International Forum on Pressure Vessels for Hydrogen and Natural Gas Vehicles

COMPOSITE TANK TESTING, CERTIFICATION, AND FIELD PERFORMANCE

Beijing

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Joe Wong

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POWERTECH – Hydrogen & CNG Services

- Certification testing of individual high pressure components
- Design Verification, Performance, End-of-Life testing of complete fuel systems
- Design, construction, and operation of Hydrogen Fill Stations
- Safety Studies
- Standards Development

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30% Hydrogen / 70% CNG Vehicles

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Hydrogen FCV Fleets (Ford) - Vancouver

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100% Hydrogen ICE Vehicles

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Hydrogen Highway to Whistler

HydrogenHighway

Composite Tank Designs

- On–board vehicle fuel systems
  - Every single hydrogen FCV OEM are using composite tanks
- Industrial gas cylinders
- Transportable bulk tanks
- Stationary ground storage

1994 Ballard Fuel Cell Bus

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Why use Composite cylinders?

- Light weight
- Lower cost for higher pressures and larger cylinders
- Less susceptible to fatigue cracks
- High toughness and elongation of liner material
- Low capital cost for manufacturing
- Capable of large diameters
- Ultra high pressure (1000bar)

Large Volume Type 4 Storage

- 38 feet long tanks (11.6M)
- 5300 lbs (2,400 kg)
- 42 inches diameter
- Holds 10,000 SCM CNG

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COMPOSITE CYLINDERS FOR STATION GROUND STORAGE

> Vehicle OEMs leading the advancement of 70 MPa onboard storage

> Up to 100 MPa storage tanks needed in the fueling stations to provide fast filling of vehicles to 70 MPa

> Traditional steel designs cannot be used for this high pressure

> Data is needed to obtain regulatory approval of composite tanks

> ASME has recently approved the use of composite tanks for hydrogen

Need for composite ground storage @100 MPa

- Steel ground storage tanks are difficult to manufacture
  - Thick wall cylinders
  - Small volume cylinders
  - Hard to get materials
  - Hydrogen embrittlement
  - High capital cost

- Composite tank designs are scaled up from 35 MPa designs
  - Only requires extra carbon fiber wraps
  - Low capital costs
  - Able to produce large volume tanks
  - Liners are resistant to hydrogen embrittlement

Vehicle Service Conditions

Road conditions very severe environment for vehicle pressure vessels

- Temperature extremes (-40ºC to +85ºC in vehicles)
- Multiple fills from full to empty
  - (pressure changes) = fatigue cracking
- Exposure to road environments and cargo spillage
- Vibration
- Vehicle fires
- Collision
- Exposure to fire sources

Ground Storage Service Conditions

Conditions less severe than vehicle tanks

- Temperature extremes (-40ºC to +40ºC in stations)
- Tanks are always near full, very low pressure changes
- No exposure to road environments and cargo spillage
- No vibration except earthquake deformation
- No flammable materials in the vicinity
- Collision protection in stations
- Clearance distance around equipment
- Pressure activated relief devices
- Emergency shutdown systems
- Heavy support frames
- Regular scheduled maintenance & calibrations

100 MPa Cylinder Development

Wall thickness comparison - 35 MPa vs 70 MPa cylinders

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APPLICABLE STANDARDS

Standard	Hydrogen	CNG	Transportable storage	Vehicle storage	Stationary Storage
DOT FRP1	X	X	X		
CAN/CSA B339	X	X	X		
DOT CFFC	X	X	X		
ISO 11119-2	X	X	X		
ISO 11119-3	X	X	X		
CSA B51 Part 2	X	X		X	
ANSI NGV2		X		X	
ANSI HGV2	X			X	
ISO 15869	X			X	
ISO 11439		X		X	
SAE J2579	X				X
CSA B51 Part 3	X	X			X
ISO TC197 WG15	X				X

