Pressure Vessels for Hydrogen Vehicles: An OEM Perspective

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700 bar type IV vessels

- Applications
- Technology
- Refueling
- Testing
- Real World Validation
- Standards / Regulations for next Vessel Generation
- China specific items

700 bar type IV vessels – History in GM FCEVs

HydroGen3

AUTOnomy

Hy-wire

Sequel

Equinox FC

GM

OPEL

700 bar type IV vessels used in world's largest FCEV fleet

Equinox FC Application

- World's largest market test with over 100 vehicles deployed on the road
- Gain real world experience and feedback on fuel cell vehicles and hydrogen refueling
- Deployment locations:
  - USA: California, New York, Washington D.C.
  - Europe: Berlin
  - Asia: Korea, China

700 bar type IV vessels - outline

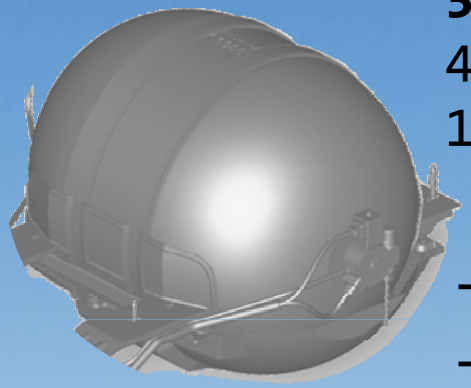
Equinox FC Technology

- 3 Vessel System
- Type: Carbon fiber composite
- Service pressure: 700 bars
- Storage capacity: 4.2 kg CGH_2

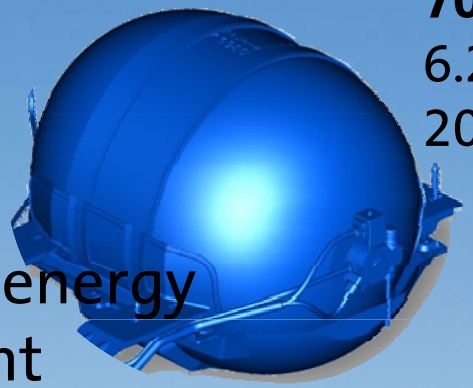
GM/SAIC EXPO FCEV Collaboration

- GM/SAIC are providing the jointly developed “Shanghai FCV” based on SAIC’s Roewe 750 model to EXPO 2010
- Vehicle uses modified Fuel Cell Propulsion System out of the Chevrolet Equinox FC
  - Includes 70MPa capable Type4 tank system

Energy implications of 700 bar storage systems

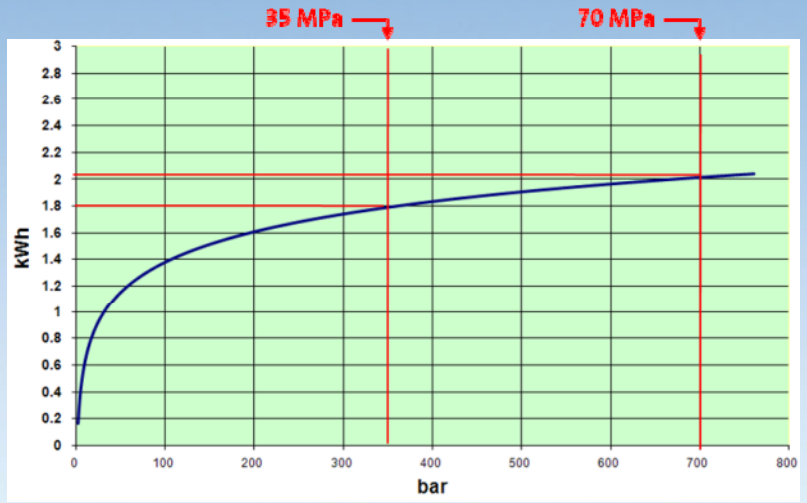


350 bar
4kg Hydrogen
133 kWh



700 bar
6.2kg Hydrogen
207 kWh

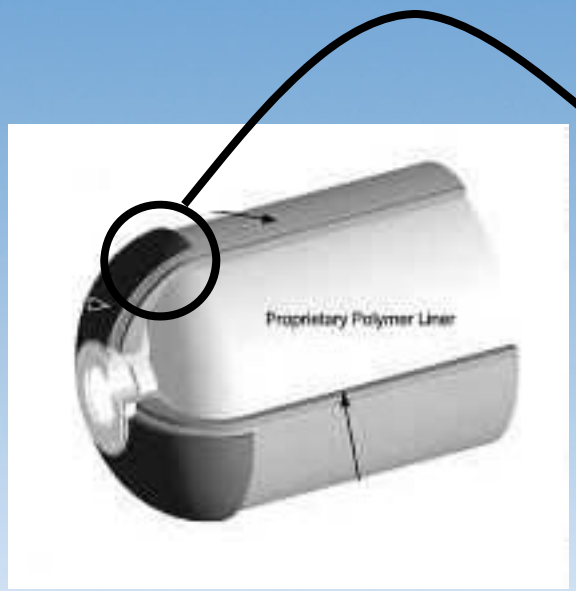
+ 10 % compression energy
+ 55% energy content

