> Powertech Labs Inc.

CNG & Hydrogen Tank Safety, R&D, and Testing

12.10.2009 | Presented by Joe Wong, P.Eng.

Powertech

PRESENTATION OBJECTIVES

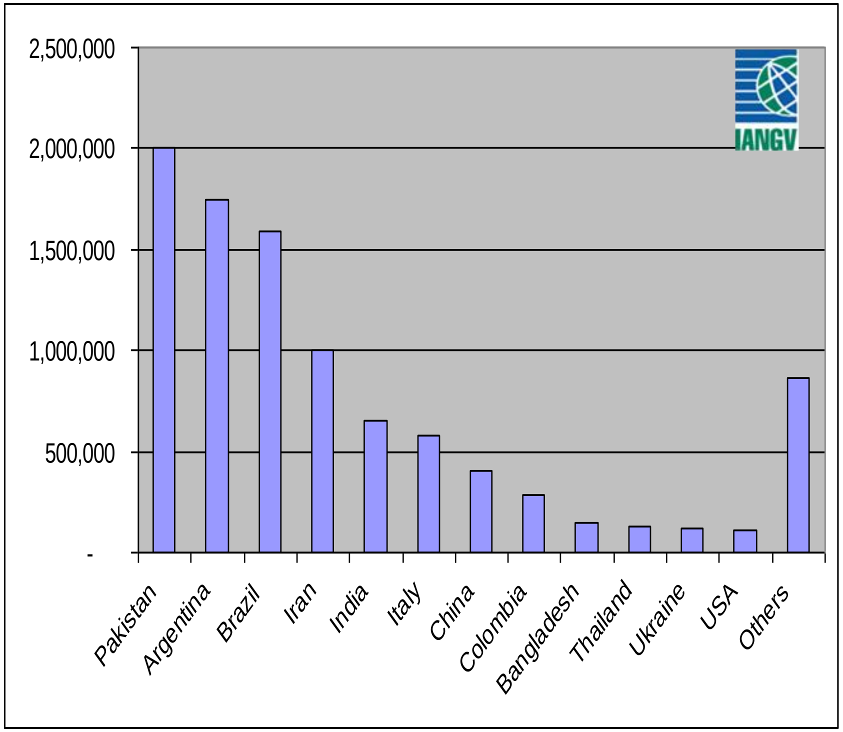
- Present experience from CNG in-service tank performance.
- The process of tank standards development.
- Discuss some of the current studies on Hydrogen tank development and safety.

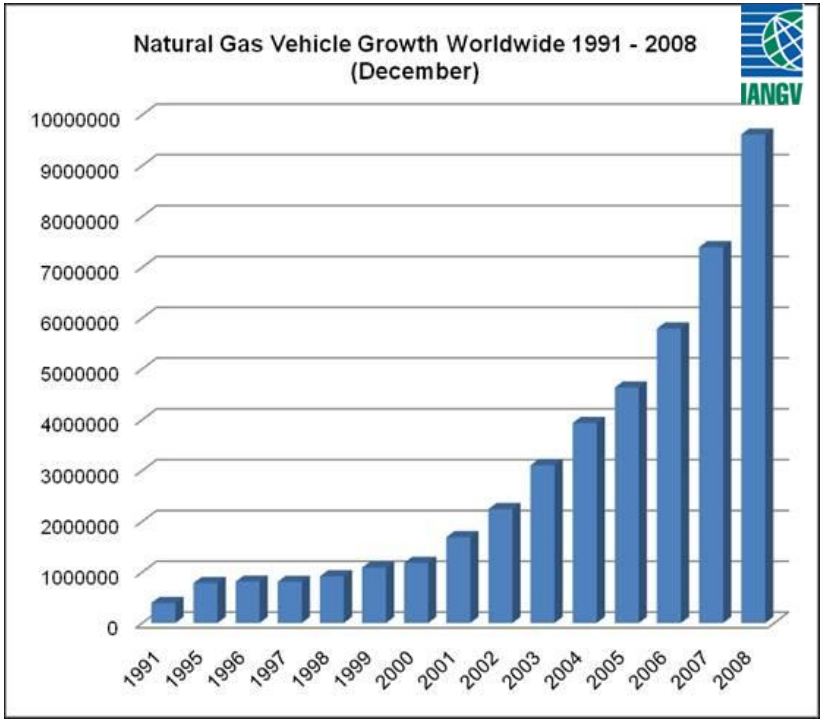
Powertech

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

Compressed Natural Gas Vehicles





9 million vehicles worldwide – 14,000 stations

Powertech

Storage Tank Technologies

4 basic types of tank designs – pressure vessels

- ❑ 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

Powertech

Tank Designs in CNG Service

- Primarily use steel tanks for CNG
- Glass fiber reinforced tank designs in CNG use since 1982
- Carbon fiber reinforced tank designs in CNG use since 1992
- Many tens of thousands carbon fiber tanks now in service (primarily transit bus use)
- Carbon fiber performance far superior to glass fibers
- Service pressures - 200 bar and 250 bar

