SAND2012-9306P

U.S. DEPARTMENT OF ENERGY

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

November 6, 2012

Korea University

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Sandia National Laboratories

Funding for the incident investigation was provided by the California Air Resources Board; funding for the broader Hydrogen Safety, Codes and Standards program is provided by the Fuel Cell Technology Program of the US Department of Energy.

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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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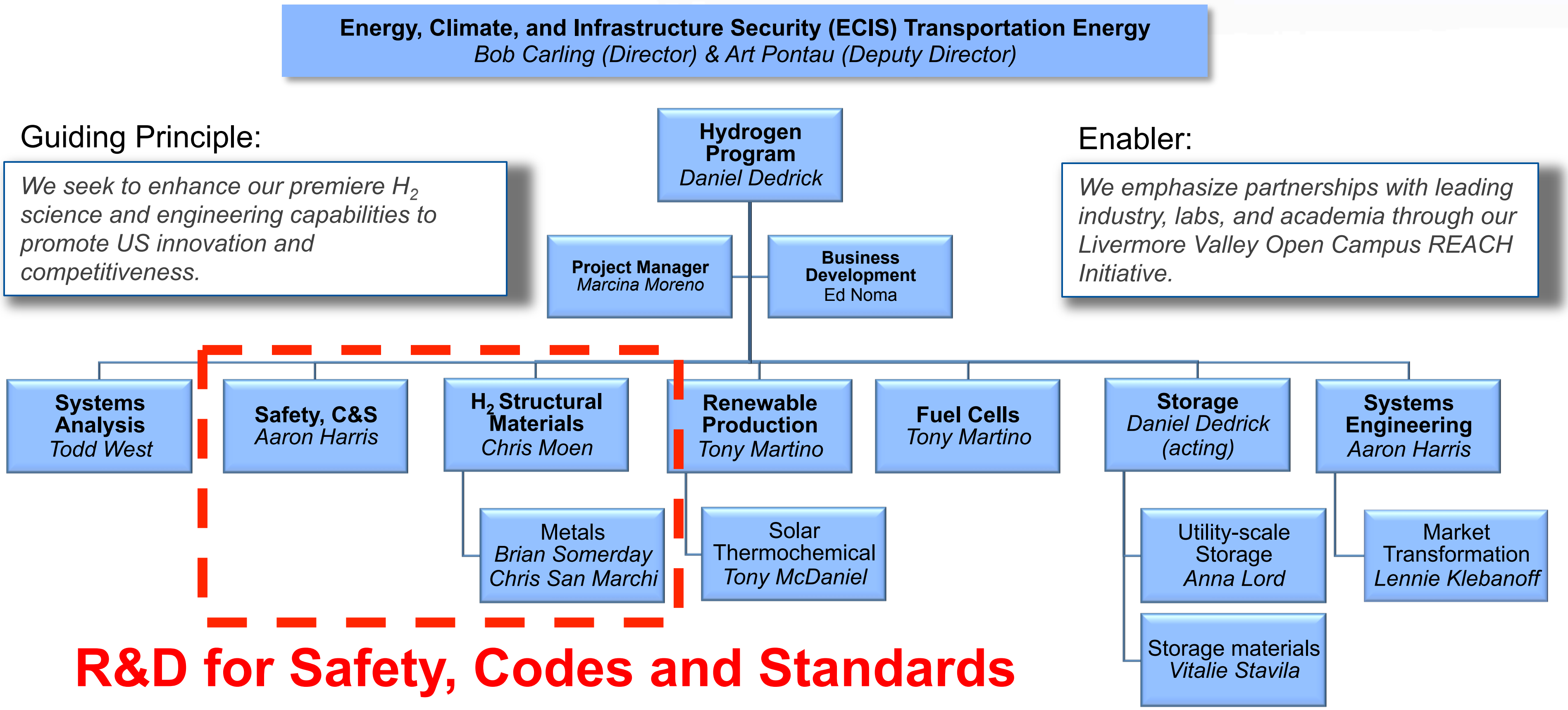
Sandia National Laboratories
“Exceptional service in the national interest”

- 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

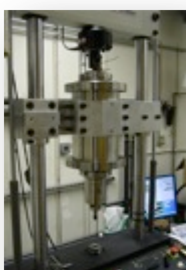
Sandia Hydrogen and Fuel Cells Program

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.



