Open Issues in the Development of Safety Standards for Compressed Hydrogen Storage at SAE-International

29 April 2010
DOE Tank Workshop
Sandia National Laboratory
Livermore, CA

Chris Sloane
Sloane Solutions

Development of Fuel Cell Vehicles

	Prototype Vehicle	Demonstration Vehicle	Low Volume Production Vehicle	High Volume Production Vehicle
Number of Vehicles	≤ 10s	~100s	~1000s	~10,000 - 100,000
Challenge	<u>Learning vehicles</u>: •improve operation •experience fueling •improve reliability	<u>Demo vehicles</u>: • monitor operation • refine fueling • improve durability & efficiency & cost • establish repair/maintenance • feedback vehicle operation & driver experience	<u>Initial production</u>: • verify reliability, efficiency durability, cost • expand fueling infrastructure • monitor driver experience • feedback to next generation	
Public Standards & Regulations	<u>Develop best practices</u> -- product design -- product efficiency testing -- product safety testing -- refueling interface	<u>Refine public standards</u> -- fueling interface -- safety -- energy efficiency		
Government Role	•Support basic research •Support technology development	<u>Support deployment</u> (vehicles & infrastructure) deployment to monitor readiness, efficiency & cost <u>Develop regulations</u> -- safety . -- emissions		

Considerations in Development of Standards / Regulations

- **Performance-based versus Prescriptive**
  - **<u>Performance-based</u>**:
    - demonstrate capability to perform under on-road conditions
    - demonstrate safe performance under extreme conditions
    - allows qualification of new technologies → rapid technology advancement
  - **<u>Prescriptive</u>**:
    - test for previous failure modes; demonstrate compliance material & manufacturing requirements
    - project safe performance under extreme conditions
    - develop new standards / regulations to accommodate new technologies → delayed technology advancement

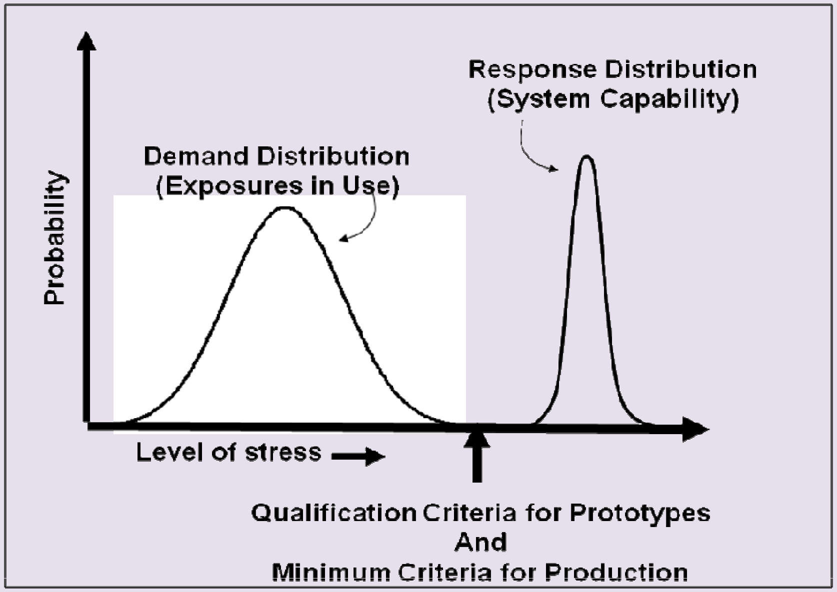
- **Design guidelines versus Safety Design Qualification (Verification) Requirements**
  - **<u>Design Guidelines</u>**

    Capture experience and methods for design development & testing: FMEA, root cause analysis, environmental factors, safety strategy, material properties and test methods, analysis and simulation tools, performance requirements
  - **<u>Design Qualification</u>**

    Capture on-road extreme demand profiles in test conditions

    Verify safety in a vehicle context

❖ On-road extreme demand profiles



No leak or rupture

- Driving (fueling/de-fueling = temp/pressure cycles)
- Parking (static pressure)
- In-use impacts
- Exposure to chemicals
- Temperature extremes
- Pressure excursions (fueling station failure)
- Residual strength
- Stability (rupture resistance)
- Fuel containment in crash scenarios

Controlled release in fire

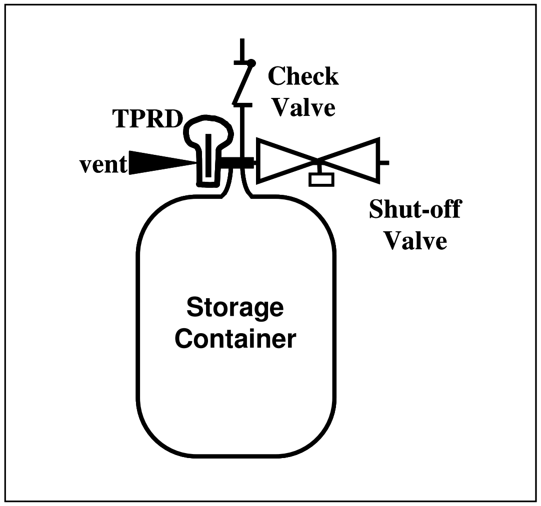
❖ Vehicle context

RISK = <u>Probability of Occurrence</u> x <u>Severity of Consequence</u>

H2 storage Occurrences with safety consequences:

Rupture – severity is high; prevent occurrence
Leak – severity is moderate; severity is managed in a vehicle context
(secondary mitigation = vehicle detection of safety risk & shut down)
-- prevent occurrence within anticipated on-road conditions

Compressed Hydrogen Storage System

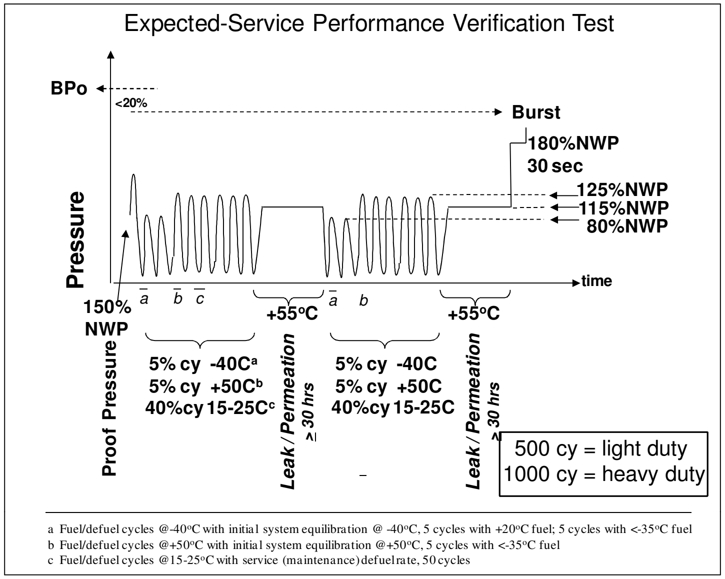


Closures:
- TPRD = thermally activated pressure relief device
- Check valve – prevents reverse flow in fueling line
- Shut-off Valve – automatic fail-safe closure valve

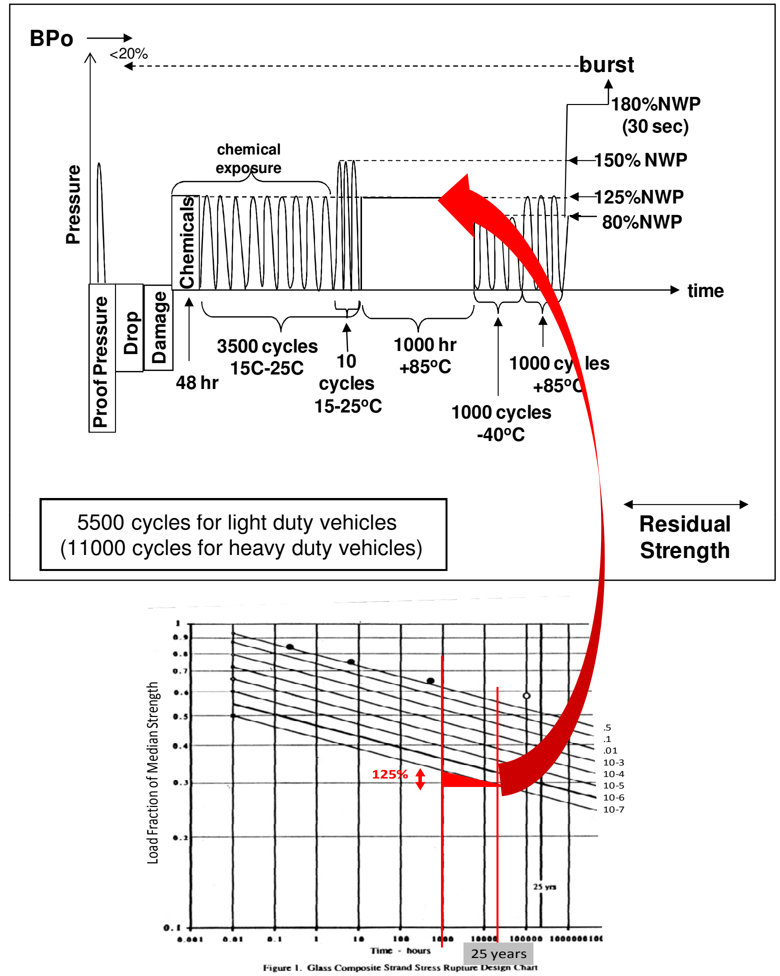
Storage containers : current technologies