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

Standards Development – CNG & Hydrogen History

- In 1983 - requested by Gas Utility to investigate CNG cylinder safety
  - Determined a lack of safety standards :
    - ISO 11439 for CNG cylinders
    - NGV2 for CNG containers
    - CSA B51 for CNG cylinders
- In 1994 - requested by Ballard to determine if safe to use CNG cylinders for hydrogen
  - Determined a lack of any standards – Powertech now:
    - ISO 15869 for Hydrogen tanks
    - HGV2 for Hydrogen tanks
    - CSA B51 (first published hydrogen fuel tank standard in world)
    - HGV3.1 for H_2 vehicle components
    - ISO 17268 for H_2 fill connectors
    - EIHP (European Integrated Hydrogen Program)
    - HGV4.3 for Station Performance
    - SAE J2578
    - SAE J2579
    - SAE J2601

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

Vehicle Service Conditions

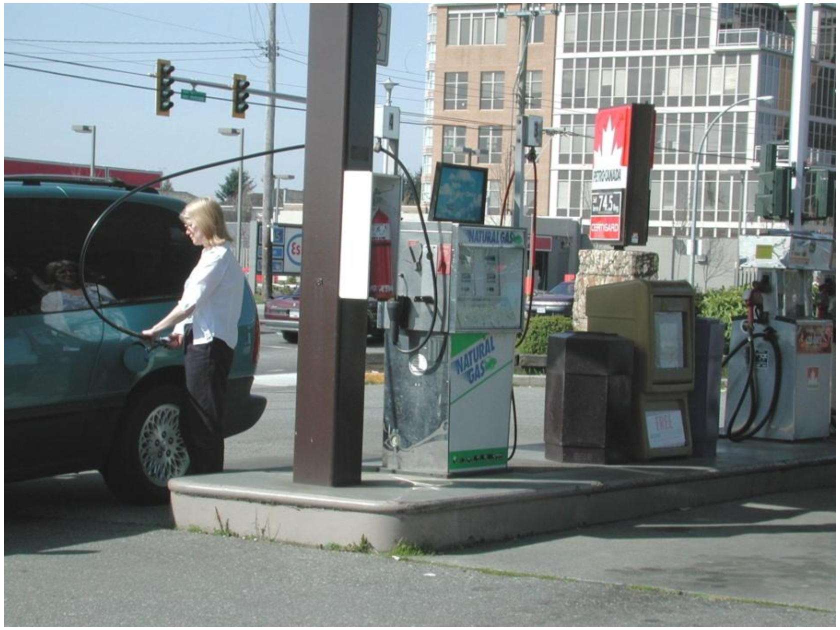
Road conditions are very severe environments for pressure vessels

- Temperature extremes (-40ºF to +185 ºF in vehicles)
- Multiple fills (pressure changes) = fatigue cracking
- Exposure to road environments and cargo spillage
- Vibration
- Vehicle fires
- Collision

Standards require tests or installation requirements for all these conditions

Consumer Desires for CNG or Hydrogen storage

- ❑ Same requirements as gasoline vehicles
  - ❑ Sufficient range
  - ❑ Same weight
  - ❑ Same storage space in trunk
  - ❑ Same level of safety
  - ❑ Same cost
  - ❑ Same fueling procedures



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)