A healthy S,C&S program is 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 fatigue life?** • **How does H_2 ignite during release?**	**Provide world's leading experts in H_2 behavior, risk assessment and H_2 effects in materials**
Regulations, C&S development committees	**Assemble and promote standards activities: NFPA, CSA, SAE, ASME, UN GTR committees**	**Measure properties, develop models and validate understanding**
Safety Panel	**Provide forum for discussion of hydrogen installations and technologies**	**Promulgate learning with site visits and online resources**

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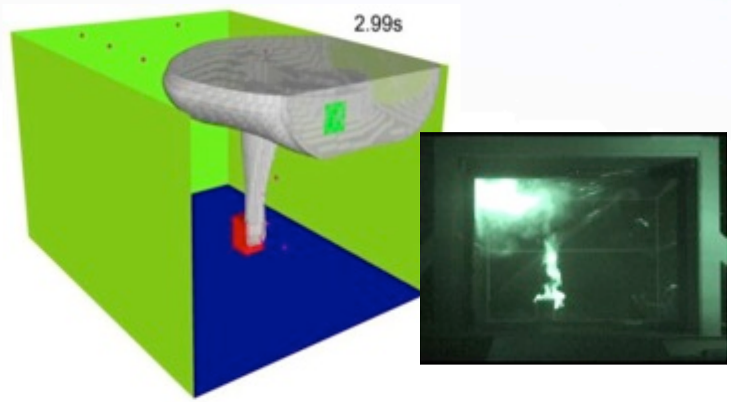
R&D program for Safety, Codes and Standards

Enabling safe, efficient, and high-performing hydrogen technologies

Hydrogen behavior



Simulation and experimental validation of release during indoor refueling

H_2 effects in materials, components, and systems

Mechanical load-frame used to characterize H_2 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

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

- Enable *market transformation* by providing data for standards and technology applied to H_2 components
  - 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
    - Examples: measure properties of H_2-exposed welds and Al alloys
  - Improve efficiency and reliability of materials test methods in standards
    - Examples: optimize fatigue crack growth testing in ASME Article KD-10 tank standard; evaluate mechanics of fracture threshold measurements
- Participate directly in standards development
  - Design and safety qualification standards for components
    - SAE J2579, CSA HPIT1, ASME Project Team on Hydrogen Tanks
  - Materials testing standards
    - CSA CHMC1
- Provide technical expertise to address challenges of industry

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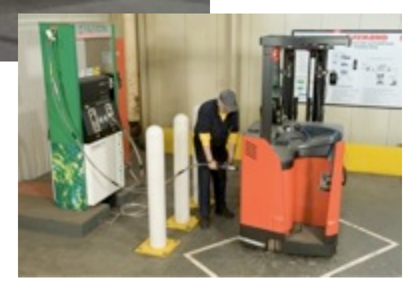
Introduction to Hydrogen Uses

