



Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility

May 8, 2013

Defense Energy Seminar, Naval Postgraduate School

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Sandia National Laboratories

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Outline of Presentation

- Provide brief overview of Sandia National Laboratories and the Hydrogen Program at Sandia
 - Emphasis on materials compatibility with gaseous hydrogen
- Brief introduction to current scale of hydrogen usage
- Description of incident at Emeryville refueling station
 - Summary of events and timeline
 - Failure analysis
 - Recommendations and Lessons Learned from the incident

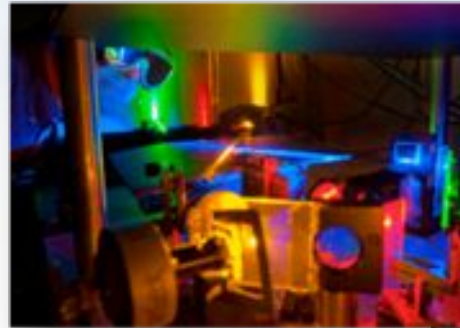
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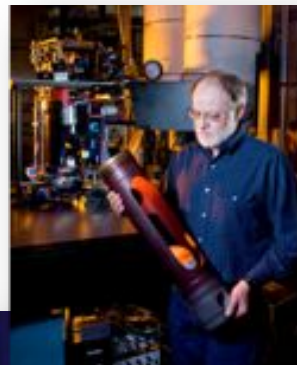
Sandia National Laboratories

“Exceptional service in the national interest”

- Largest national lab in US
 - Department of Energy (DOE)
 - ~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



Albuquerque, New Mexico



Livermore,
California



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.

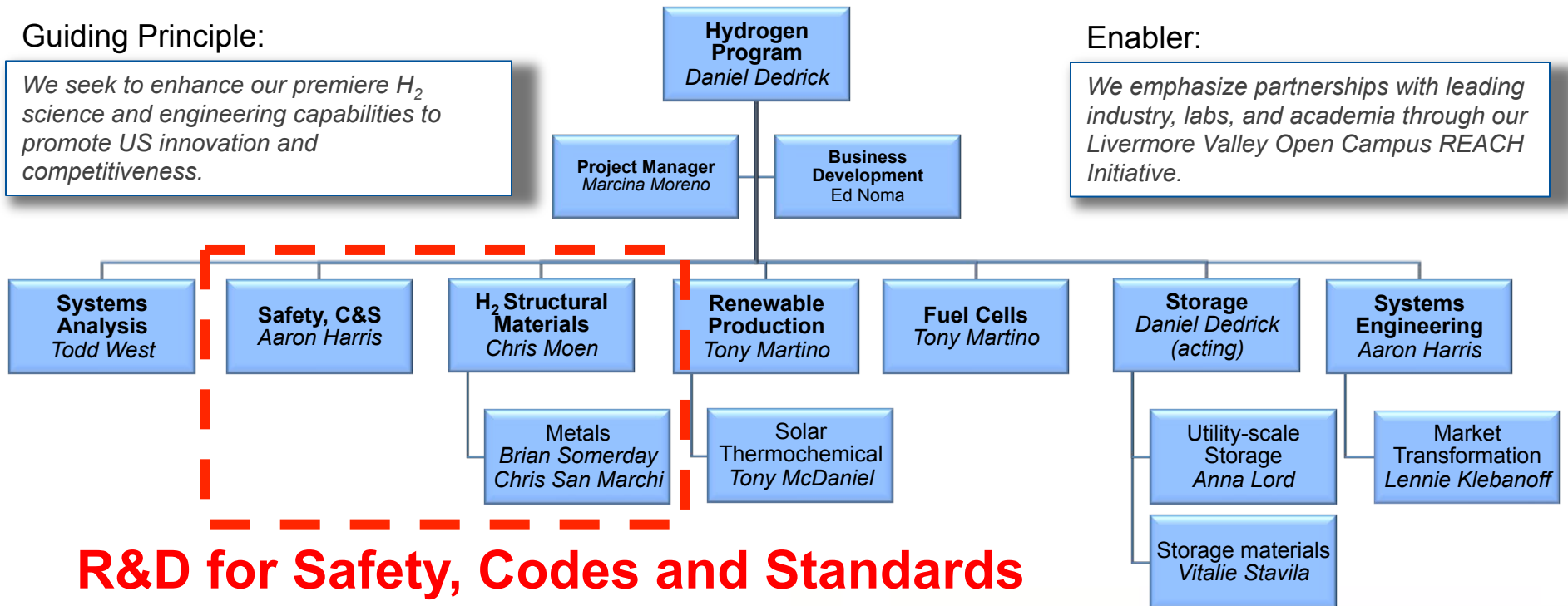
Energy, Climate, and Infrastructure Security (ECIS) Transportation Energy
 Bob Carling (Director) & Art Pontau (Deputy Director)

Guiding Principle:

We seek to enhance our premiere H₂ science and engineering capabilities to promote US innovation and competitiveness.

