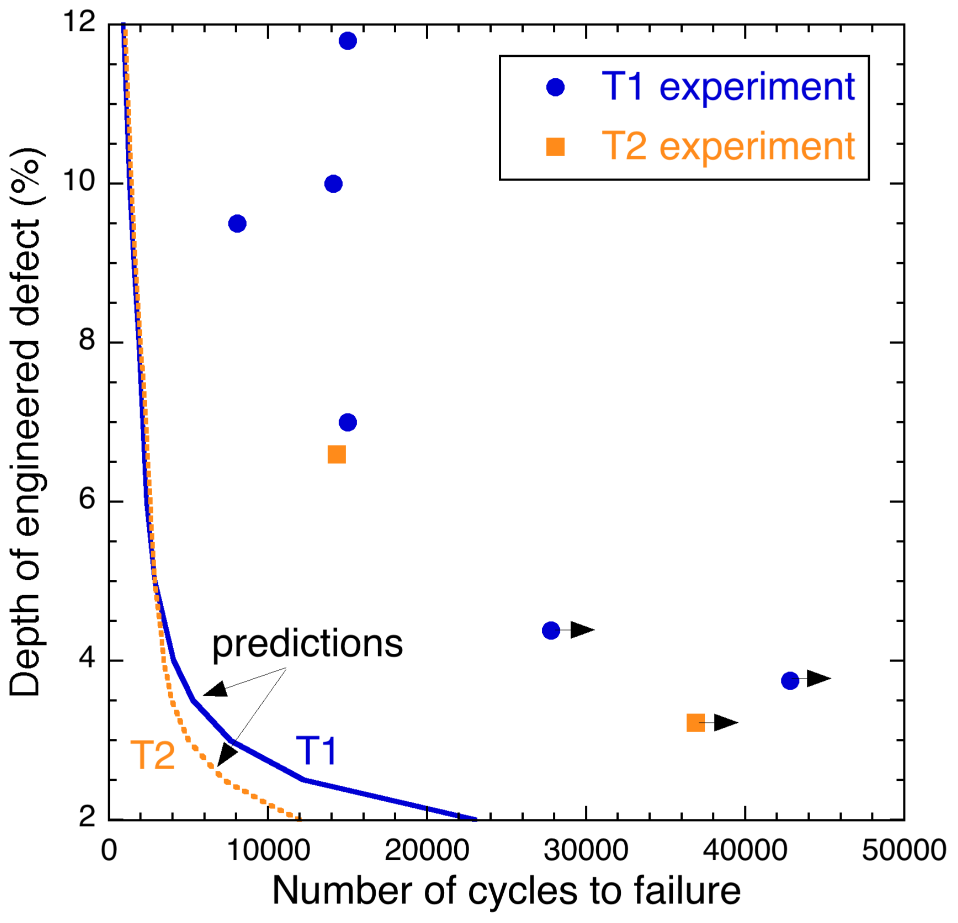
- All failures occur during pressure ramp
- At failure, pressure vessel “slowly” leaks gas into secondary containment
- After failure, vessels can be pressurized to ~10 MPa without leakage
- Through-wall crack cannot be detected visually



Fatigue cracks extend from all engineered defects



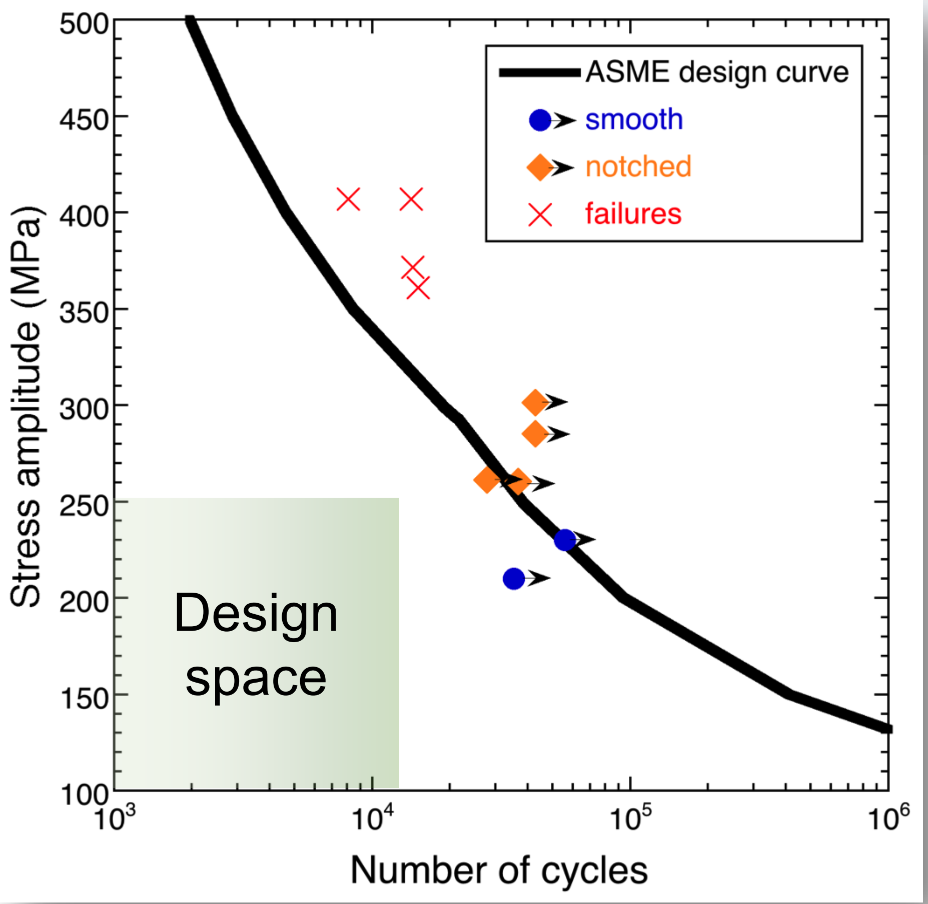
Fracture mechanics approach is conservative for small initial defects