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



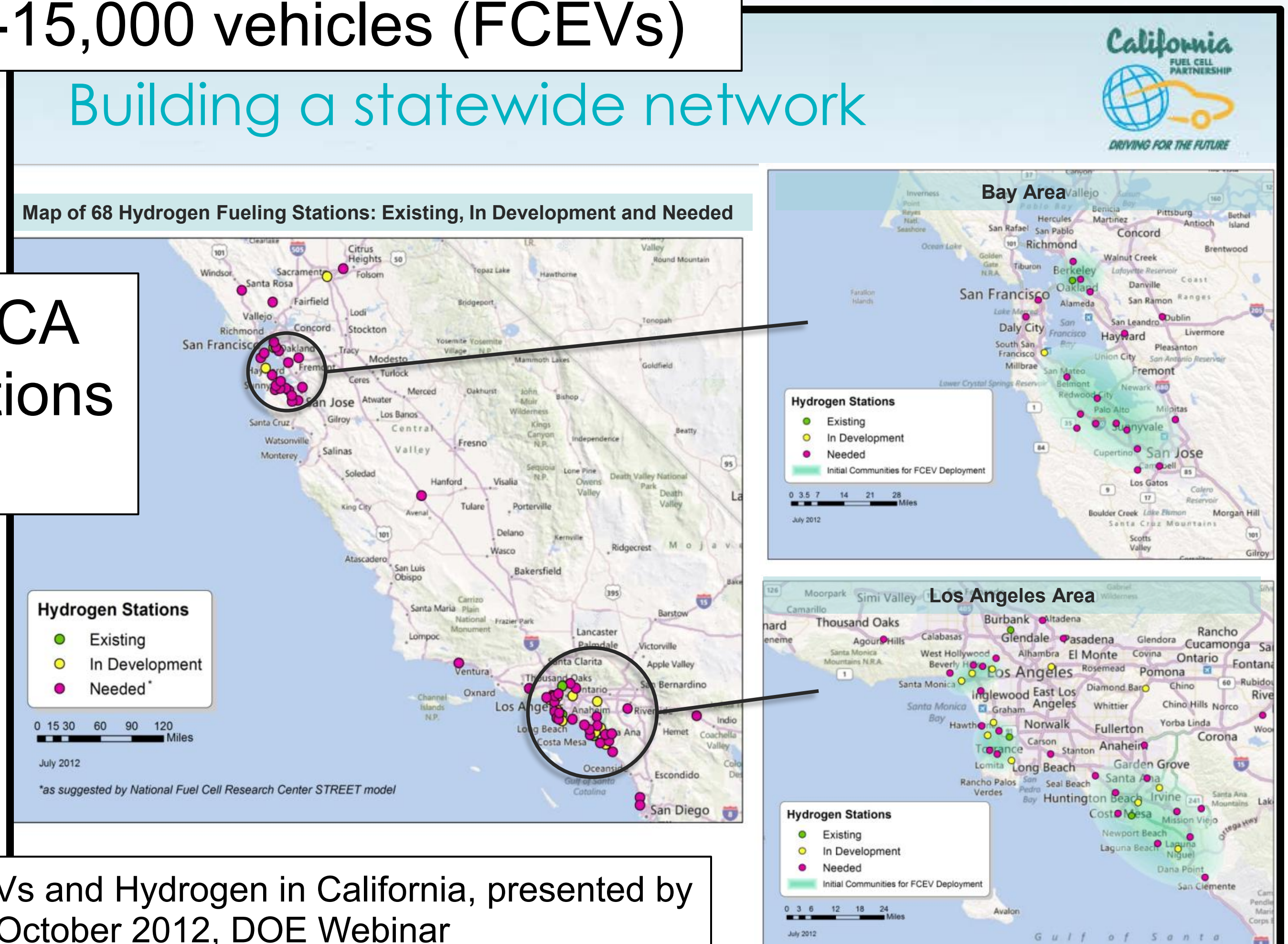
Hydrogen Vehicles and Fueling Stations

- 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)

End of 2012 in CA
- 13 fueling stations
- 312 FCEVs



Source: California Fuel Cell Partnership (cafcp.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