Enabler:

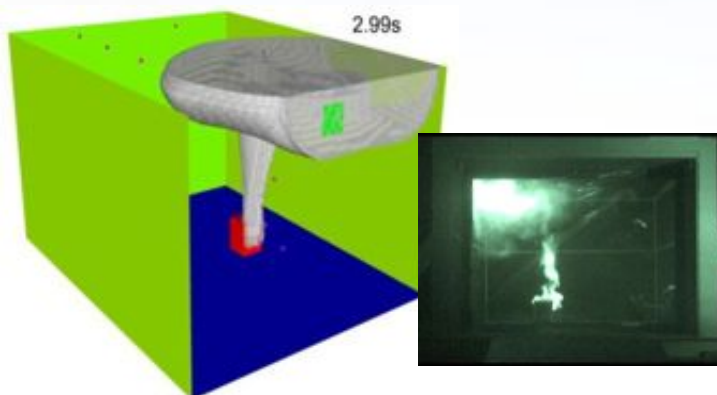
We emphasize partnerships with leading industry, labs, and academia through our Livermore Valley Open Campus REACH Initiative.



R&D program for Safety, Codes and Standards

Enabling safe, efficient, and high-performing hydrogen technologies

Hydrogen behavior



Simulation and experimental validation of release during indoor refueling

H₂ effects in materials, components, and systems



Mechanical load-frame used to characterize H₂ effects in materials

Online Technical Reference

<http://www.sandia.gov/matlsTechRe>

Quantitative Risk Assessments



Quantitative Risk Assessment helps establish requirements for hydrogen installations

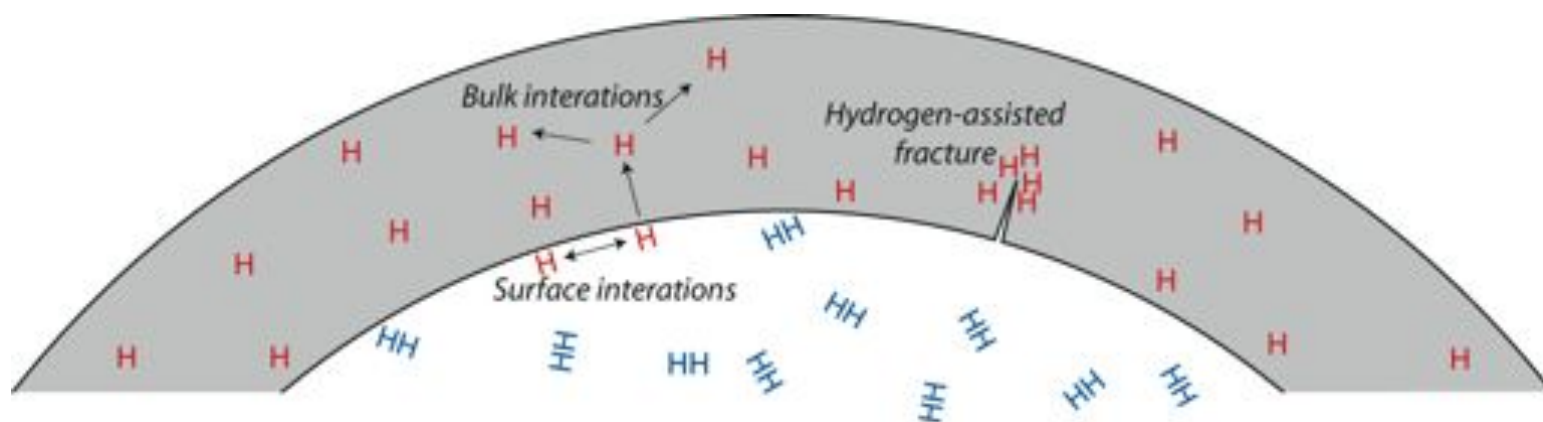
C&S development support



Regulations Codes and Standards Advocacy

Hydrogen dissolves into metals and affects the properties of the metal

- 1) **Hydrogen-surface interactions:** molecular adsorption and dissociation producing atomic hydrogen chemisorbed on the metal surface
- 2) **Bulk metal-hydrogen interactions:** dissolution of atomic hydrogen into the bulk and segregation to defects in the metal (i.e., transport and trapping)
- 3) **Hydrogen-assisted cracking:** interaction of hydrogen with defects changes local properties of the metal leading to embrittlement and possibly failure

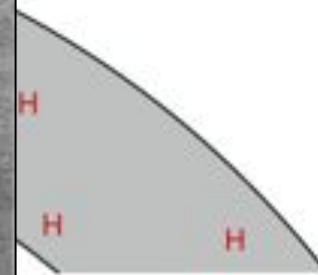
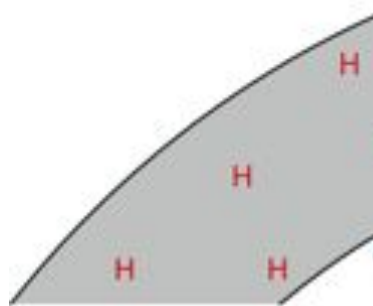