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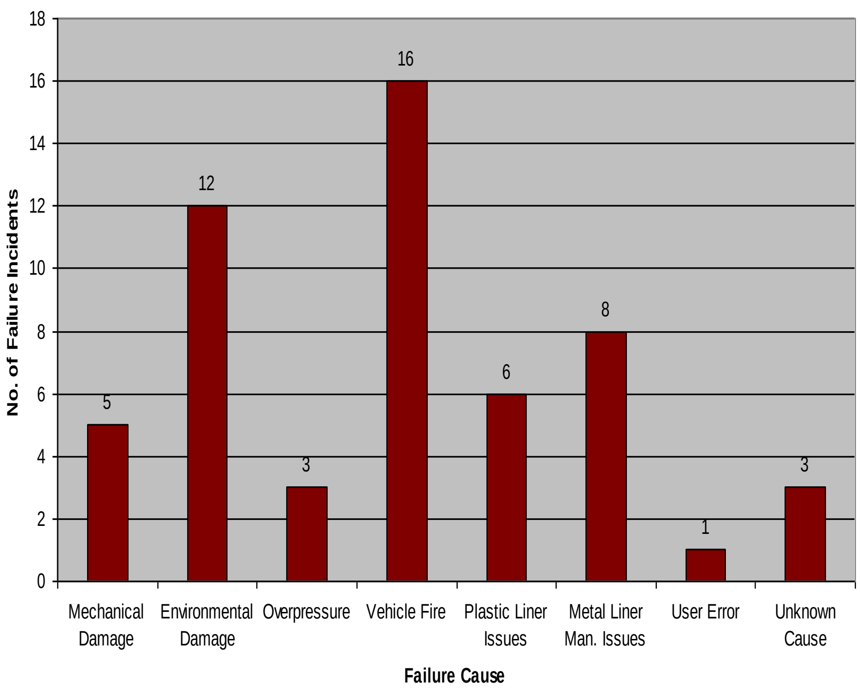
FAILURE INCIDENTS REPORTED BY FAILURE CAUSE



Data classified according to unique failure causes:

- Mechanical Damage – External abrasion and/or impact
- Environmental Damage – External environment assisted, typically SCC
- Overpressure – Faulty fueling equipment or faulty CNG cylinder valves
- Vehicle fire – Faulty PRDs or lack of PRDs; localized fires
- Plastic Liner Issues – Man. defects incl. cracking at end boss/liner interface, flawed welds, liner seal failures
- Metal Liner Issues – Man. defects incl. pinhole leaks, laminations, poor heat treat practice

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Standard Tests for Design Qualification

Performance tests were designed and validated including:

- ❑ Ambient Cycling Test
- ❑ Environmental Test
- ❑ Extreme Temperature Pressure Test
- ❑ Hydrostatic Burst Test
- ❑ Composite Flaw Test
- ❑ Drop Test
- ❑ Accelerated Stress Rupture Test
- ❑ Permeation Test
- ❑ Hydrogen Cycling Test
- ❑ Bonfire test
- ❑ Gunfire Penetration Test

Test Methods

- Performance based standards require testing conditions that closely simulate service conditions

- Need to ensure accuracy measurement and control of:
  - tank temperature
  - tank pressure
  - test medium
  - rate of testing