Comparison of life predictions based on fracture mechanics (ie *crack growth* only) and full-scale measurements

- Predictions are conservative by factor of 4 or more
- For small initial defects, effective safety factor approaches 10

Fatigue-life methods offer framework for incorporating crack initiation



Comparison of design curve for fatigue in air from ASME BPVC VIII.3 KD-3 and measurements

- By understanding the design space of hydrogen tanks, forklift tanks can be shown to be safe
- CSA HPIT1 defines allowable design space to ensure conservative design

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Draft CSA Standard for Compressed Hydrogen Powered Industrial Truck On-Board Fuel Storage and Handling Components (HPIT1)

Performance requirements

- Leak-before-break requirements
  - type 1, 2 and 3: ASME VIII.3 KD-141
  - type 4: ISO 15869 Annex B.8
- Two design options:
  - Fatigue life verification by ***testing*** with engineered defect

    OR
  - Fatigue life qualification by ***analysis***

3X maximum fill cycles specified by manufacturer

Maximum fill cycles determined from ASME BPVC VIII.3 KD-3

What this means:

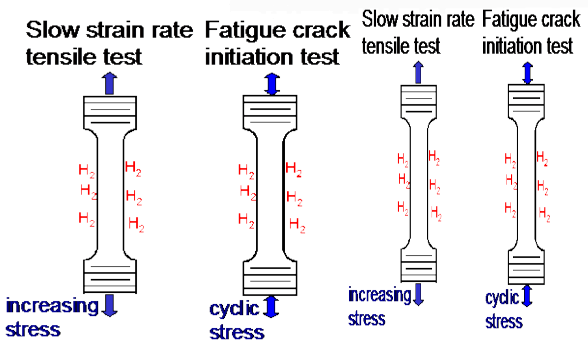
- The OEMs have non-prescriptive options for qualification and are not restricted to a certain facility or method – ***supports innovation***

CSA HPIT1 will be published this year (2012) and provides a persistent template for safe tank design

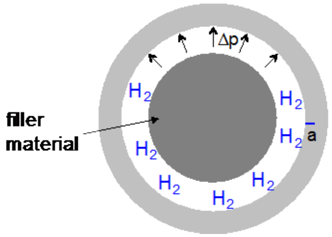
Program investments led to three new sections in SAE J2579 that enable H_2 compatibility qualification

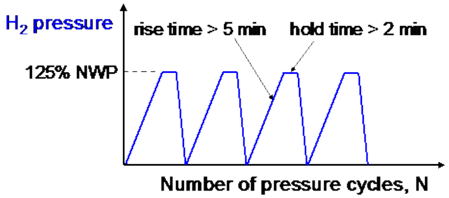
Qualification tests incorporated to evaluate "durability" under H_2 gas pressure cycling, i.e., hydrogen embrittlement

- Materials compatibility exemption (Appendix B.2.3)
  - ***Sandia and partners worked together to gain consensus***



- Design Unrestricted (Appendix C.15)
  - Materials testing procedures in SAE J2579 ***developed through collaboration U.S., Japan, and Europe***
  - May eventually point to *CSA CHMC1* for materials testing





- Design Restricted Qualification (Appendix C.14)
  - Test procedures ***based on Sandia tank testing and CSA HPIT1 activities***

SAE working group on H_2 embrittlement represents international effort and is being leveraged for the GTR