In-Service CNG Tank Ruptures

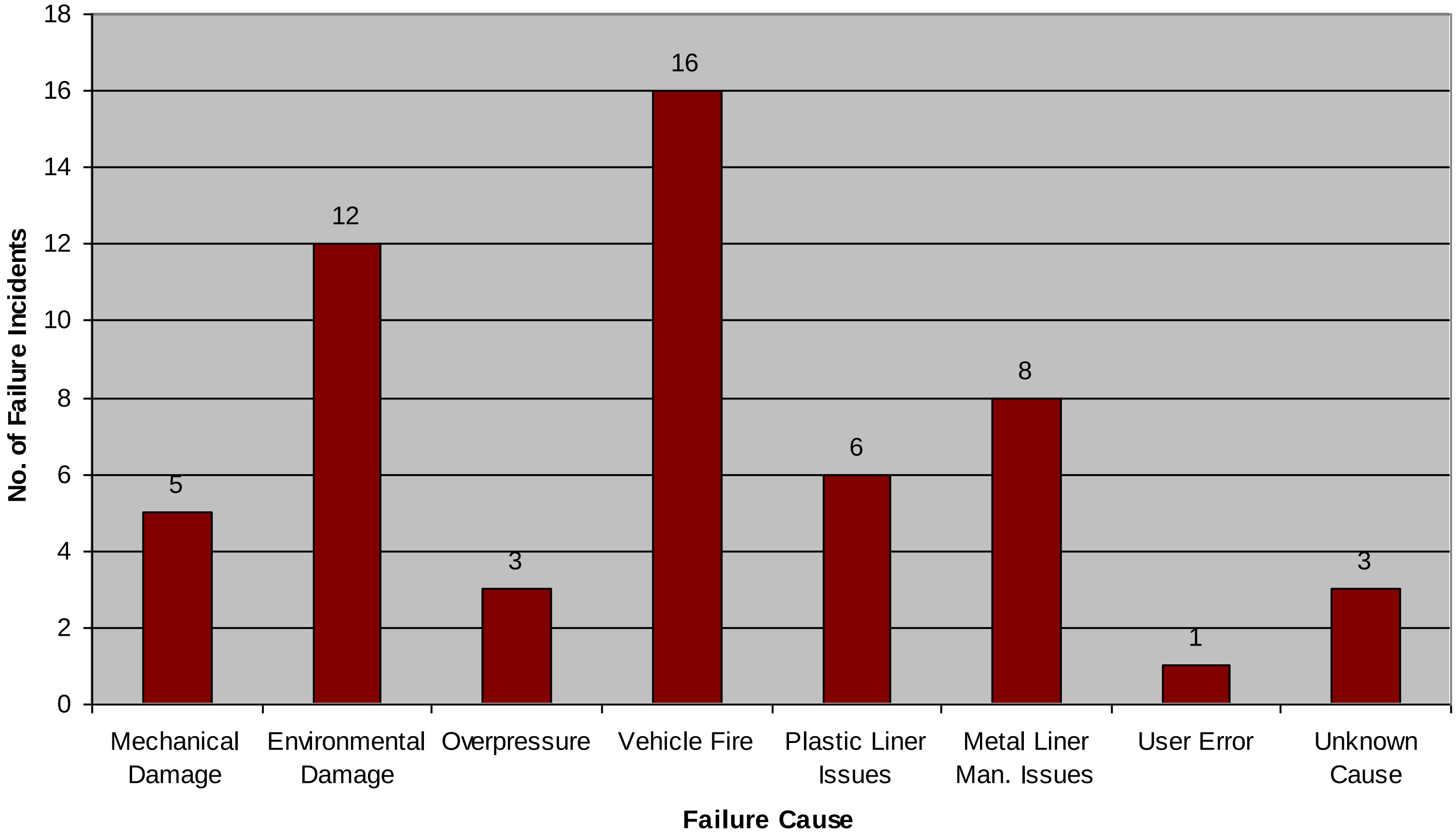
Powertech

FAILURE INCIDENTS REPORTED BY FAILURE CAUSE

Data classified according to eight 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

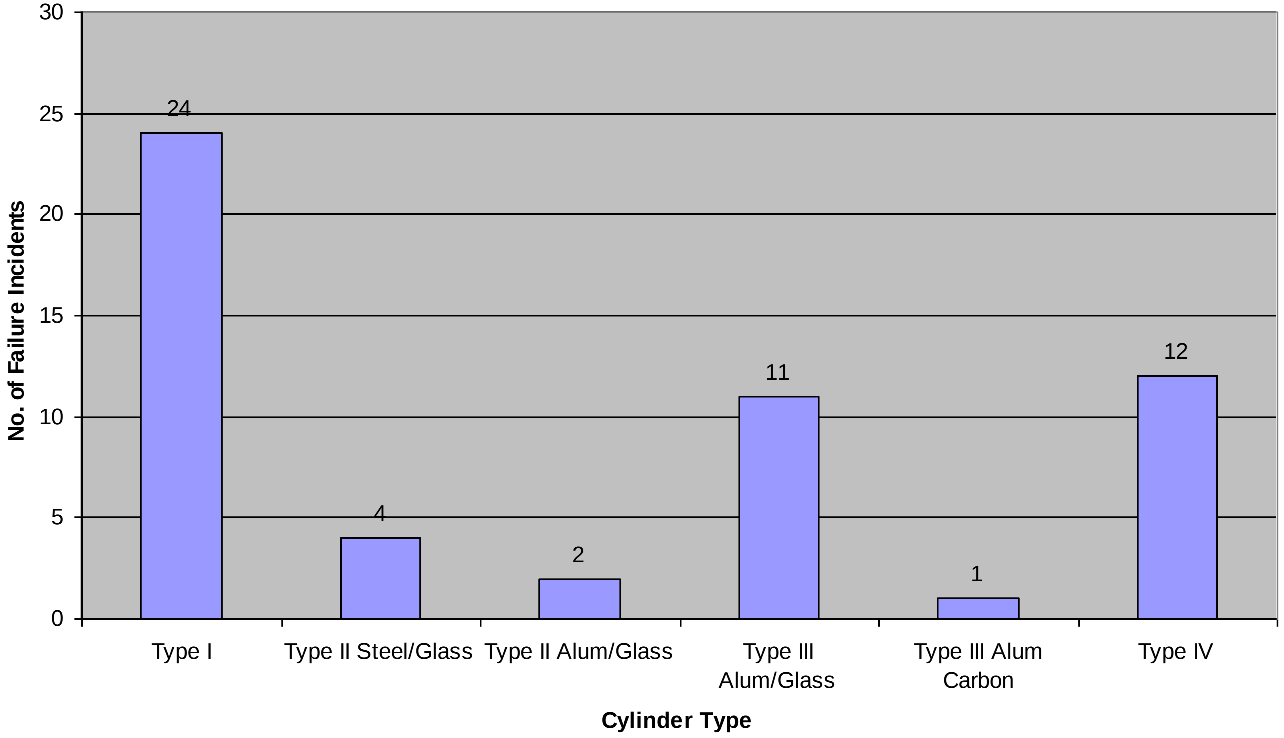
FAILURE INCIDENTS REPORTED BY FAILURE CAUSE