Tank Testing - Burst Test

Burst testing up to 2,800 bar

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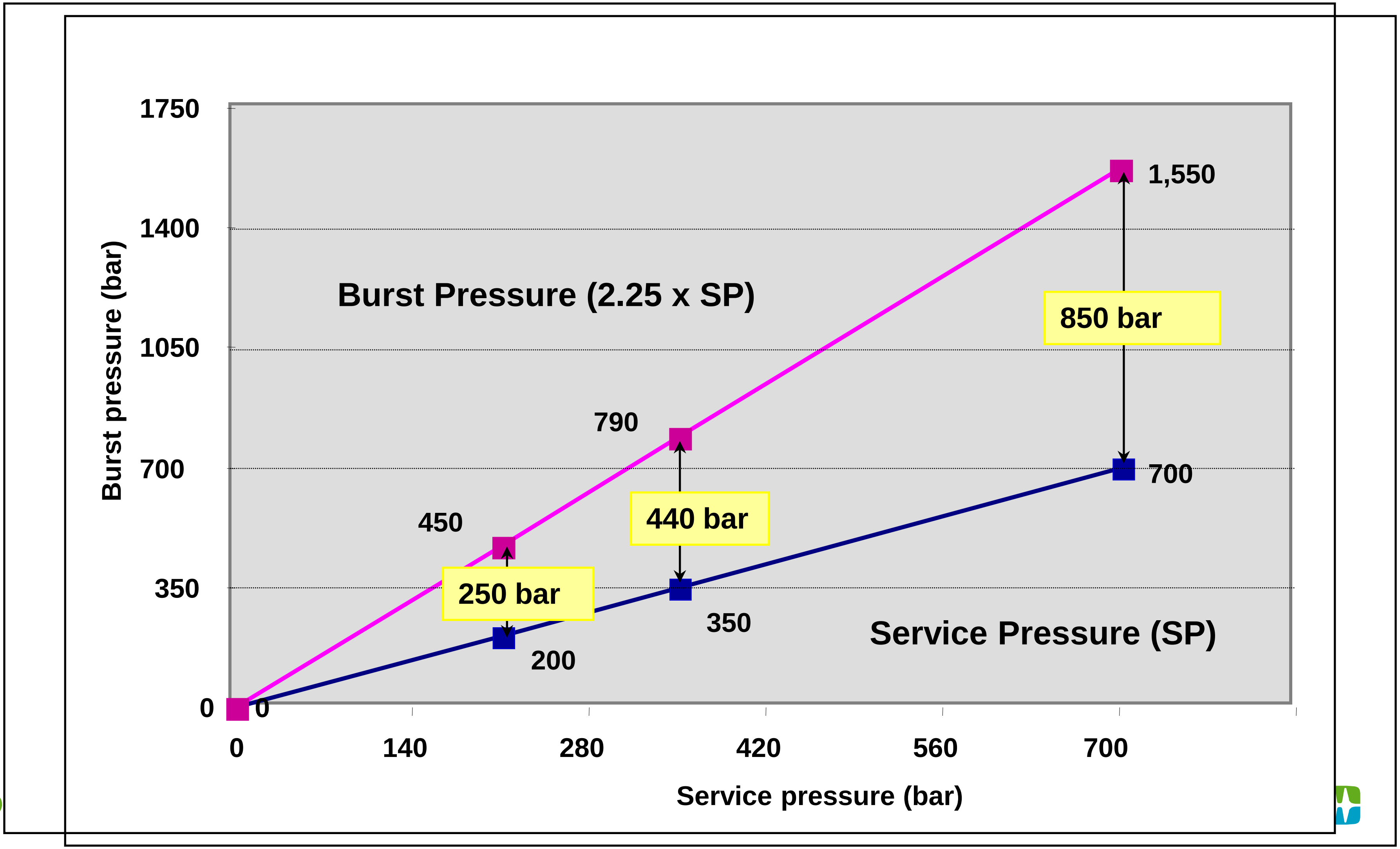
BURST PRESSURE VERSUS WORKING PRESSURE



Tank Testing - Hydraulic Pressure

Environmental and chemical effects

Powertech Cylinder Test Facilities

- Hydraulic pressure cycling up to 1,500 bar

Flaw/Damage Tolerance

Extreme temperature cycle test

Drop Test

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Pressure Cycle Testing – Vehicles

- Minimum pressure - 10% service pressure –
- Maximum pressure - 125% service pressure
- Failure mode must be leak, not rupture
- Minimum # of cycles 11,250 cycles (ANSI/CSA NGV2)
- 2 fills per day x 15 years = 10,950 fills
- 10,950 fills = 5.5 million kilometers