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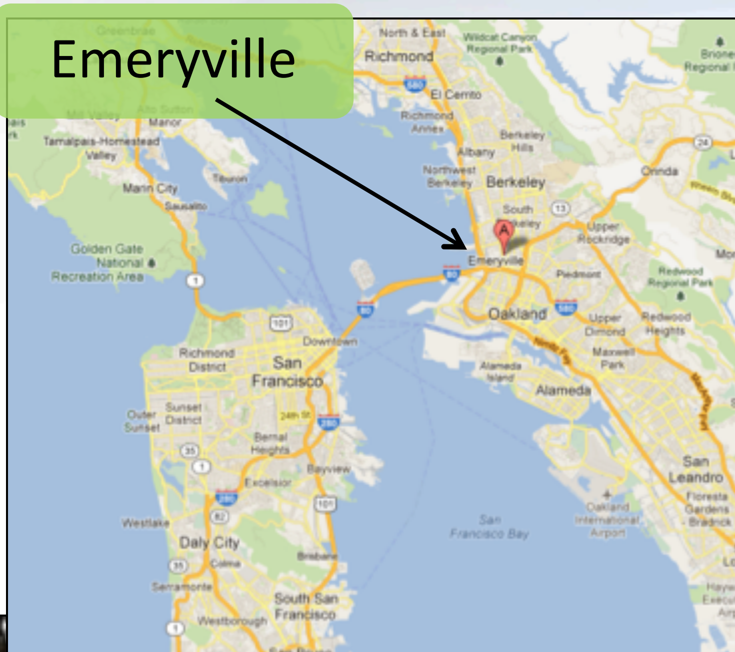
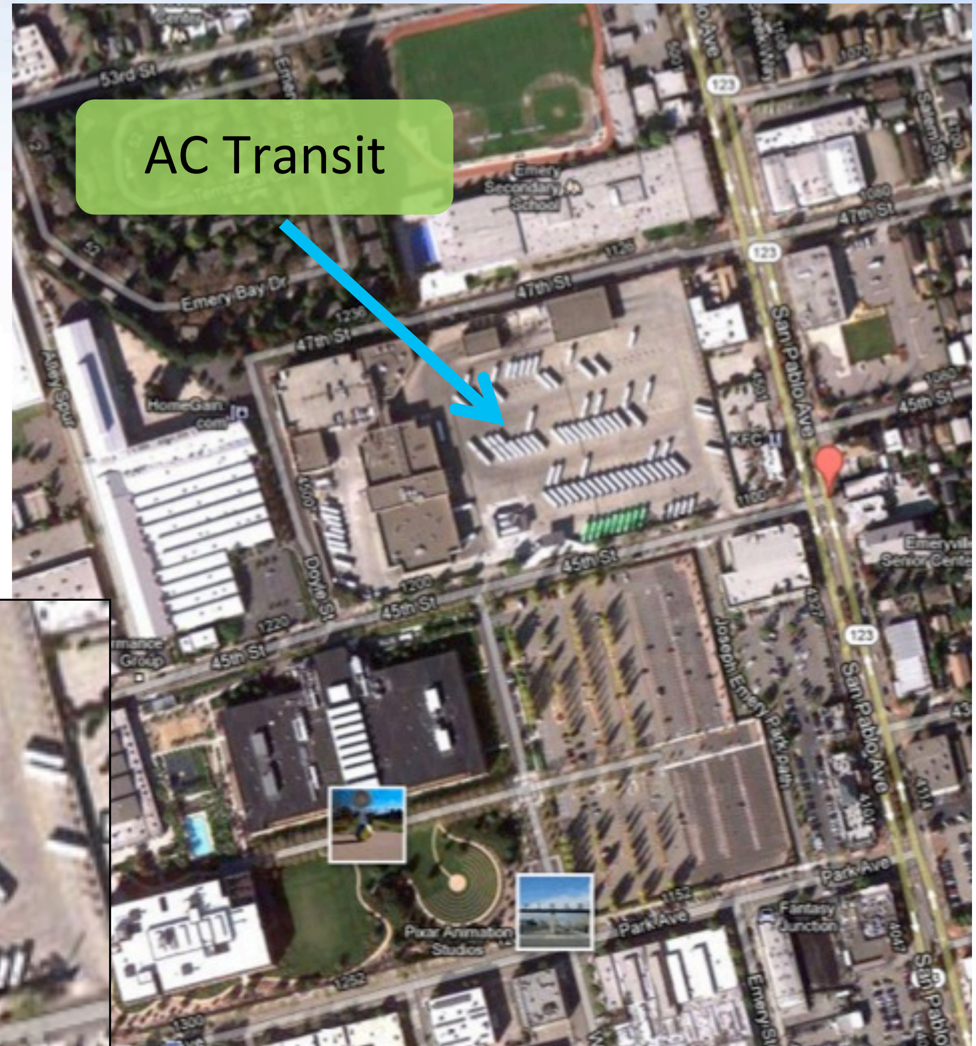
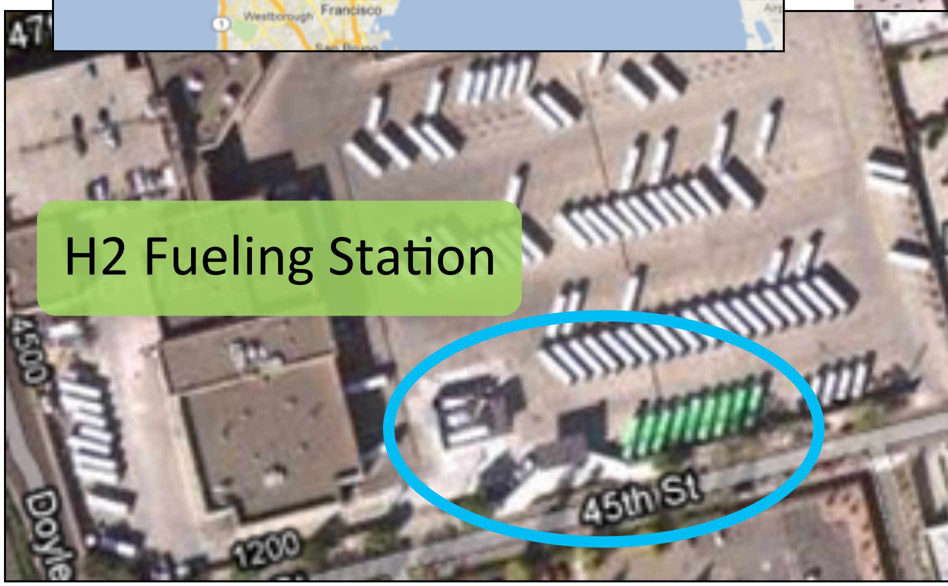
Locational Context