Science-based understanding of embrittlement essential for ensuring safety and reliability of hydrogen technology

Hydrogen dissolves into metals and affects the properties of the metal

- 1) *Hydrogen-surface*
producing atomic
- 2) *Bulk metal-hydrogen*
bulk and segregation
- 3) *Hydrogen-assisted*
local properties

dissociation
surface
hydrogen into the
(diffusion and trapping)
defects changes
possibly failure



Science-based
for ensuring s

essential
technology

Objectives of materials R&D at Sandia for Hydrogen Safety, Codes and Standards

Objectives:

- (1) Enable *market transformation* by supporting national and international codes and standards development activities
 - (2) Provide *international leadership* on testing and evaluation of materials for hydrogen service
- Develop *testing methods* and benchmark test data
 - Critical assessment and demonstration of test methods
 - Full-scale testing of components (including pressure vessels)
 - Standardize *design methods* for hydrogen containment structures
 - Life prediction based on crack initiation and growth (HPIT1 and CHMC1)
 - Life prediction based on crack growth only (ASME KD-10)
 - *Fundamental study* of hydrogen effects on deformation and fracture
 - Provide *technical expertise* to address challenges of industry

Materials selection for hydrogen service includes diverse range of product



Hydrogen delivery

- e.g., hydrogen pipelines: carbon steels
- Challenge: cyclic pressure

Mobile storage (fuel tanks)

- e.g., hydrogen forklifts: Cr-Mo ferritic steels
- Challenge: cycling ~6/day



Pressure manifold components

- Austenitic stainless steels
- Challenges: low temperature, lower-cost alternatives (e.g., *aluminum*), alloy content

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Introduction to Hydrogen Uses

Hydrogen is commonly used today:

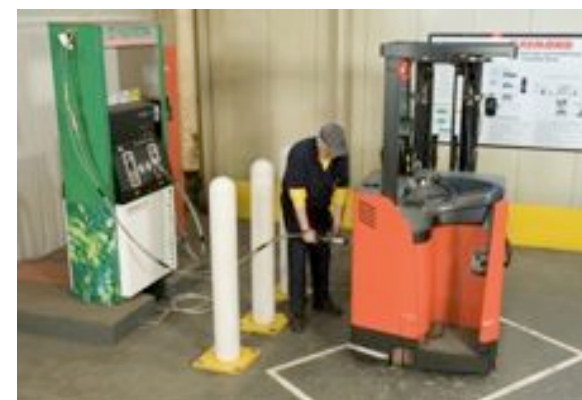
- 9 million tons annual in US (56 Bkg global)
- Oil Refinery
 - 60% of current hydrogen use
 - “Sweetens” and removes sulfur
 - 21 Million Fuel Cell Vehicles (FCVs) equivalent
- Food – partially-hydrogenated fats
- Electrical power equipment coolant
- Ultra Clean heating ovens – metals, silicon wafers, etc.

Emerging technologies:

- Personal vehicles, private residences
- 12,000 hydrogen stations would put hydrogen within two miles of 70 percent of the U.S. population
- Backup power, off-grid power



Hydrogen Vehicles and Fueling Stations



- Growing markets (worldwide estimates)
 - 200-400 light duty vehicles (automobiles on the road)
 - 100-150 heavy duty vehicles (buses, dump-trucks, yard-haulers, etc.)
 - 3,000 industrial trucks (forklifts)
 - >200 fueling stations for buses and automobiles
 - >50 forklift indoor/outdoor fueling sites
- Onboard storage pressure: 35MPa and 70MPa

Hydrogen in California

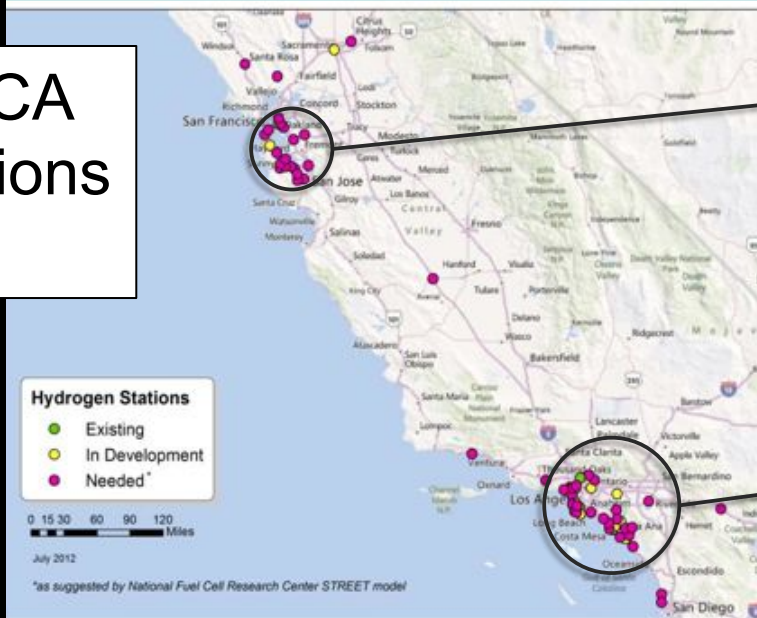
Goal for California:

- 68 fueling stations by the end of 2015
- serving 5,000-15,000 vehicles (FCEVs)

Building a statewide network



Map of 68 Hydrogen Fueling Stations: Existing, In Development and Needed



End of 2012 in CA

- 13 fueling stations
- 312 FCEVs

Source: California Fuel Cell Partnership
(cafc.org/roadmap)



Slide taken from: FCEVs and Hydrogen in California, presented by Catherine Dunwoody, October 2012, DOE Webinar

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Setting and Brief Incident Description

- AC Transit operates fleet of 12 fuel-cell buses serving the public in Alameda and Contra Costa counties in the San Francisco Bay Area
- Emeryville fueling station (capacity of 425 kg/day) serves bus fleet and is publicly accessible for fueling passenger vehicles
- More than 1,000 refueling operations prior to event

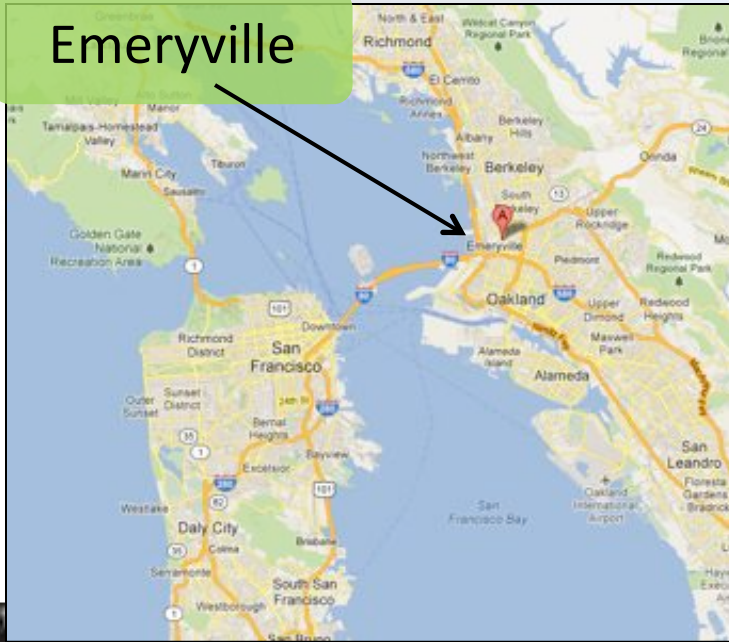


May 4, 2012: Witnesses reported loud “boom”, followed by continuous “jet” sound

- Hydrogen release and subsequent fire
- No injuries or fatalities
- Minimal damage
- Widely misrepresented in the press

Locational Context

Emeryville



AC Transit



H2 Fueling Station



<http://www.actransit.org/environment/the-hyroad/energy-stations>

Summary of the Event

Initiation

May 4, 7:45 AM
pressure relief valve fails

Conclusion

May 4, 10:12 AM
failed valve isolated



- Details and Impact

- Vented approximately 300 kg of hydrogen (150 kg in first 15 min)
- Venting hydrogen ignited at vent stack outlet
- Hydrogen flame impinged upon canopy (making flames visible)
- 9th Alarm fire event – local and county police/fire response
- Evacuation of local businesses, including Pixar Studios and two nearby schools

Incident Timeline



Pressure Relief Vents

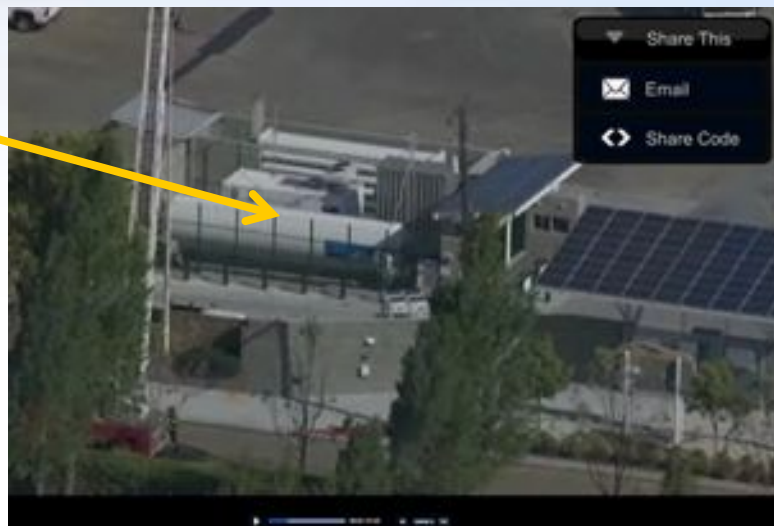


Pressure Relief Valves

- | | |
|---------|--|
| 7:45 AM | <ul style="list-style-type: none">• Pressure relief valve fails, releasing hydrogen• Hydrogen ignites and impinges on nearby canopy• Employee presses e-stop isolating high pressure gas storage |
| 7:57 AM | <ul style="list-style-type: none">• Fire Department arrives• About 150 kg of high pressure hydrogen already released• Gas supplier technicians remotely access station data |