Powertech

FAILURE INCIDENTS REPORTED BY CYLINDER TYPE

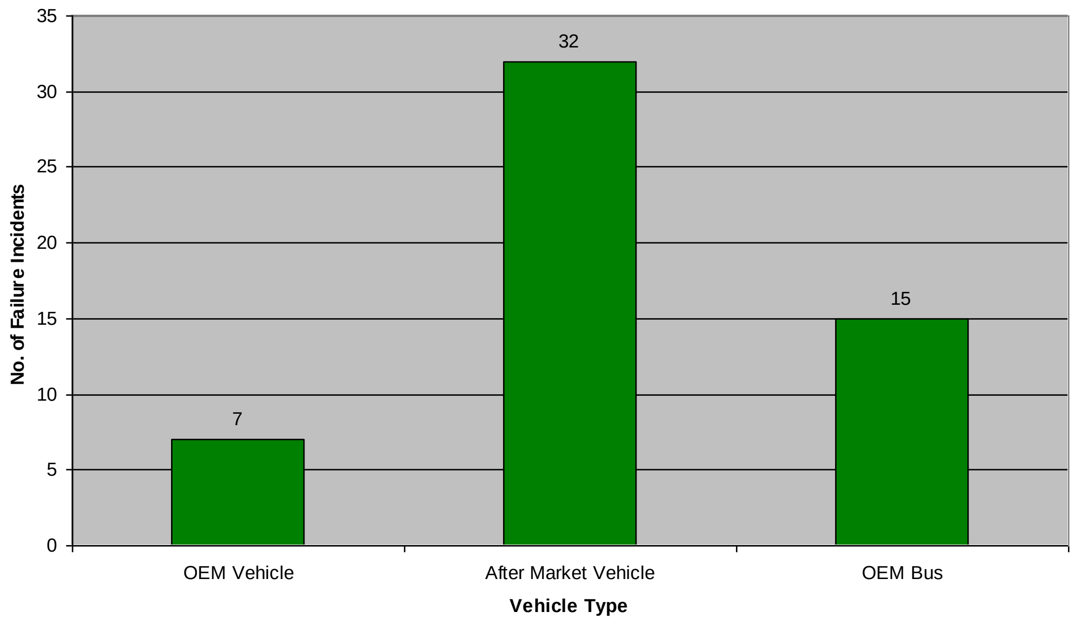
- Type 1 steel cylinders involved in nearly 50% of failure incidents



Powertech

FAILURE INCIDENTS REPORTED BY VEHICLE TYPE

- Aftermarket vehicles represent just over 50% of failure incidents
- Data is related as most aftermarket conversions employ low cost/readily available Type 1 cylinders
- Many of the installations less likely to follow sound engineering practice (regarding use of standards, materials/workmanship quality, installation codes, maintenance/inspection procedures)

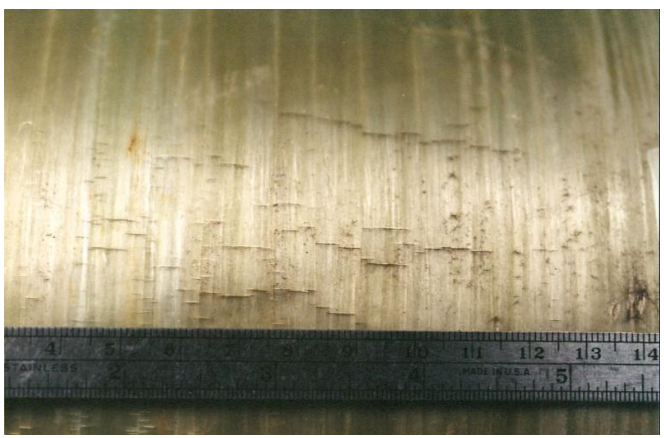


Powertech

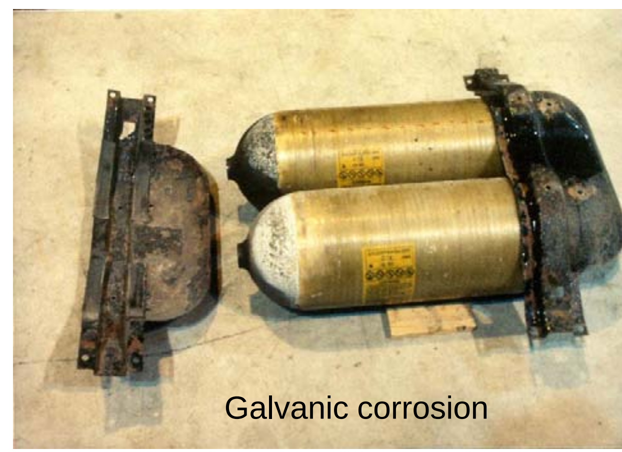
In-service Damage Experience

Tank dragged on road under vehicle after support strap broke.