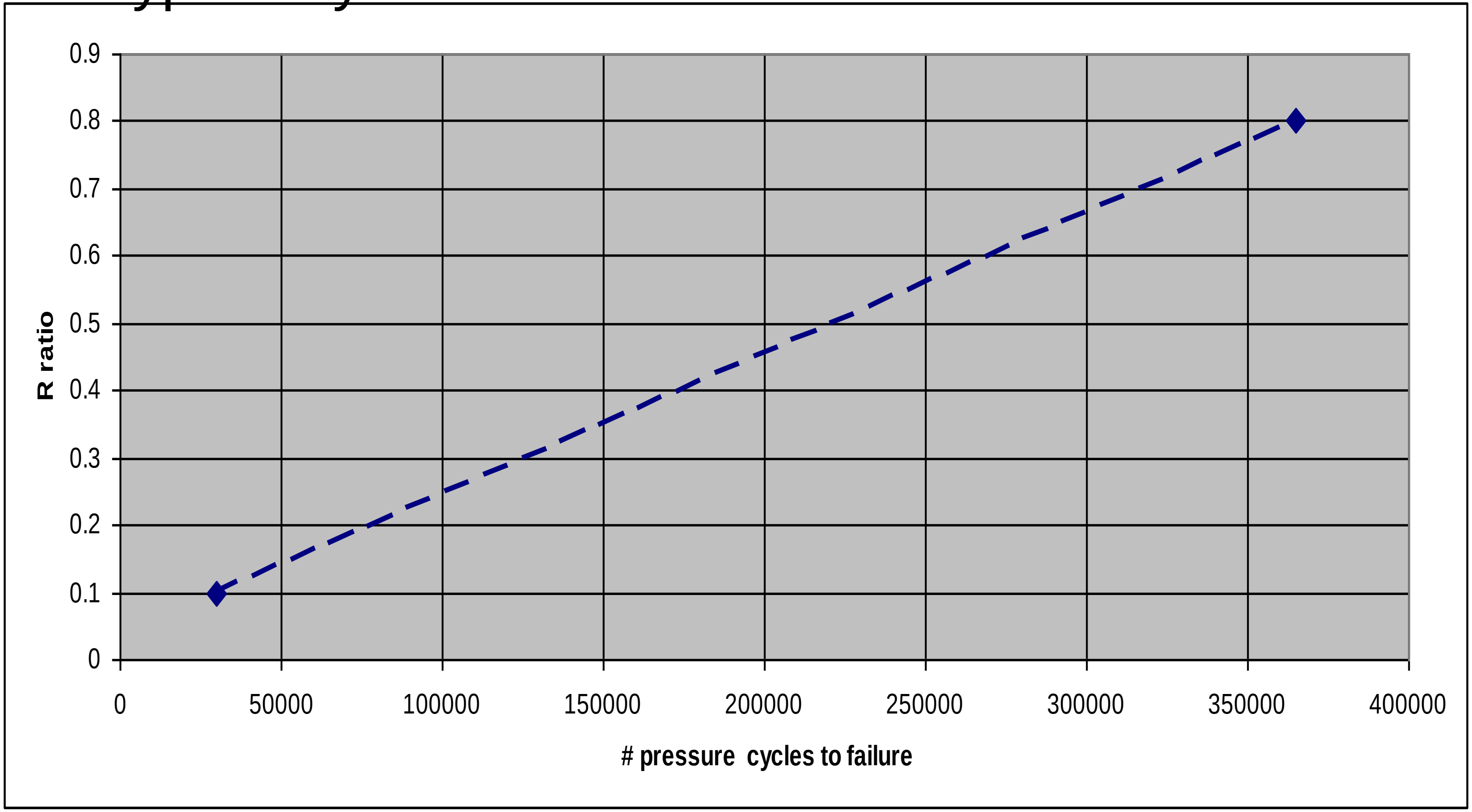
Pressure Cycle Testing – Ground Storage

- Study by Powertech on pressure fluctuation in CNG fueling stations
- Monitored pressure in cascade storage banks in 3 fueling stations
- Station fueled approximately 100 vehicles per day
- Findings for cycle pressure range:
  - Worst case 50% -100% approx 5000 cycle per year
  - Typical 70 % - 125% approx.10000 cycle per year

  - Worst case for vehicles 10% -125% of service pressure

Pressure Cycle Testing - Ground Storage
R ratio = min pressure /max pressure

Type 3 Cylinder



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Damage Tolerance – Gunfire Test