Japan
JARI
AIST/HYDROGENIUS

Europe
Adam Opel
BMW
Robert Bosch
Linde

- SAE J2579 Appendix B.2.3
- SAE J2579 Appendix C.15
- SAE J2579 Appendix C.14

USA
GM
Sandia National Laboratories

GTR
Global Technical Regulation

1998 Agreement to harmonize vehicle regulations

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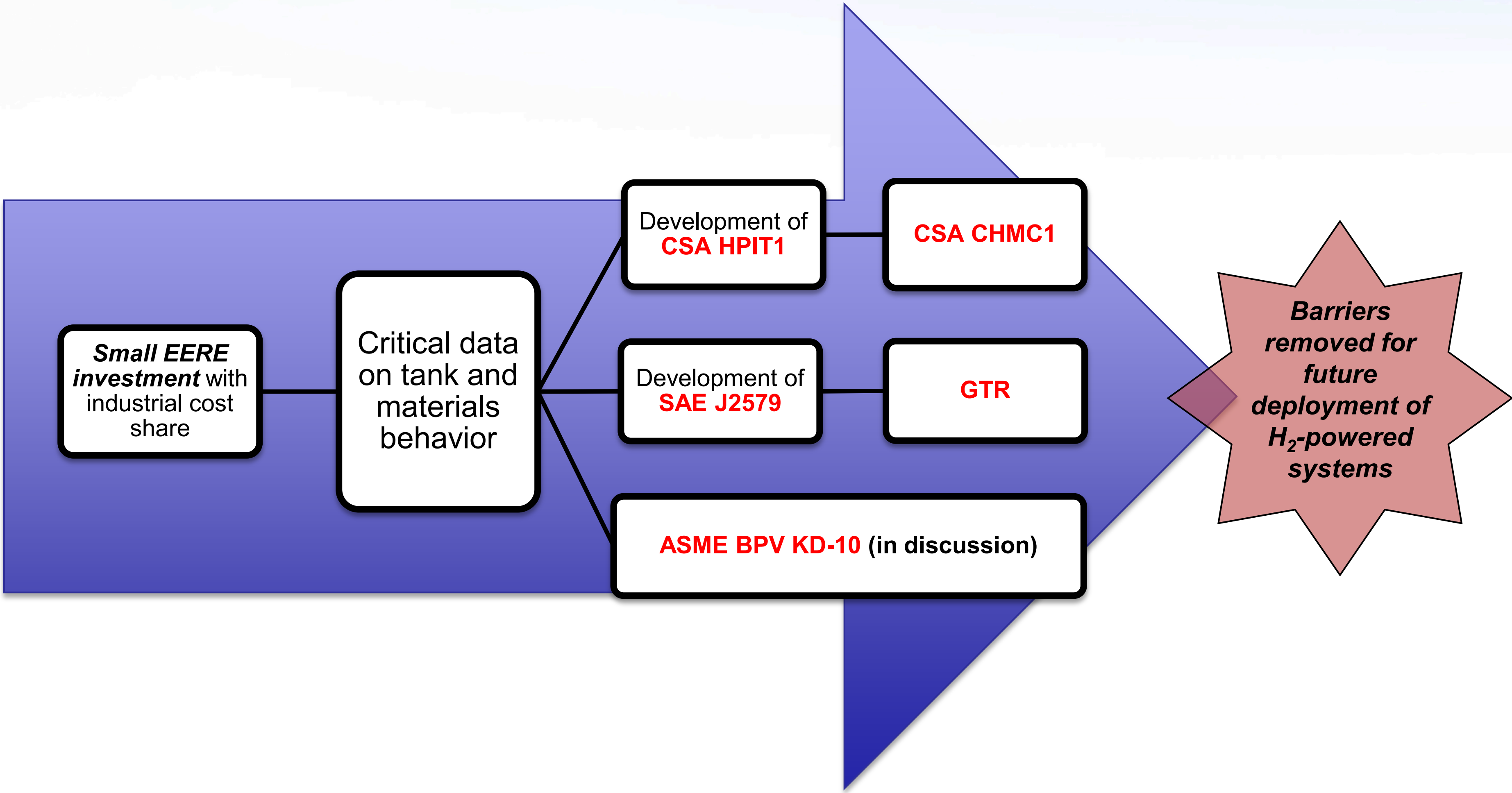
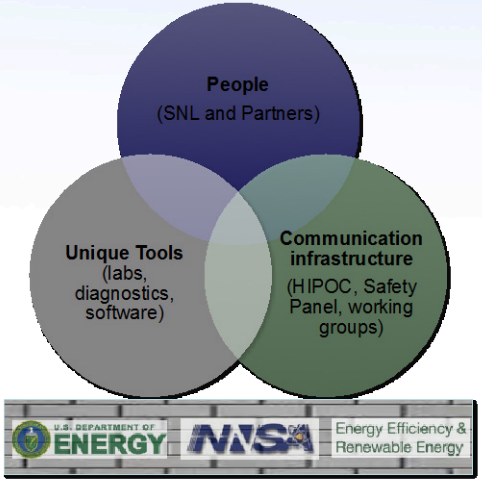
Summary: This timely investment by EERE has enabled development of 5 critical Regulations, Codes, and Standards



How do we replicate this success when the next challenge presents itself?

- Continue to foster enduring capabilities
- Emphasize industrial partnerships
- Maintain effective dialog between industry, research and S,C&S community



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