CNG vehicle crash – no tank rupture

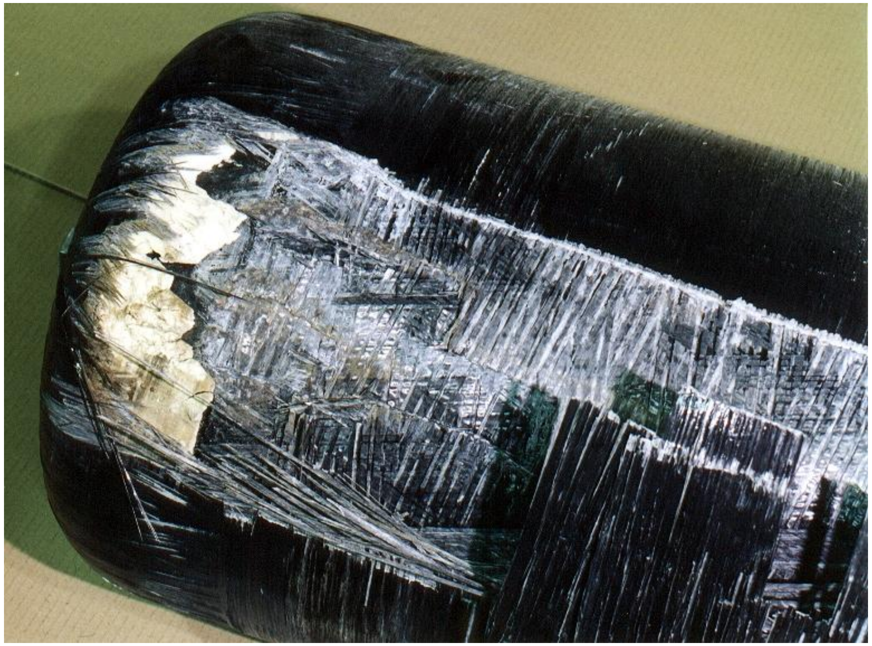


Stress corrosion cracking due to acid attack on fibers

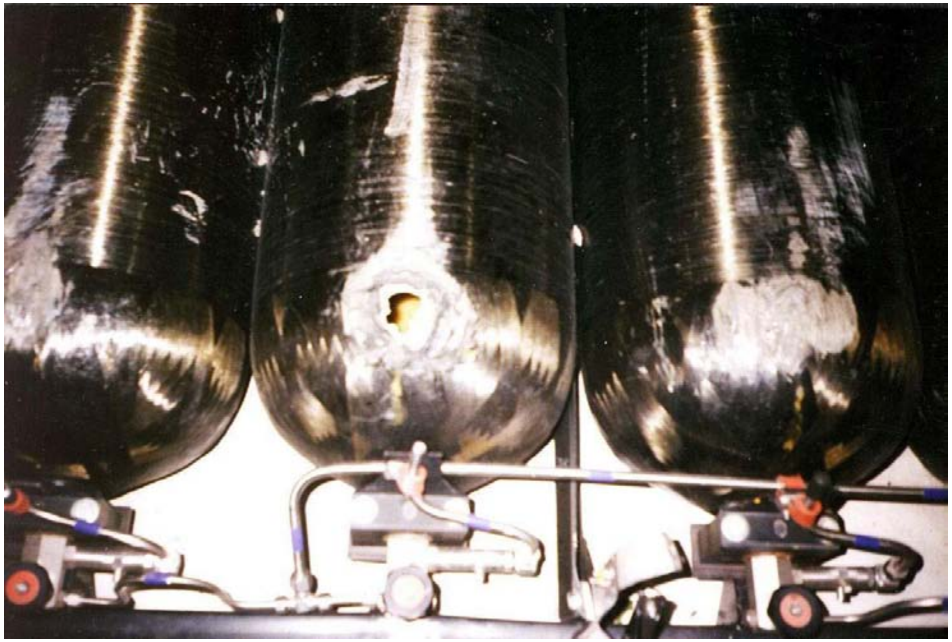


Galvanic corrosion

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.