Type 3 composite tank

First bullet made 75 mm cut in carbon fiber and exposed aluminum liner

Second bullet caused the release of the tank's hydrogen gas

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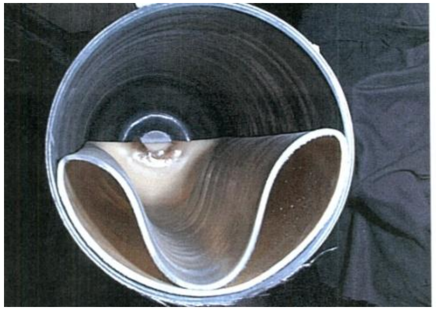
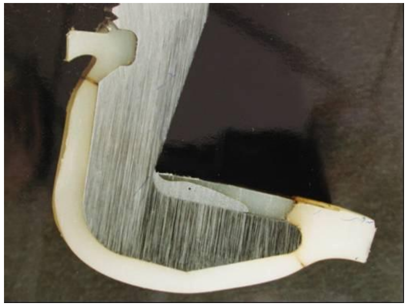
Plastic Liner Issues

- The long term integrity of the connection between the plastic liner and the metal end boss
  - Different designs: mechanical connection, O ring seal, adhesive seal
- Different liner materials
- Aging effects on the plastic liner due to extreme temperatures
- Welding of plastic liners
- Permeations issues
- Liner buckling
- Static Discharge





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Recent Work to Support Standards Development

- Hydrogen test validation for SAE J2579 - NREL
- Localized fire testing - NHTSA
- Crash Integrity of Tanks - Battelle
- Fueling protocol testing for SAE J2601 - SAE

SAE J2579 Program Overview

Tests to validate SAE J2579 composed of three parts:

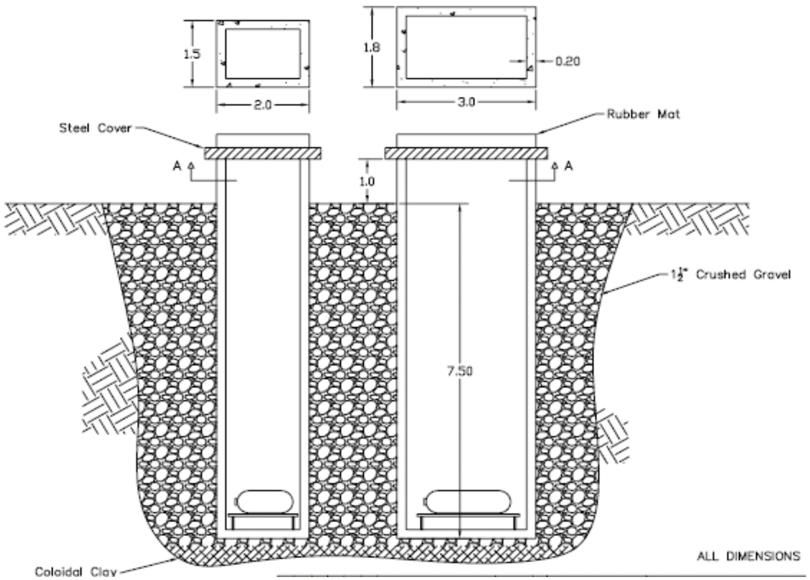
I. Verify that the vehicle storage validation tests specified in J2579 can be performed by a test facility