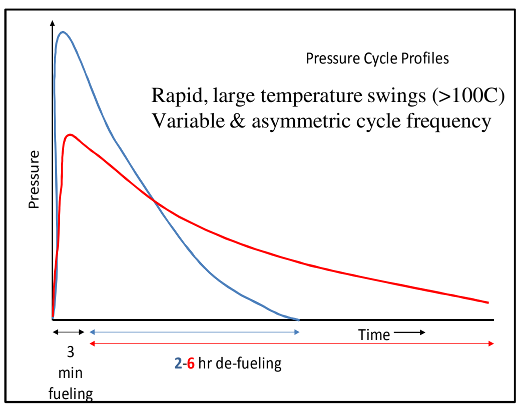
- metal or composite wrap for structural integrity (rupture resistance)
  -- resin-impregnated carbon or glass fiber strands wrapped in helical and cylindrical laminar patterns – heat cured
- aluminum or steel or polymer (plastic) liner as barrier to hydrogen leak/permeation
- metal boss (continuously formed with metal liner or stainless steel imbedded in polymer liner)

1. Pneumatic sequence (H_2 gas is fluid)



2. Hydraulic sequence (liquid is fluid)





3. Fire Test

4. Conformity of Production Tests
-- includes Leak-Before-Burst in Design Qualification
(within 22000 cycles; 5500 cycles > 1.8million km)

Open Issues in Development of the Safety Design Qualification Requirements For Compressed Hydrogen Storage

- Hydrogen embrittlement

- Fire test – duration of localized exposure
  -- temperature at system surface
  -- duration of engulfing fire exposure

- Permeation
  -- criterion for steady-state permeation
  -- clarity in equivalence of SAE and EU-HySafe

Hydrogen Embrittlement

Challenge is to establish performance-based criteria (not prescriptive)

Placeholder text for high pressure applications is prescriptive:

Steel Hydrogen Compatibility

In all applications where steel comes in contact with hydrogen, hydrogen compatibility should be demonstrated.

- Steels that meet requirements of 6.3 and 7.2.2 of ISO 9809-1:1999 are recognized as hydrogen compatible for low stress applications
- Steels must be qualified for high pressure hydrogen gas applications by meeting the following performance-based test requirements:

  TBD

  The following steels are recognized as suitable for high pressure hydrogen gas applications, and hence, are not required to undergo this embrittlement testing in design qualification: SUS316L, AISI316L, AISI316 and DIN1.4435; all must have ≥ 12% nickel composition and ≤ 0.1% magnetic phases by volume. These high pressure applications may not include welds.

Aluminum Alloy Hydrogen Compatibility

In all applications where aluminum comes in contact with hydrogen, hydrogen compatibility should be demonstrated.

- Aluminum alloys that meet requirements of 6.1 – 6.2 of ISO 7866-1:1999 are recognized as hydrogen compatible for low stress applications
- Aluminum alloys must be qualified for high pressure hydrogen gas applications by meeting the following performance-based test requirements:

  TBD

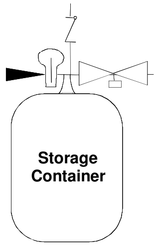
  The following aluminum alloys are recognized as suitable for high pressure hydrogen gas applications, and hence, are not required to undergo this embrittlement testing in design qualification: A6061-T6, A6061-T62, A6061-T651 and A6061-T6511. These high pressure applications may not include welds.

Discussion with Embrittlement Experts at 2010 HydroGenius Meeting (HydroGenius = Japan government project) about How to Test for the Most Critical Risk Factors When Developing Storage Performance Test(s) for Embrittlement

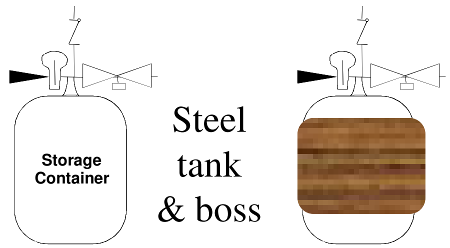
Embrittlement

Risk = Probability of Occurrence x Severity of Consequence

Composite wrap
Polymer liner
Stainless Steel boss



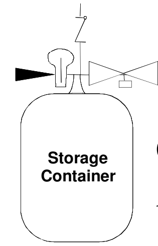
- **Probability is low for boss low stress application**
- **Severity is mitigated <u>IF</u> leak is only outcome (leak detection/shut down)**



Steel tank & boss

composite hoop wrap

- **Probability is high high stress application**
- **Failure modes:**
  - **<u>acceleration</u> of crack growth rate leading to leak at lower number of cycles (LBB during service life)**
  - **<u>transition</u> of crack growth pattern to cause failure by rupture (not LBB)**



Composite wrap
Aluminum liner/boss

- **Severity is mitigated <u>IF</u> LBB establishes wrap handles burst resistance when liner fails; leak is mitigated by leak detection/shut down**

Open Issues in Development of the Safety Design Qualification Requirements For Compressed Hydrogen Storage

- Hydrogen embrittlement

- Fire test – duration of localized exposure
  -- temperature at system surface
  -- duration of engulfing fire exposure

- Permeation
  -- criterion for steady-state permeation
  -- clarity in equivalence of SAE and EU-HySafe

DRAFT FIRE TEST CURRENTLY UNDER DISCUSSION AT SAE

Based on temperature monitoring in vehicle fire tests by JARI, GM & Powertech & Other OEM members
-- tests used to identify the temperature and duration of local heat impact (>300C) prior to engulfing fire