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
- ❑ Natural Gas or Hydrogen Cycling Test
- ❑ Bonfire test
- ❑ Gunfire Penetration Test

Powertech

Tank Testing - Hydraulic Pressure

Environmental and chemical effects

Burst Test

Powertech Cylinder Test Facilities

- Burst test up to 2,800 bar
- Hydraulic pressure cycling up to 1,500 bar

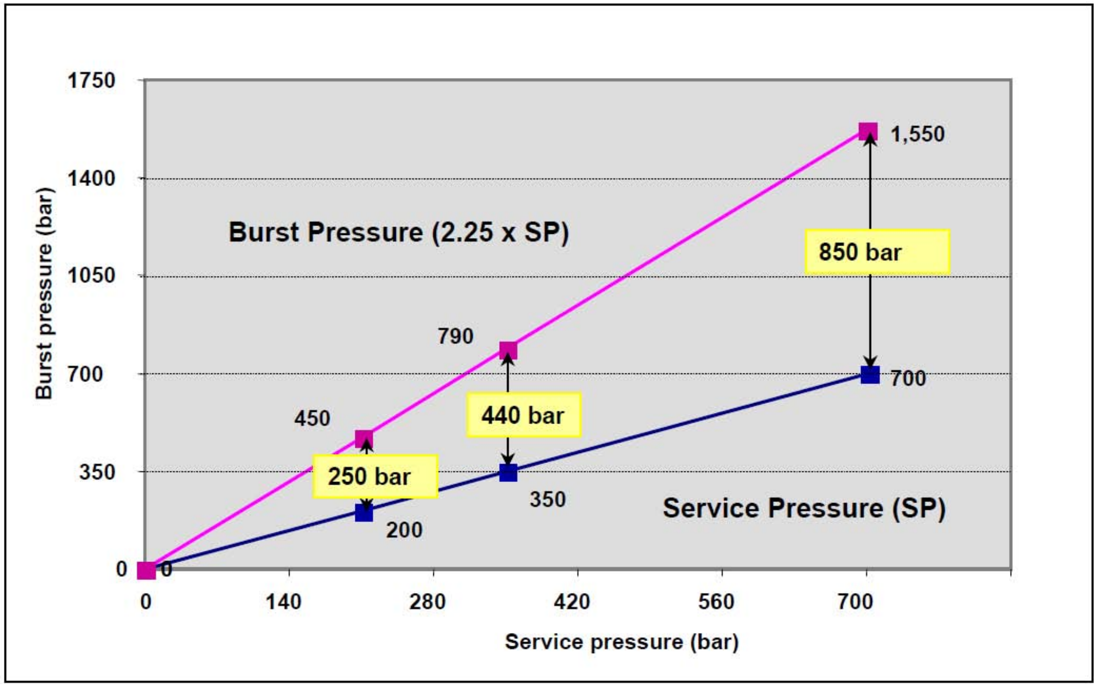
Flaw/Damage Tolerance

Drop Test

Powertech

Development of 700 bar Tanks

Wall thickness comparison - 35 MPa vs 70 MPa cylinders



Powertech

Destructive Safety Testing Facilities

- Bonfire Testing
- Bonfire without PRD
- Penetration (Gunfire) Testing
- Flammable Gas Ignition
- High Pressure Gas Release
- Crush Testing (Static and Dynamic)
- Laminate Damage Tolerance
- Vehicle Fire
- Vehicle Crash

Powertech

CNG and Hydrogen Cylinder Gunfire Penetration Tests

Vehicle Fire Tests - CNG & Hydrogen Tanks

Powertech

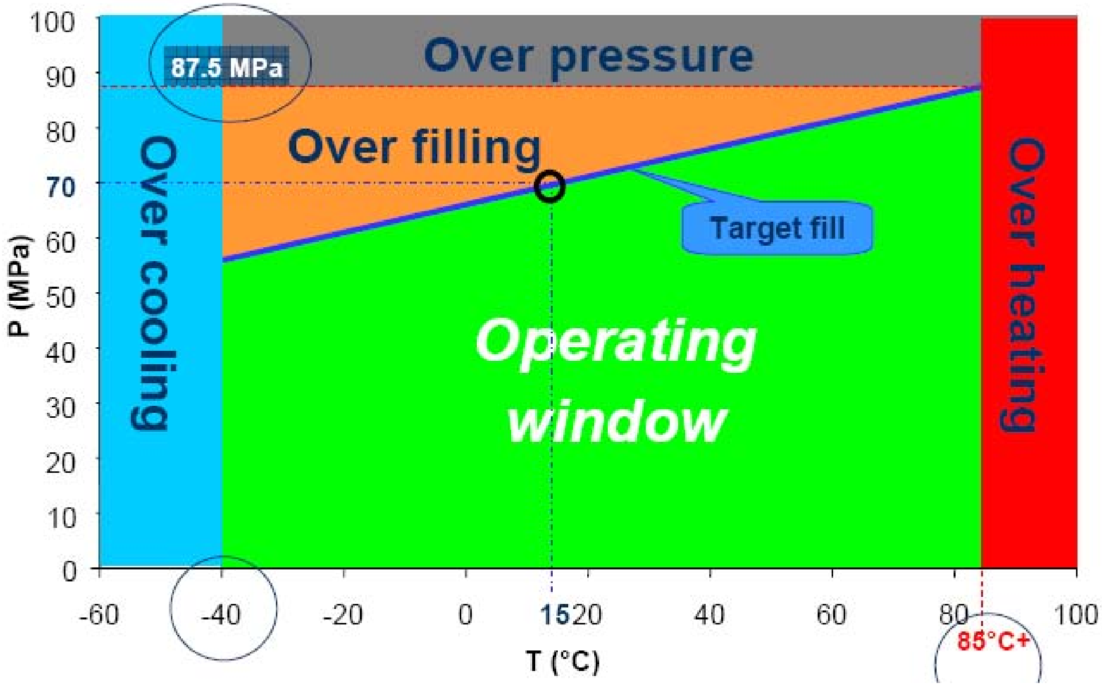
Dynamic Crush Test Overview - Valve end impact @ 35 MPa hydrogen