Incident Timeline

Storage area



- 07:45 Valve failure
- 07:57 Fire Department arrives
- 08:10 – 09:00 Response to incident escalates
- Approx. 09:00 Evacuations of nearby businesses and schools ordered
- Approx. 10:00 Storage area entered and failed valve isolated
- 10:58 Incident command terminated

Basic Design of Pressure Relief Valve

Inlet base (1)

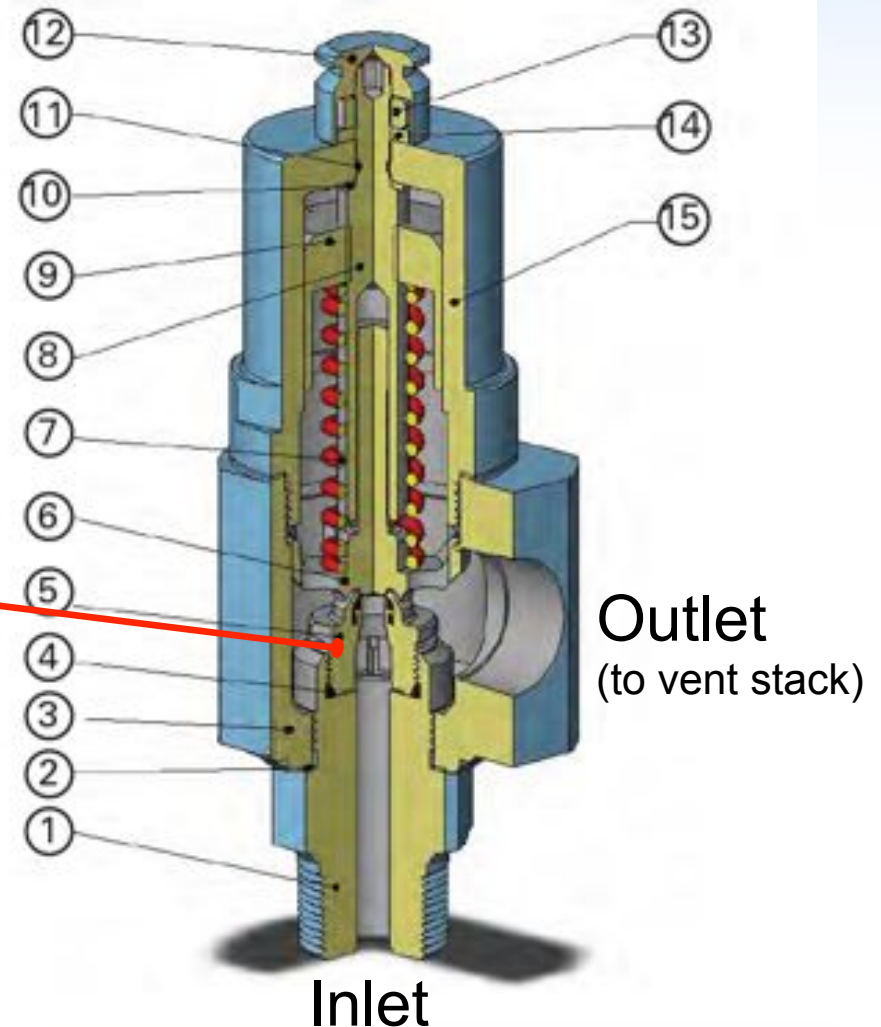
- *Exposed to hydrogen at pressure*
- Material of construction: type 316 austenitic stainless steel

Body subassembly (3)

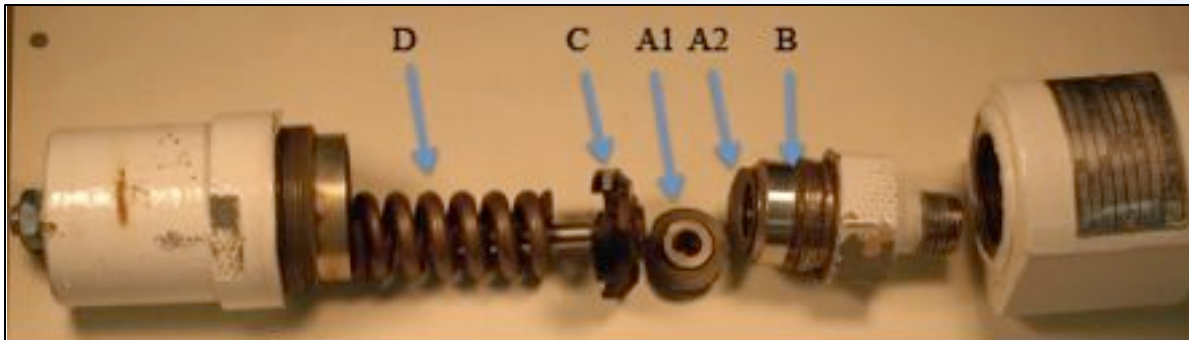
- *Non-wetted, except during activation*
- Material of construction: carbon steel

