DOE Tank Safety Workshop
Hydrogen Tank Safety Testing

04.29.2010 | Presented by Joe Wong, P.Eng.

Powertech

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

Powertech

PRESENTATION

- Discuss CNG Field Performance Data
- Discuss Safety Testing of Type 4 Tanks
- Current work to support Codes & Standards Development

Storage Tank Technologies

4 basic types of tank designs

- Type 1 – all metal
- Type 2 – metal liner with hoop wrapped composite
- Type 3 – metal liner with fully wrapped composite
- Type 4 – Plastic liner with fully wrapped composite

Tank Designs in Hydrogen Service

- Primarily use composite tanks for hydrogen fuel cell vehicles
- 250 bar carbon fiber reinforced tank design in fuel cell bus demonstration in 1994.
- Storage pressures increased to 350 bar in 2000
- Today, most auto OEMs have 700 bar tanks for on-board storage
- 500 km range with 5kg H2

1994 Ballard Fuel Cell Bus

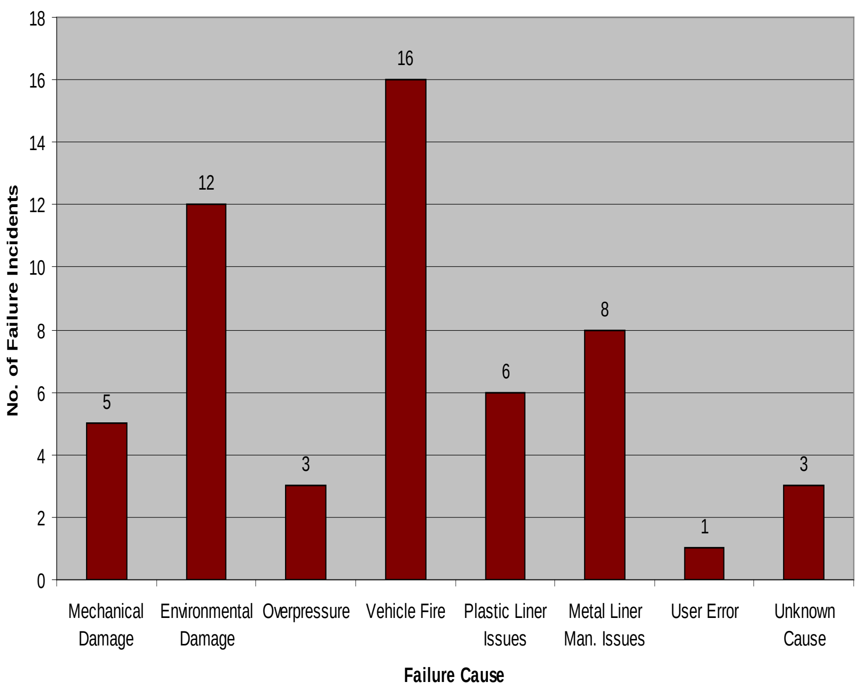
Powertech

CNG Experience In-service Failures

- Powertech has been testing CNG storage systems since 1983
- Powertech has maintained a cylinder failure database through world wide contacts
- Examined CNG cylinder field failure database to determine if trends evident
- Limited to incidents involving catastrophic rupture of cylinders, although major leaks attributed solely to the cylinder were included
- From 2000-2008, there were 26 CNG cylinder failures.
- Other multiple cylinder failures attributable to “leakage failure mode”:
    - Type 1 steel pinhole leaks (<50)
    - Type 4 plastic liner leak incidents (100’s)

Powertech

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

Powertech

Why use Type 4 cylinders?