Powertech

Dynamic Crush Test Detail -
Valve end impact @ 35 MPa hydrogen

Powertech

Filling Conditions with Hydrogen



- How to ensure a "full' fill?
- Heating of H2 during filling
- 700 bar @15C and 875 bar @ 85C
- Communication between vehicle & dispenser?
- Flow control?
- Pre-cooling of gas?

Figure from :Schneider, J., Gambone, L., McDougall, M., et al., "70 MPa Hydrogen Storage Fueling Testing", Proceedings of the Zero Regio Workshop, World Hydrogen Technologies Conference 2007, November 4-7, 2007, Montecatini, Italy.

Multi-Client 70 MPa Hydrogen Fast Fill Study

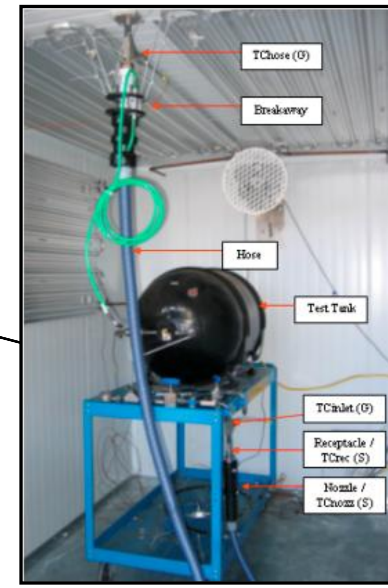
Outputs of the study:

- 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 (flow meter, flow controller, nozzles, hoses, compressors, etc.)