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

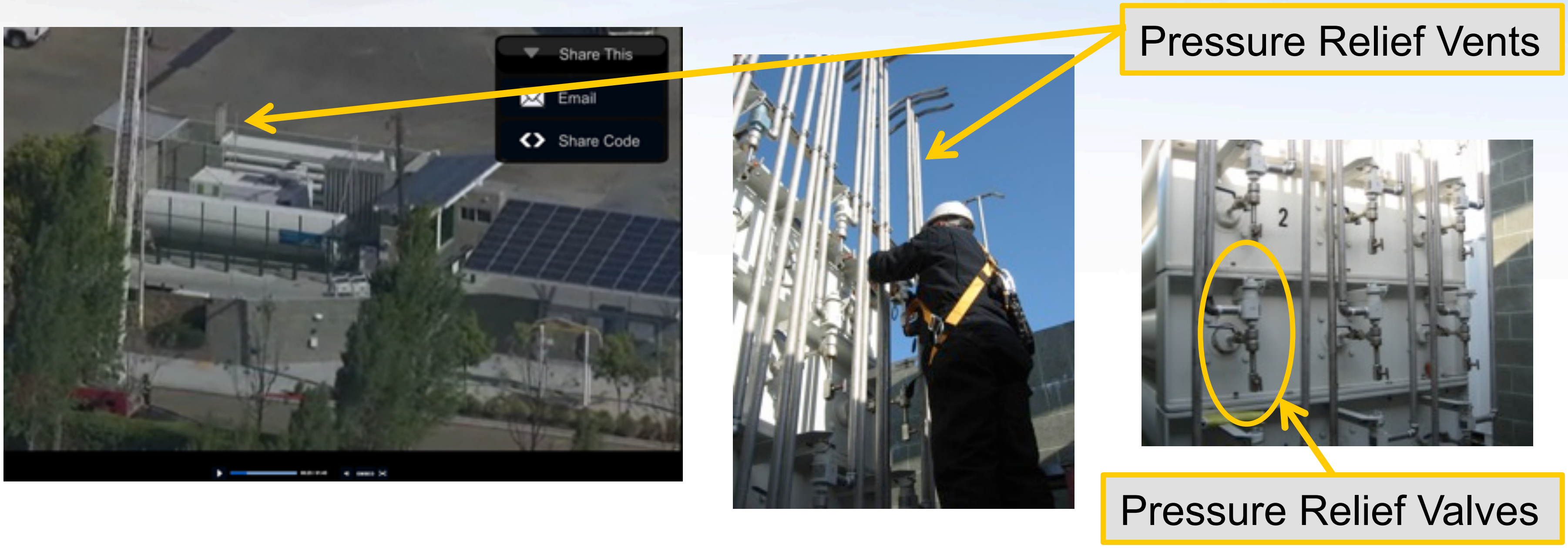
Summary of the Event

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 (150kg 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



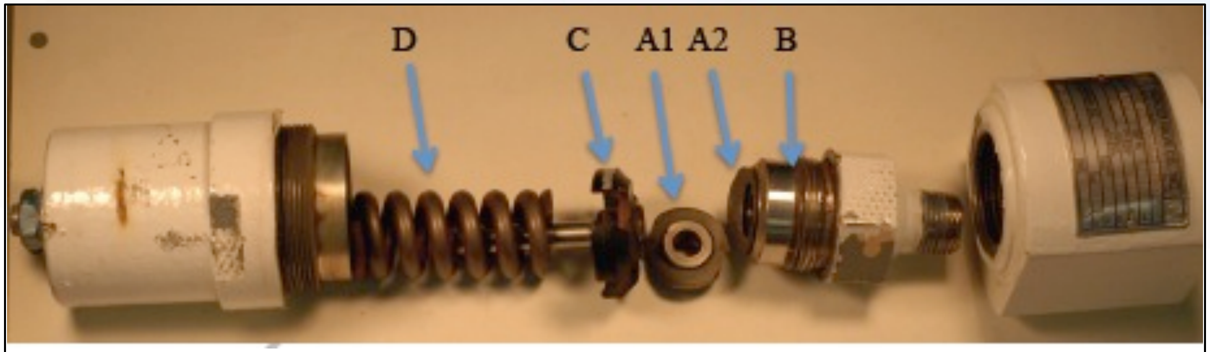
7:45 AM	• Pressure relief valve fails, releasing hydrogen • Hydrogen ignites and impinges on nearby canopy • Employee presses e-stop isolating high pressure gas storage
7:57 AM	• Fire Department arrives • About 150 kg of high pressure hydrogen already released • Gas supplier technicians remotely access station data