Nozzle Subassembly (5) *failed part*

- *Exposed to hydrogen at pressure*
- *Choice of materials available*
- Material of construction: type 440C martensitic stainless steel

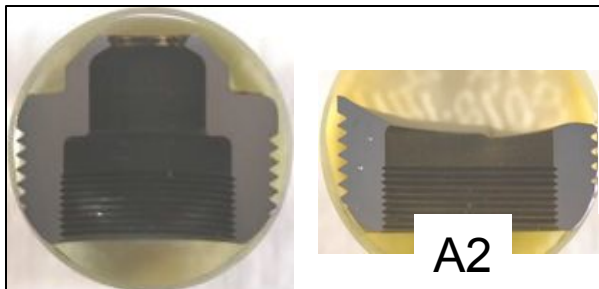


Failure Analysis and Component Evaluation



A1/A2 Nozzle subassembly
B Inlet base

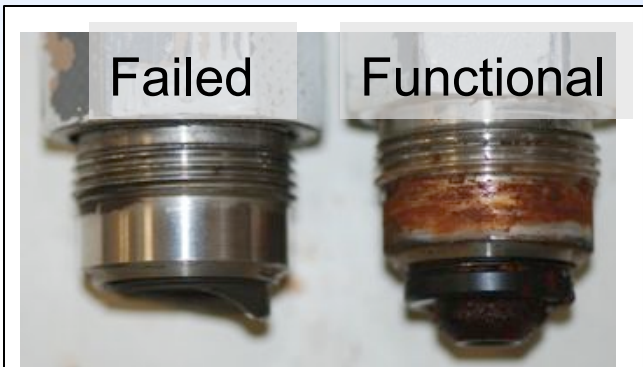
C Disk subassembly
D Set spring



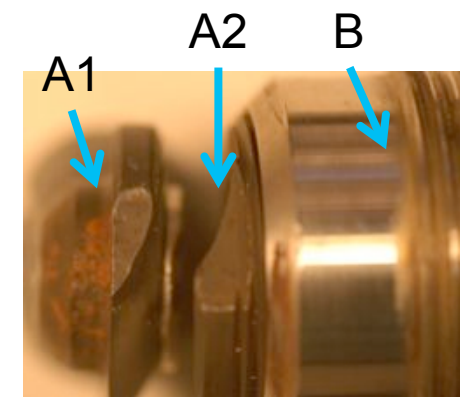
Cross section of nozzle
(far left) and failure (left)

A2

- Nozzle seals against base inlet
- Disk subassembly seals against “top” of nozzle
- Nozzle failed at internal corner
 - associated with external thread root and wrench flats

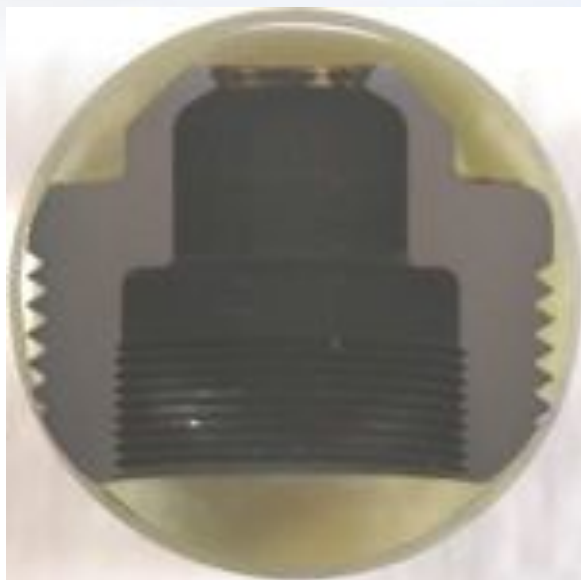


Nozzle in base



Polished Sections of Nozzle

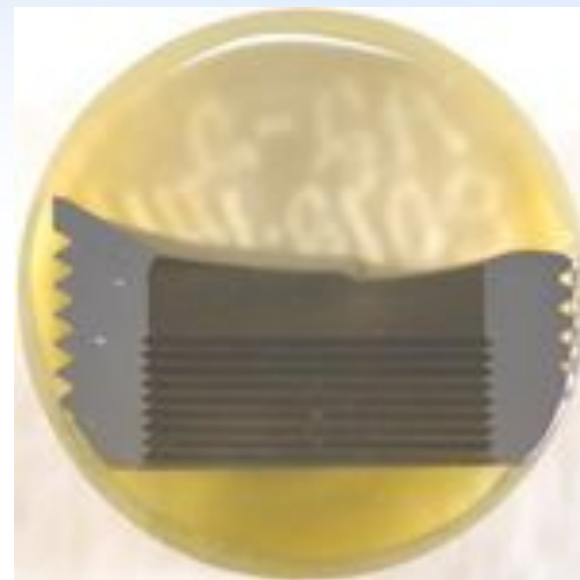
MOC: Type 440C martensitic stainless steel