- Light weight
- Lower cost than seamless metal liners
- 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)

Powertech

Large Volume Type 4 Storage

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

Type 4 In-service Failures - leaks

Learnings from CNG in-service experience

- Type 4 plastic liner leak incidents (100's)
- Some 12,000 type 4 cylinders manufactured by 1 company (no longer in business)
- SWRI inspected a large number of tanks in 1997

Fleet location	No of tanks	Total Leaks	% leaks
Salt Lake City	237	13	5.5
Las Vegas	254	2	0.8
Tacoma	492	3	0.6
Sacramento	360	4	1.1
New York	310	19	6.1
Total	1653	41	2.5

Powertech

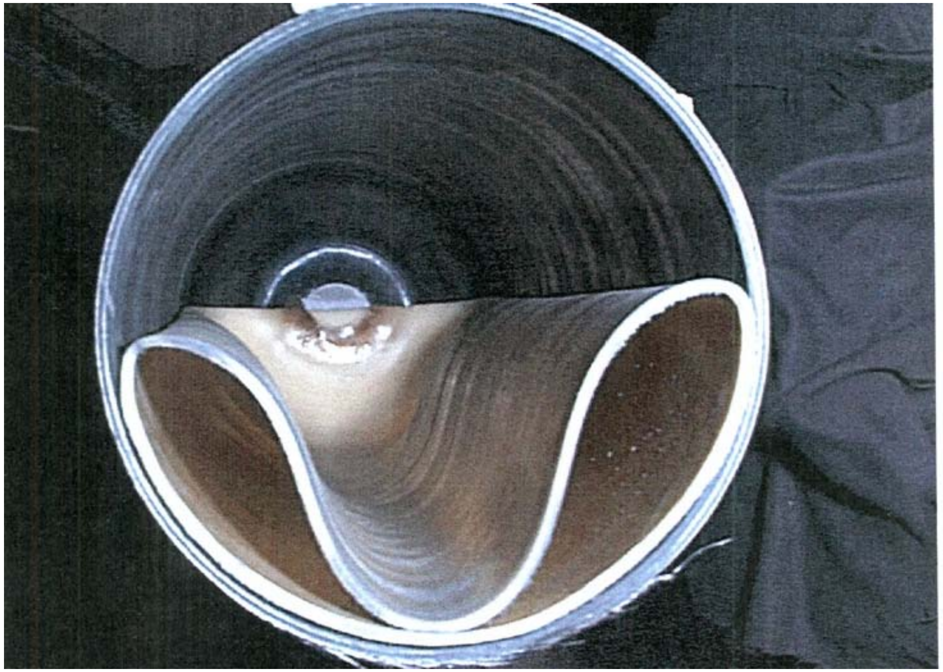
Plastic Liner Issues

- 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

Powertech

Liner Buckling

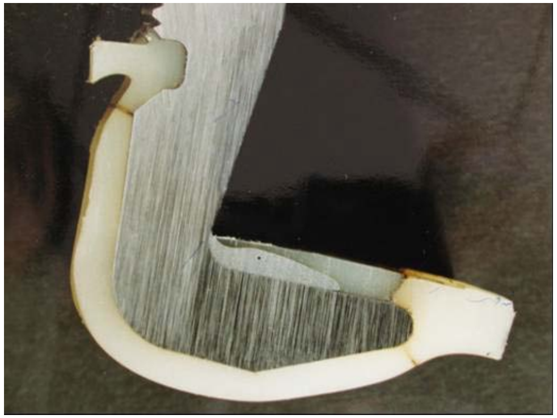
- Trapped gas between the space between the liner and the composite
- Liner buckles inward when the tank is depressurized
- Causes fatigue cracks and mechanical damage to the end boss interface