Incident Timeline

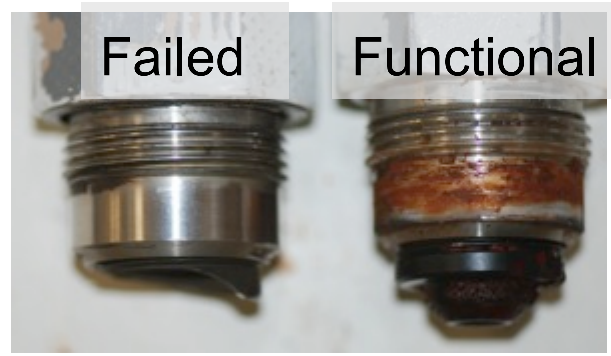
Storage area

•	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

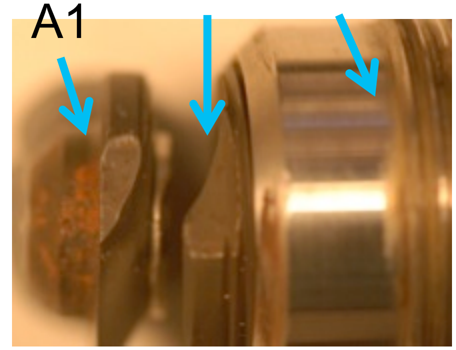
Failure Analysis and Component Evaluation

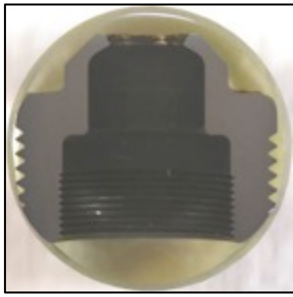


A1/A2 Nozzle subassembly C Disk subassembly
B Inlet base D Set spring



Nozzle in base





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

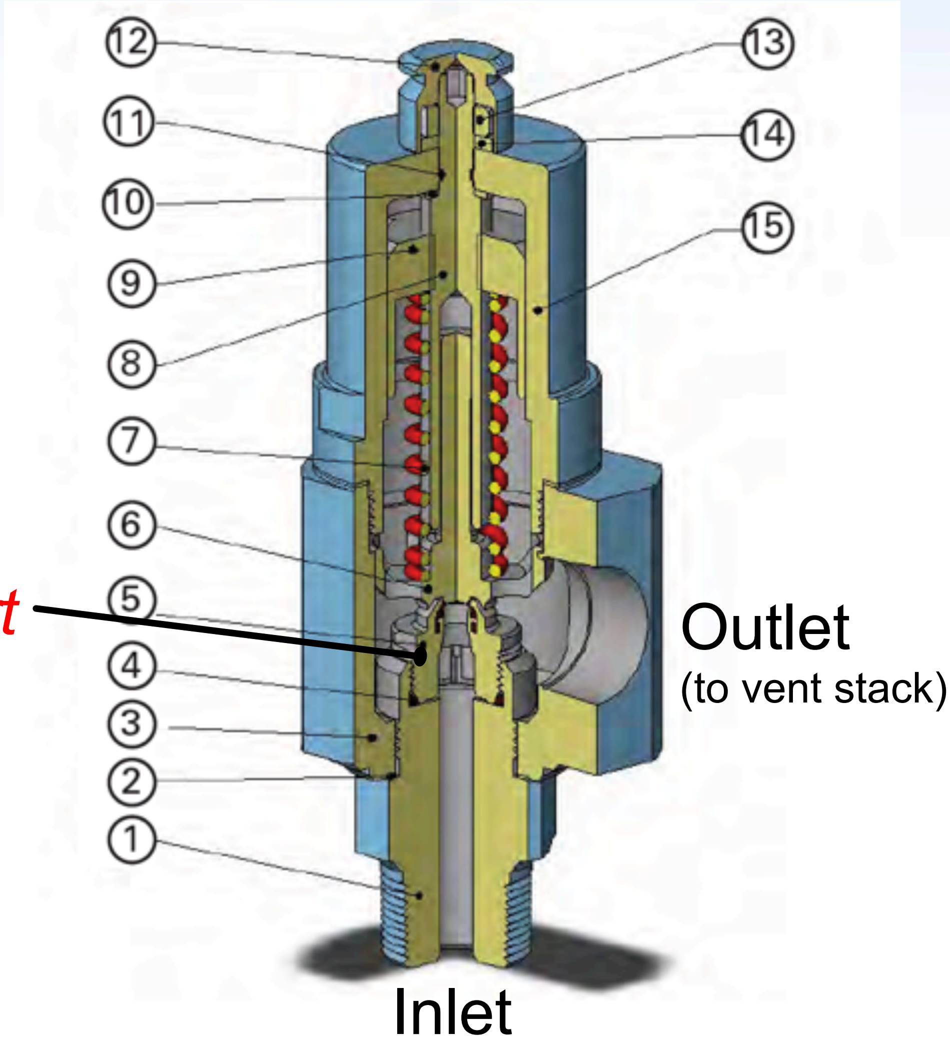
- Nozzle seals against base inlet
- Disk subassembly seals against “top” of nozzle
- Nozzle failed at internal corner
  - associated with external thread root and wretch flats