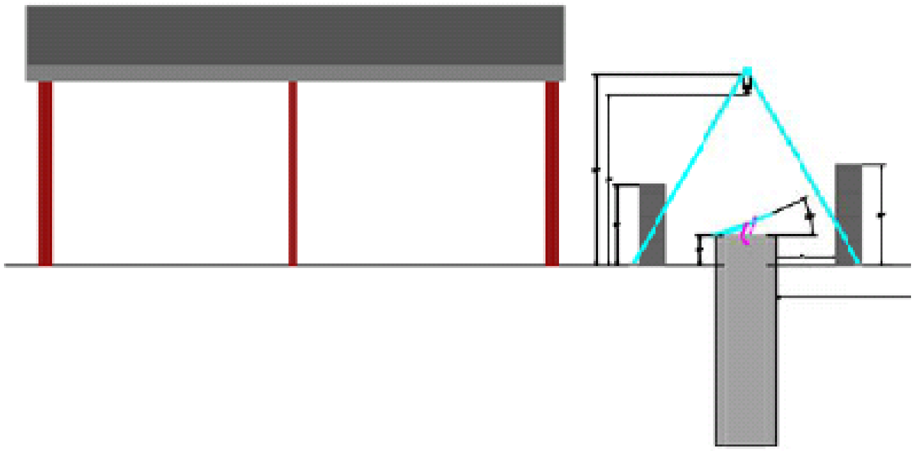
II. Verify that vehicle storage systems that have failed in past vehicle service would not pass the J2579 tests

III. Verify that vehicle storage systems that have not failed in past vehicle service will either: 1) pass the J2579 tests or, 2) fail the J2579 tests only when the reasons for failure are understood and would be expected to occur in vehicle service.

Contract by the National Renewable Energy Laboratory (NREL), working with the Society of Automotive Engineers International (SAE).

Validation of Test Sequence
Safety Concerns





Powertech SAE J2579 Test Setup Safety Considerations

Ignition of 25% Hydrogen Mixture (approaching stoichiometric)

Localized Fire Testing – Purpose of NHTSA Program

- Since year 2000, leading cause of CNG cylinder failures is vehicle fire, and single leading cause of vehicle fire failures is localized fire effects
- Objective is to verify effectiveness of a localized flame test developed previously in a Transport Canada study
- Objective to be achieved by the "…evaluation of various fire protection technologies that will reduce the risk of cylinder failure during a vehicle fire"
  - The localized fire test developed for Transport Canada involved meeting several precise time and temperature criteria occurring on a tank surface as defined by an OEM, and was found not to be adaptable to evaluating the performance of various fire protection technologies
  - A more versatile flame impingement test was developed based on vehicle fire data
    - Maximum temperature exceeding 900ºC
    - Duration of 30 minutes (duration of tire fire)
    - Fire length that is 25% of the length covered by a standard 1.65m fire

Localized Fire Test Programs - Conclusions

- There are protective coating and wrap systems that work
- Protective systems are available that are:
  - Cost-effective, minimal added weight, minimal added wall thickness
- There are remote fire detection systems that work

Intumescent epoxy after 30 min @ 1000 deg C test

Thermal wrap undergoing localized fire

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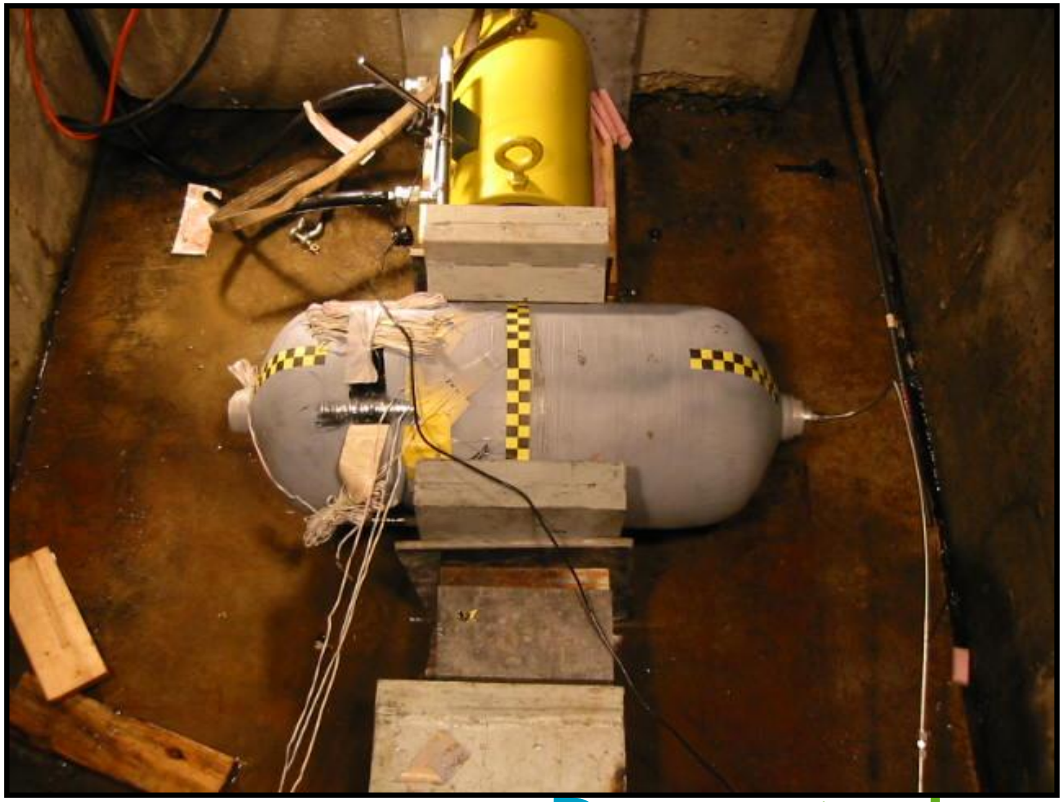
Hydraulic Crush Test (150,000 kgf)