Powertech

CNG Cycle Test

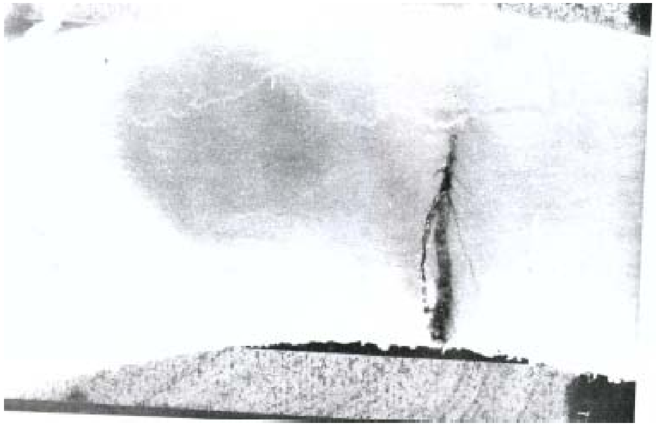
- Closed loop gas cycle test
- Cracks in liner
- Poor end boss design
- Static discharge



Powertech

Electrostatic Discharge

- ❑ Measurement of static charge in the surface of plastic pipe
- ❑ Flowing CNG with contaminants causes high static charge
- ❑ Pinhole puncture through 6 mm pipe
- ❑ No substantial static charge buildup with hydrogen – clean fuel



Powertech

Standards Development

CNG Standards developed from in-service experience

- Vehicle service conditions
- End user requirements
- In-service failures / known failure mechanisms
- In-service abuse
- Collision
- Manufacturing problems
- Design problems

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

Powertech

Tank Testing - Hydraulic Pressure

Environmental and chemical effects

Flaw/Damage Tolerance

Powertech Cylinder Test Facilities

- Hydraulic pressure cycling up to 1,500 bar

Drop Test

Extreme temperature cycle test

Powertech

Tank Testing - Burst Test

Burst testing up to 2,800 bar

Powertech

Current Work to Support Standards Development

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

SAE J2579 Program Overview

Powertech performed tests specified by the SAE Safety Working Group for the purpose of validating the SAE J2579 requirements for storage of gaseous hydrogen on passenger vehicles.

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

Powertech

Program Overview

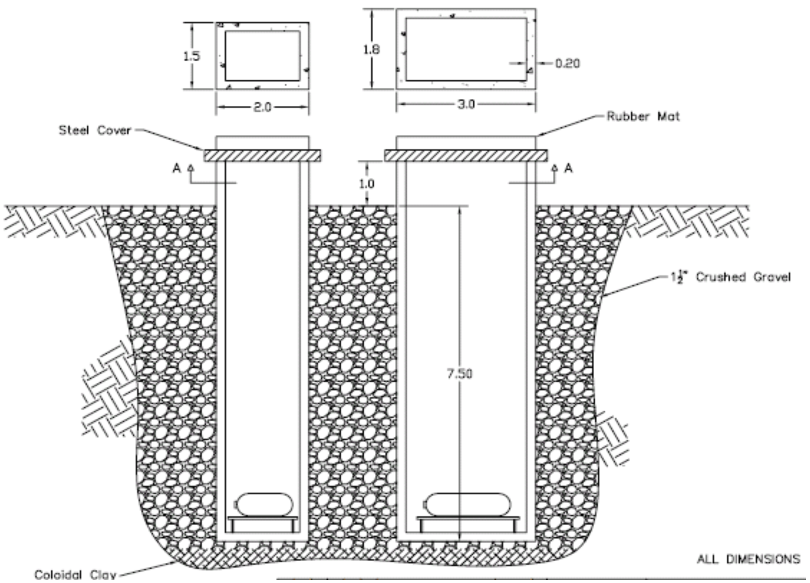
Tests to validate SAE J2579 composed of three parts:

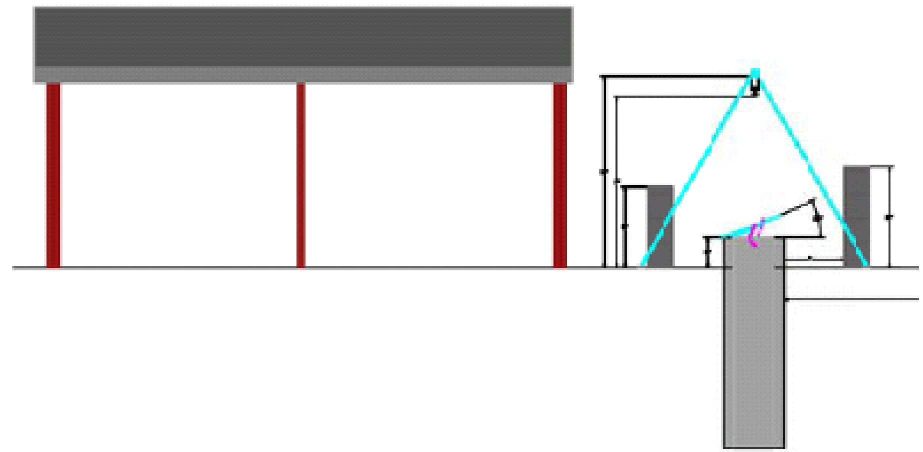
I. Verify that the vehicle storage validation tests specified in J2579 can be performed by a test facility

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.

Validation of Test Sequence
Safety Concerns





Powertech SAE J2579 Test Setup Safety Considerations

Powertech

Validation of Test Sequence
Test Equipment Requirements

Powertech has designed and built 2 parallel test setups for the pneumatic sequence specified in SAE J2579

Each test setup consists of the following equipment:

1. Environmental chamber for the test tank
2. Hydrogen gas pre-cooler
3. Hydrogen gas flow control system (inlet & outlet)
4. Hydrogen compression
5. High-pressure hydrogen storage (88MPa)
6. Low pressure hydrogen storage (1MPa)

Validation of Test Sequence
Safety Concerns

The potential for tank rupture or high-volume hydrogen release must be accounted for in test setup

Powertech has designed & validated a safety system incorporated into the SAE J2579 test setup

The Powertech safety system will:

1. Allow excessive hydrogen leakage to be safely vented
2. Contain a hydrogen ignition/detonation
3. Not contain a tank rupture

As an added safety measure, all vehicle fuel systems under test must meet the requirements of the hydraulic test sequence prior to undergoing the pneumatic test sequence

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

Powertech

Thin Thermal Wrap Material - Fire Test

Powertech

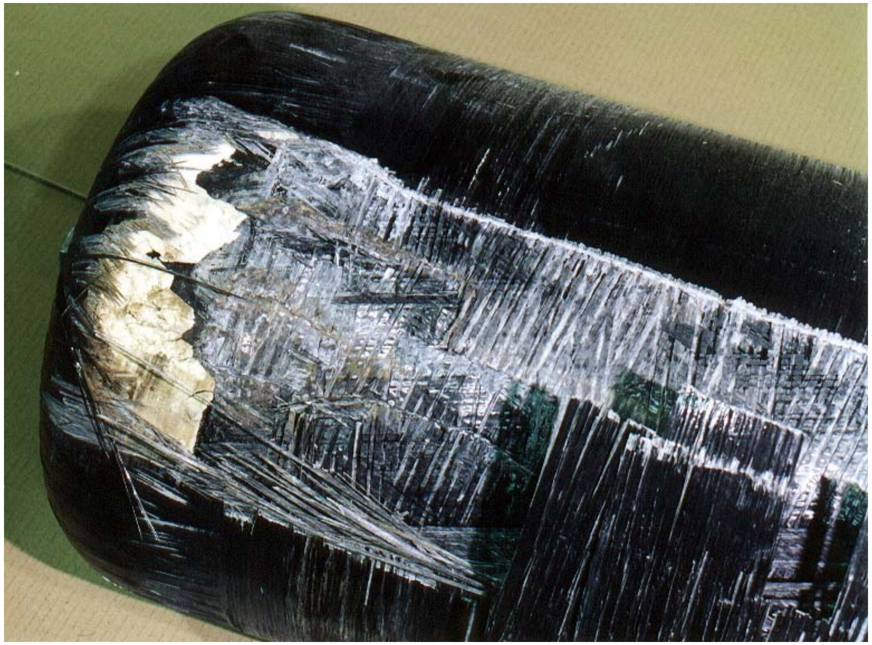
200 bar Fire Test –
Heat damage to intumescent epoxy after 30 minutes at 1000ºC