Basic Design of Pressure Relief Valve

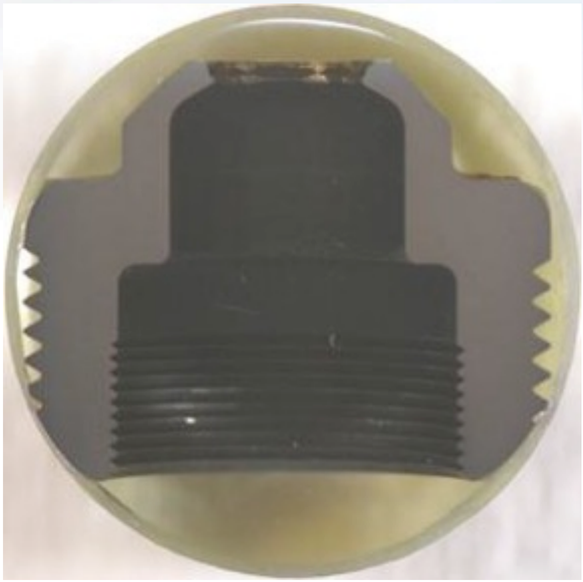
Inlet base (1)
- *Exposed to hydrogen at pressure*
- Material of construction: type 316 austenitic stainless steel

Body subassembly (3)
- *Non-wetted, expect during activation*
- Material of construction: carbon steel

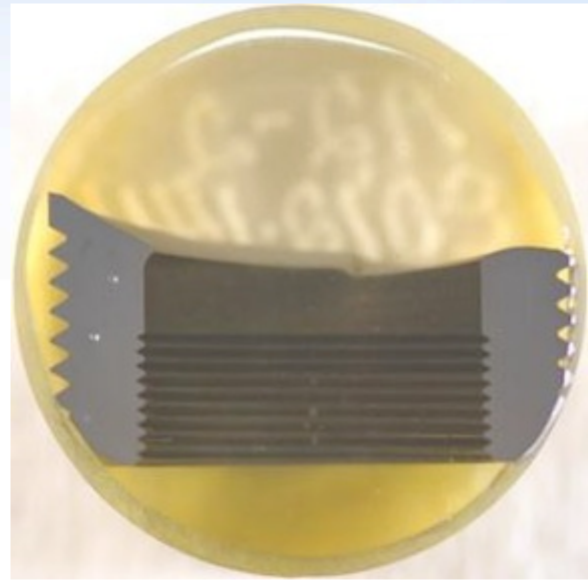
Nozzle Subassembly (5) *failed part*
- *Exposed to hydrogen at pressure*
- *Choice of materials available*
- Material of construction: type 440C martensitic stainless steel