Used hydraulic ram to attempt crush of pressurized hydrogen tank

Test ended at 150,000 kgf when reinforced concrete wall on opposite side of ram broke



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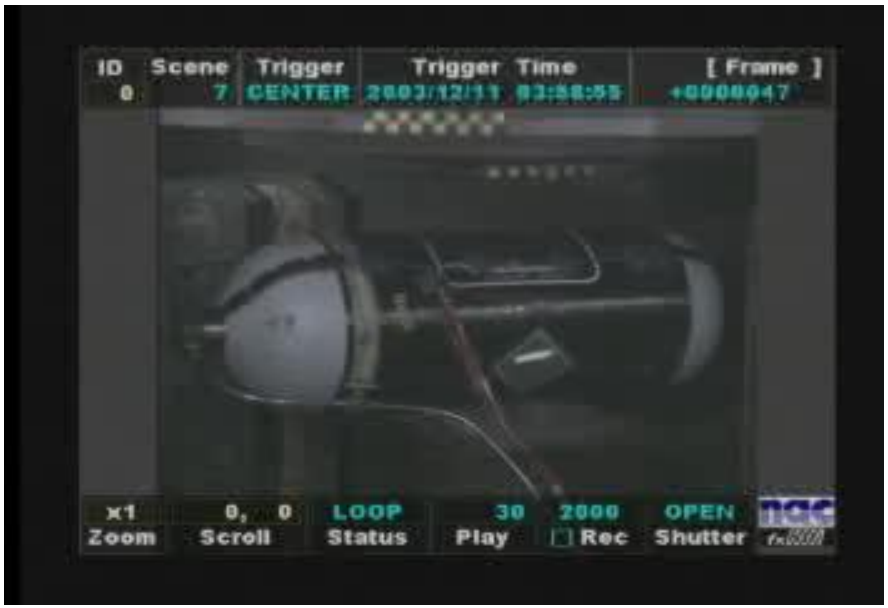
2 Ton Impact on Tank



- ❑ Battelle Program funded by NHTSA
- ❑ Type 3 and Type 4 tanks
- ❑ vertical and horizontal impacts
- ❑ 350 and 700 bar tanks

Multi-Client 70 MPa Hydrogen Fast Fill Study

Outputs of the study to support J2601:

- ❑ Minimum fueling time at each ambient condition to safely fill all fuel systems
- ❑ Pre-cooling levels for each ambient condition
- ❑ Energy required for pre-cooling
- ❑ Temperature gradients throughout the fuel system
- ❑ Durability of fuel system under extreme fueling conditions
- ❑ Performance data of station components (flowmeter, flow controller, nozzles, hoses, compressors, etc.)

Consortium members: Air Liquide, BP, Nippon Oil, Sandia (US DOE), Shell, Iwatani, Chrysler, Ford, GM, Nissan, Honda, Toyota.

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