Localized Fire Test Programs – Conclusions

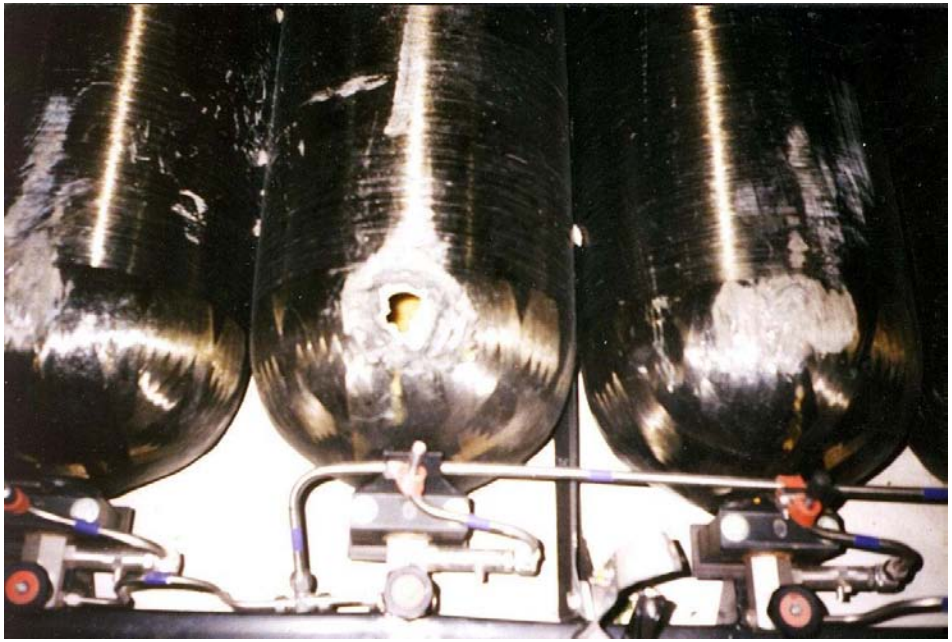
- There are:
  - Protective coating and wrap systems that work
  - Remote fire detection systems that work
- Protective systems are available that are:
  - Cost-effective
  - Minimal added weight
  - Minimal added wall thickness
- Systems can protect against fires even more localized, and even longer duration, than the fire source used in the testing program

Powertech

Type 4 Composite Tank Collision Damage



Tanks mounted on CNG bus roof. The bus impacted a low overhead, collapsing the roof. Tank still exceeded minimum burst pressure.