Polished Sections of Nozzle
MOC: Type 440C martensitic stainless steel



Functional nozzle
Measured hardness: 500 HVN
Estimated: 49 HRC

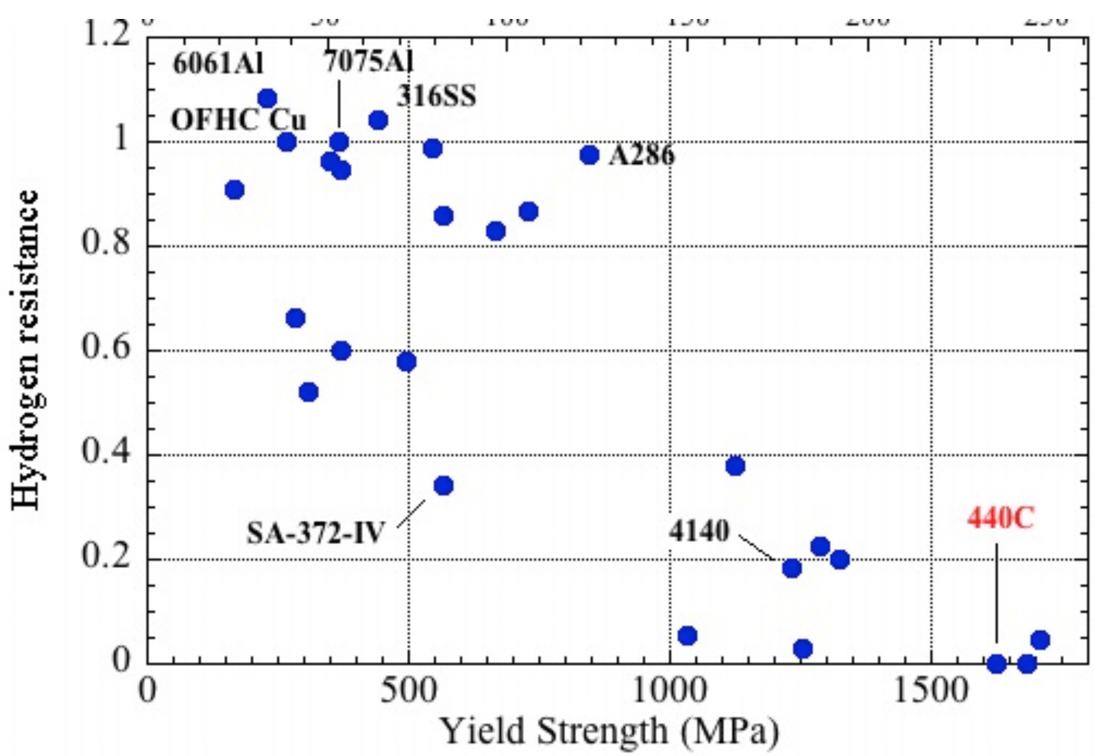


Failed nozzle
Measured hardness: 600 HVN
Estimated: 55 HRC

- 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

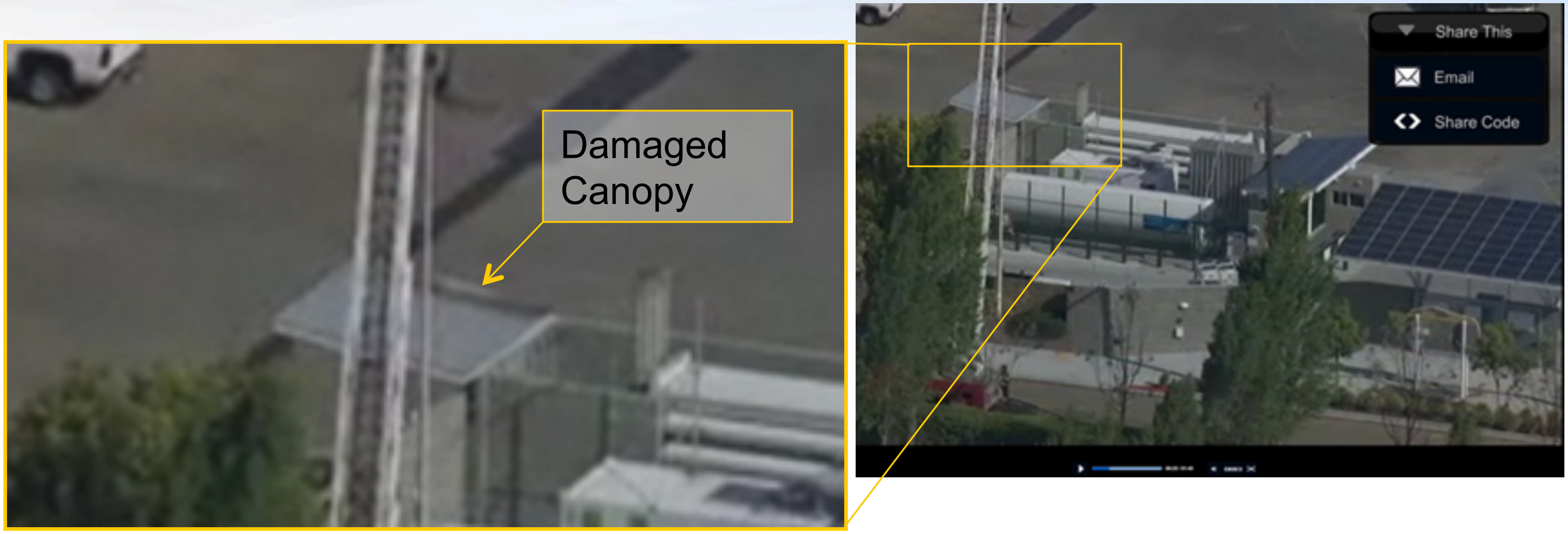
- High-strength steels are very susceptible to embrittlement in gaseous hydrogen
- Type 440C martensitic stainless steel is not recommended for hydrogen service → ***root cause***



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 to isolated (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
   - Lesson Learned: communicate design changes to all project participants
6. Identify opportunities to limit the quantity of hydrogen released from a single point failure (Lesson Learned)
7. Evaluate and implement changes to fire detection system to identify hydrogen flames on the system

Thank You for Your Attention

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- 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 Program.

- 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.