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

70 MPa Hydrogen Fast Fill Test Facility

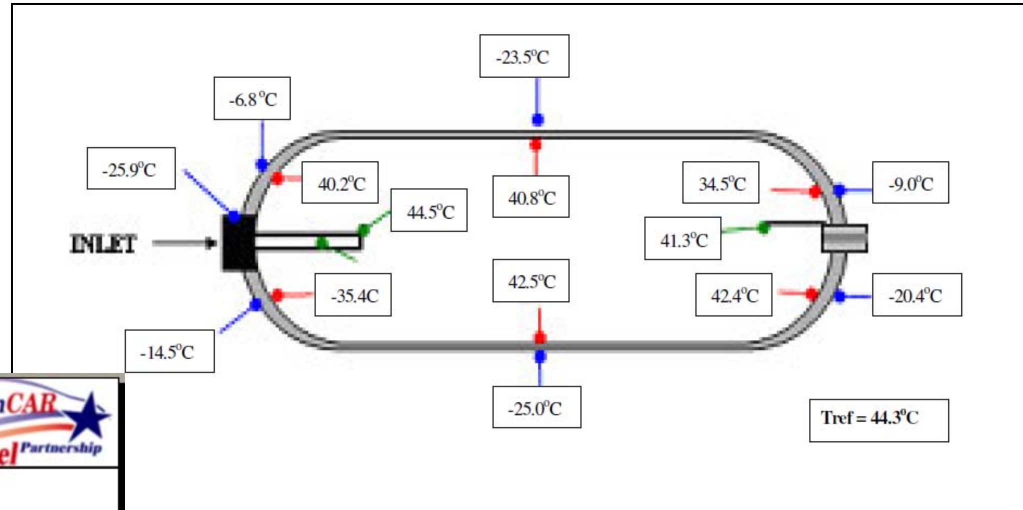
Fueling Station Simulator



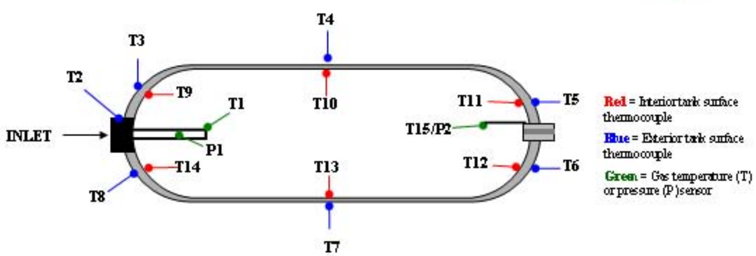
Fuel System Chamber
-40C to +50C

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

70 MPa Fast Fill – 3 Minutes – Ambient Temp -40C



Proposed Tank Instrumentation for OEMs

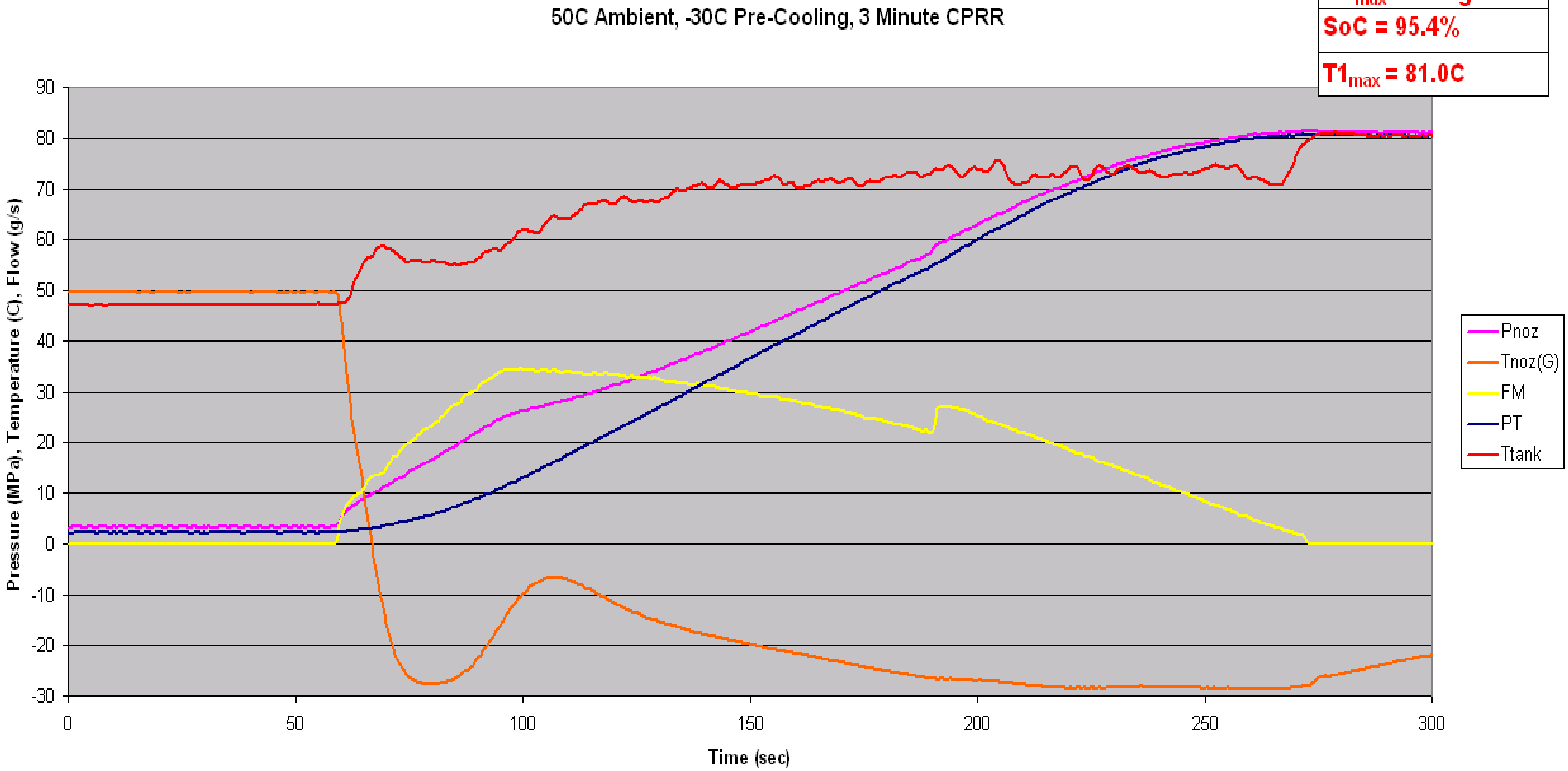


- T1: Gas temperature sensor
- T2: Exterior surface inlet thermocouple
- T3-T5: Exterior surface thermocouples – located near the inlet (as close as possible to the TRD), middle and end respectively
- T6-T8: Exterior surface thermocouples – located near the end plug, middle and PRD - 180° from T5 – T3 respectively as shown above
- T9-T14: Interior tank surface thermocouple – located as shown
- T15: Gas temperature sensor – located near end of tank
- P1: Existing tank pressure transducer
- P2: Pressure transducer located near end of tank

Powertech

OEM 2 +50C, -30C PC, 3 Minute CPRR

$PT1_{max}$=80.8MPa
FM_{max} = 34.4g/s
SoC = 95.4%
$T1_{max}$ = 81.0C



*Powertech Fuel System of same size and type as Nissan Fuel System

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
- ❑ Higher pressures are required for hydrogen storage in order to achieve the range targets for vehicles.
- ❑ Studies are underway to provide data to standards being developed by organizations such as SAE, ISO, and CSA.
- ❑ Areas of study include:
  - ❑ Fire safety
  - ❑ Fueling protocol
  - ❑ Impact resistance