Functional nozzle

Measured hardness: 500 HVN

Estimated: 49 HRC



Failed nozzle

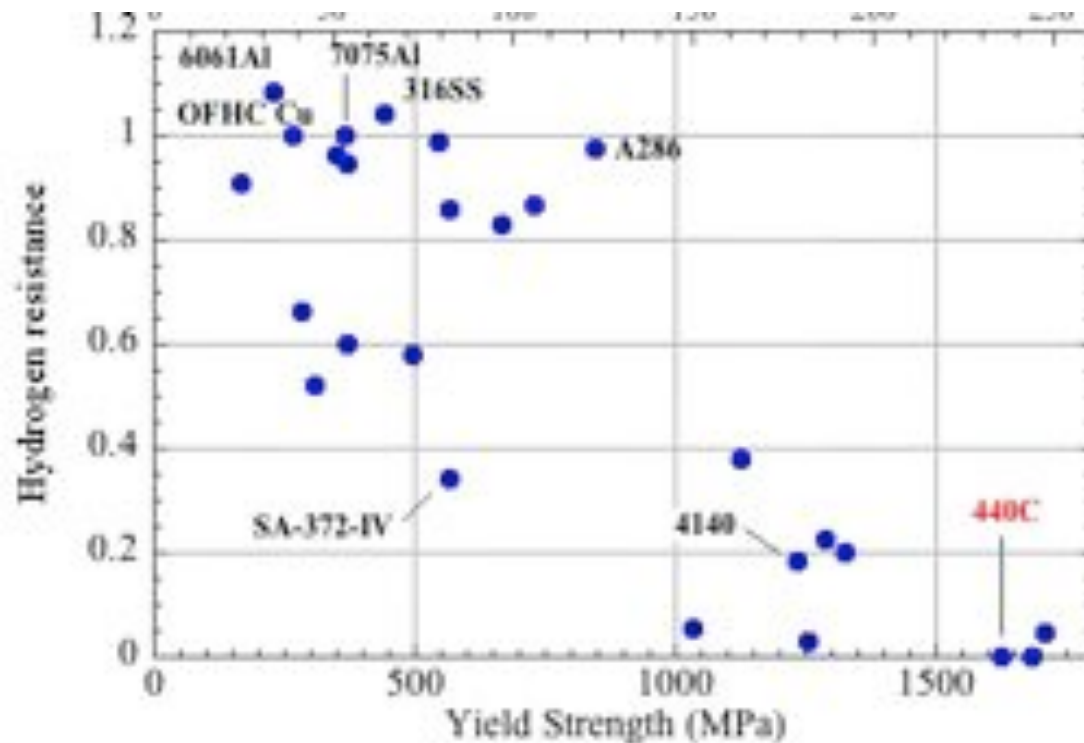
Measured hardness: 600 HVN

Estimated: 55 HRC

- Functional nozzle: hardness is consistent with specification
- Failed nozzle: hardness exceeds manufacturer's specification
- Estimated difference in yield strength: ~300 MPa

Hydrogen Compatibility of Metals

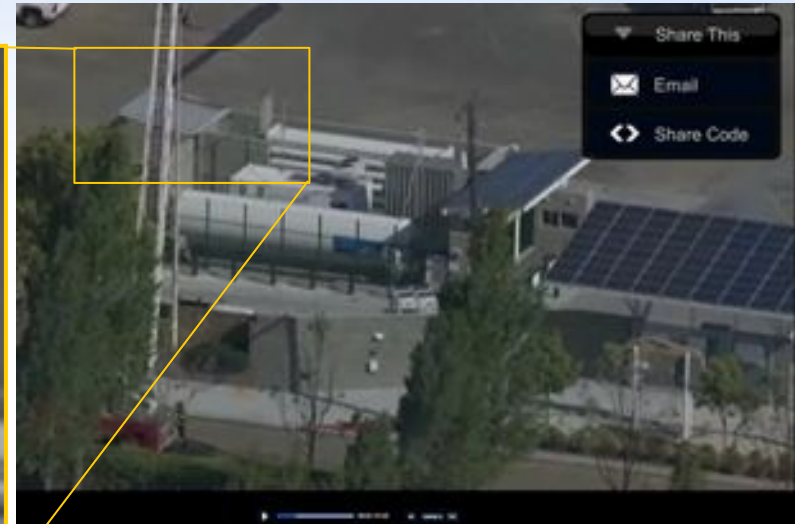
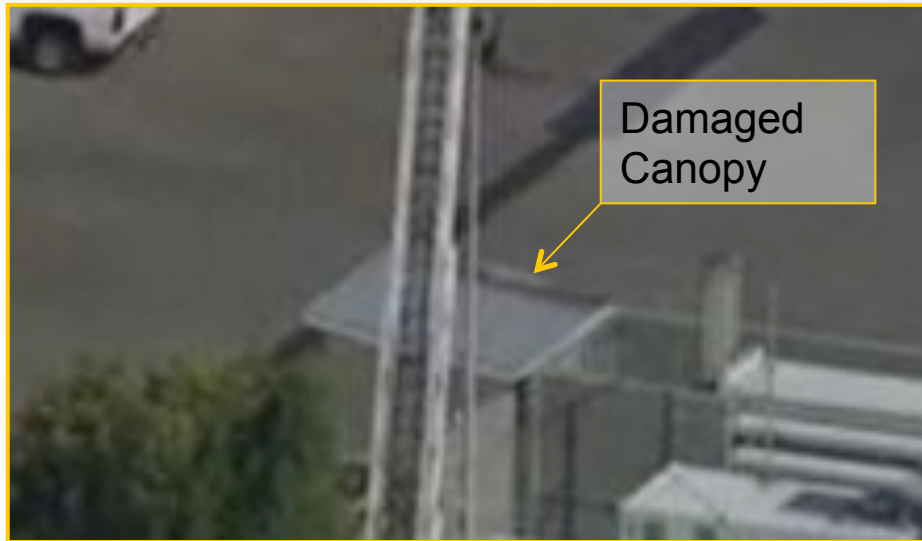
- High-strength steels are very susceptible to embrittlement in gaseous hydrogen
- Type 440C martensitic stainless steel is not recommended for hydrogen service → *root cause*