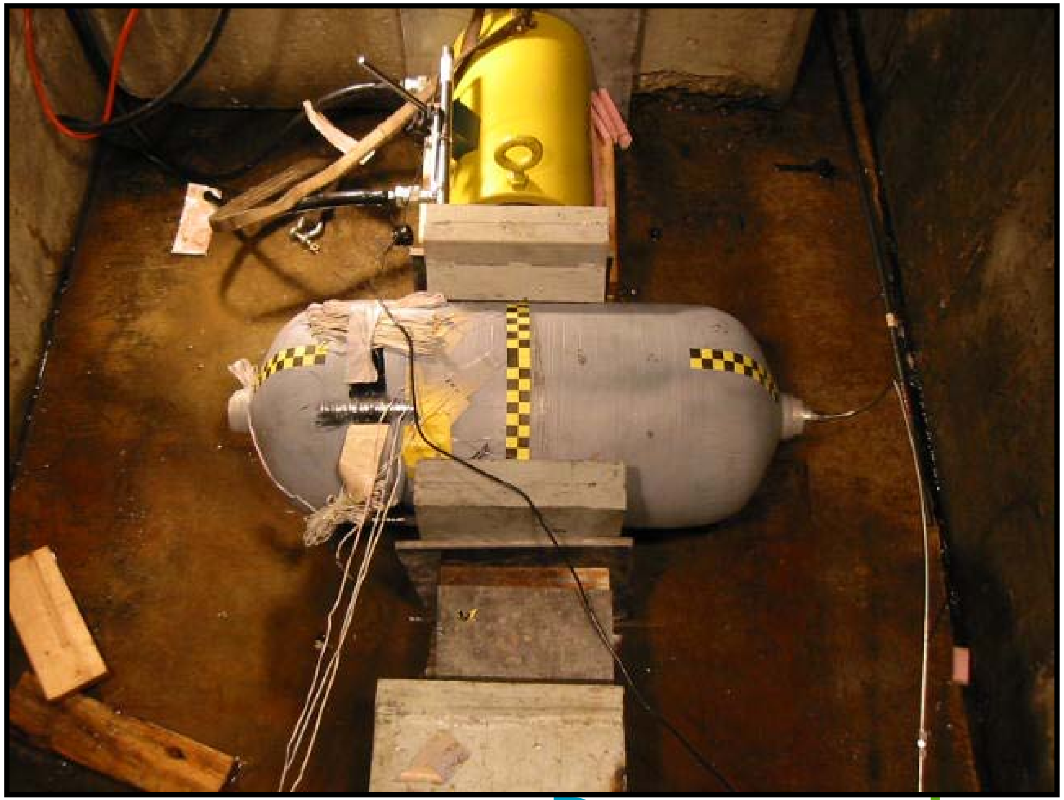


Tanks mounted on CNG bus roof. The bus impacted a low overhead, collapsing the roof. Tank punctured, released gas but did not rupture.

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



Powertech

2 Ton Drop Impact on Pressurized Tanks

Powertech

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:

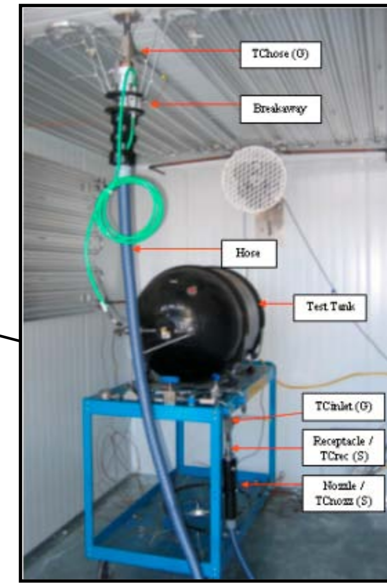
- Minimum fueling time at each ambient condition to safely fill all fuel systems
- Pre-cooling levels for each ambient condition
- Energy required for pre-cooling
- Temperature gradients throughout the fuel system
- Durability of fuel system under extreme fueling conditions
- Performance data of station 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.

Powertech

70 MPa Hydrogen Fast Fill Test Facility

Fueling Station Simulator



Fuel System Chamber
-40C to +50C

Ground Storage Chamber
875 bar -40C to +50C

Multi-Client 70 MPa Fast Fill Study
OEM-1 Fuel System

Ambient Temperature	Fueling Time	Pre-Cooling Temperature
-40°C	3 Minutes	No Pre-Cooling
-10°C	3 Minutes	No Pre-Cooling
0°C	3 Minutes	No Pre-Cooling
15°C	3 Minutes	No Pre-Cooling
30°C	3 Minutes	0°C
50°C	3 Minutes	-15°C*

*Test repeated with Powertech system of same type and volume

SUMMARY

- In-service experience with CNG tanks have provided input into the development of CNG & Hydrogen tank standards
- Studies are underway to provide data to standards being developed by organizations such as SAE, ISO, and CSA including:
  - Tank Safety
  - Fire safety
  - Fueling protocol
  - Impact resistance