HVN of 500-600 represents yield strength of approximately 1600-2000 MPa

- Hydrogen resistance determined from tensile testing
- Ratio of reduction of areas: gaseous hydrogen relative to helium at pressure of 69 MPa
- Ref: Jewitt et al NASA CR-2163

Contributing Factors



- Vent system was too close to the canopy
- First responders did not tailor the response to the conditions, due to:
 - Poor communication of critical data during the event
 - Poor understanding of written emergency protocols
- No mechanism for subsystem isolation
 - Isolation would have limited the release and shortened the event

Summary of Incident and Failure Analysis

- Pressure relief valve failed due to inappropriate materials selection for hydrogen service
 - Subassembly (nozzle) manufactured from high-strength type 440C martensitic stainless steel (not compatible with hydrogen)
 - Contributing factor: material did not meet manufacturer specification
 - Existing component option for hydrogen service (nozzle can be manufactured from hydrogen compatible type 316 austenitic stainless steel)
- Poor communication and understanding of the system led to unnecessary escalation of incident
 - Estimated that half of release was complete prior to arrival of first responders
 - Conditions were stable and required system isolation (or left to vent)
- Improved system design may have resulted in conclusion of the events prior to arrival of first responders
 - Hydrogen release would have been reduced if each storage sub-unit (storage and relief valve) was isolated from one another

Recommendations and Lessons Learned

Report ref. SAND2012-8642

1. Replace pressure relief valves with devices specifically designed for hydrogen service
 - evaluate all material of construction as part of safety review process, particularly safety critical components
2. Update communications plan
 - establish process ‘ownership’ to better centralize the flow of information
3. Update training documentation based on timeline analysis
4. Perform emergency action plan drills with key response personnel
5. Evaluate and implement vent systems relative to surrounding structures
 - communicate design changes to all project participants
6. Identify opportunities to limit the quantity of hydrogen released from a single point failure
7. Evaluate and implement changes to fire detection system to identify hydrogen flames on the system

Thank You for Your Attention

- The participation of Sandia National Laboratories in this investigation is due in part to the ongoing support from the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office.
- The investigation summarized in this presentation was a collaborative effort with key contributions from AC Transit and The Linde Group. Participation of the investigation team is also acknowledged.
- The investigation was funded by the California Air Resources Board.
- A publicly available report (ref. SAND2012-8642) describing the investigation of this incident is available from the Sandia Technical Library.

Other Hydrogen Embrittlement Incidents

www.h2incidents.org – data from PNNL

High-Pressure Burst Disk Failure

A hydrogen tube-trailer burst disk failed at approximately 5200 psig (designed for 10,000 psi). Product literature stated burst disk was fabricated from stainless steel but was actually nickel.

Stainless Steel (403) Failure in Liquid Hydrogen Line

A bourdon tube ruptured in a pressure gage after 528 hours of operation in a liquid H₂ system. Tube was manufactured from 403 SS, suggested change to 303 SS.

Water Electrolysis System Explosion

Electrolysis system separator plate failed. Embrittlement may have been contributing factor. Explosion could have been prevented by process gas sensor. Explosion resulted in fatality. (no material information provided)

Failure of Stainless Steel Valves due to Hydrogen Embrittlement

Valve springs made from 17-7PH were found in pieces, causing valves to fail. Valve manufacturer was not informed of hydrogen service, suggested change to stainless steel materials.

Shafts Can Blow Out of Some Models of Check Valves and Butterfly Valves

Check valve failure caused by embrittlement of highly loaded hardened steel dowel pin, resulting in millions of dollars worth of equipment damaged from explosion of released gas. Suggest using blow out resistant design.