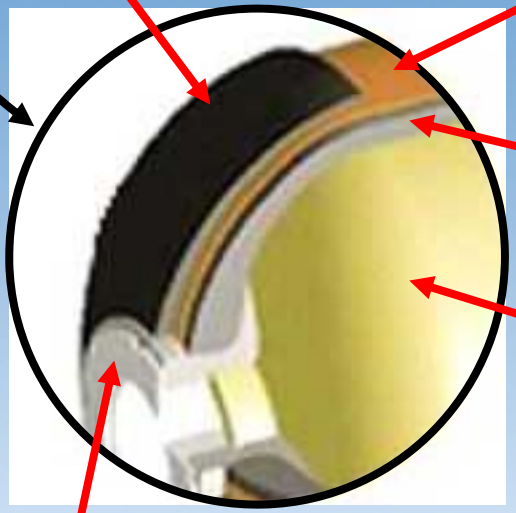


- Most compression energy is expended at lower pressures
- **10%** additional compression energy to get from 350 bar to 700 bar…
- …leads to **55%** increase in energy content

700 bar type IV vessels - details

Equinox FC Technology





Foam dome

Protection layer
(glass fibers/epoxy)

Reinforcement
(carbon fibers/epoxy)

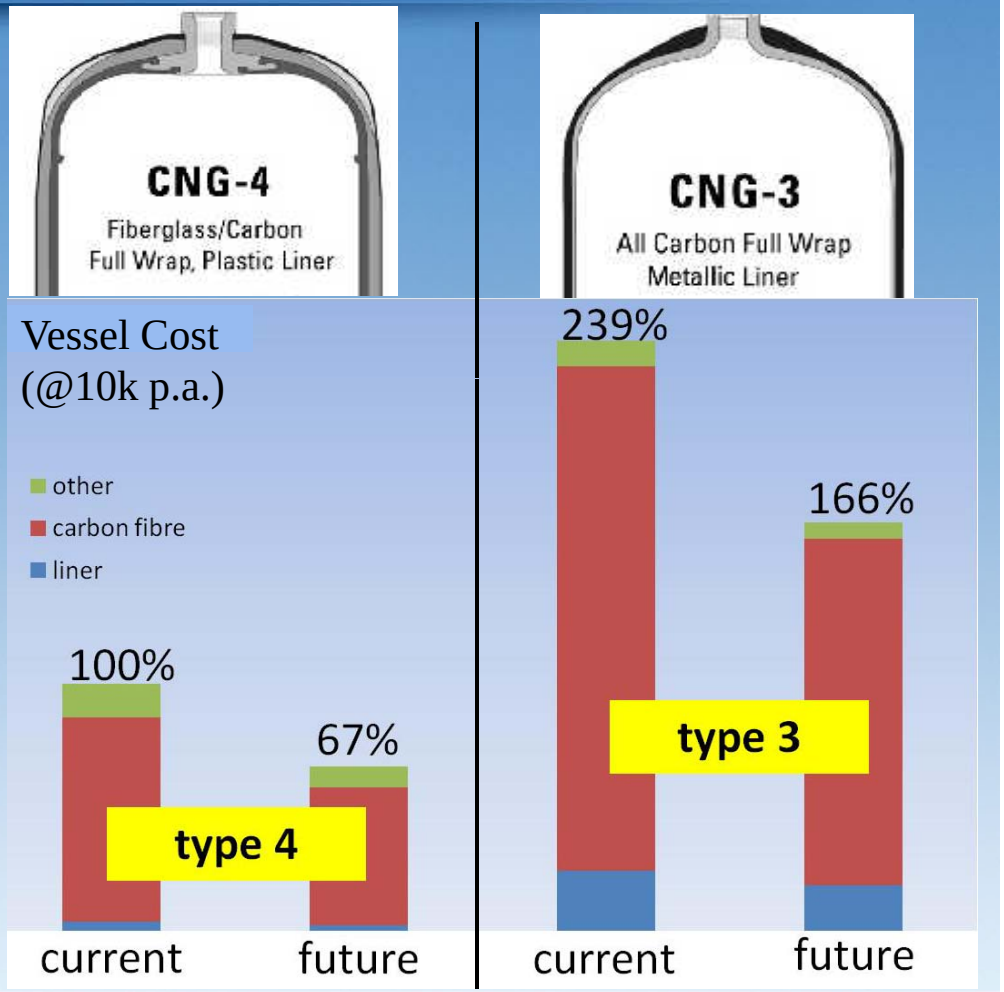
Liner (HDPE)

Polar end boss
(Steel)

700 bar type IV vessels compared to type III vessels

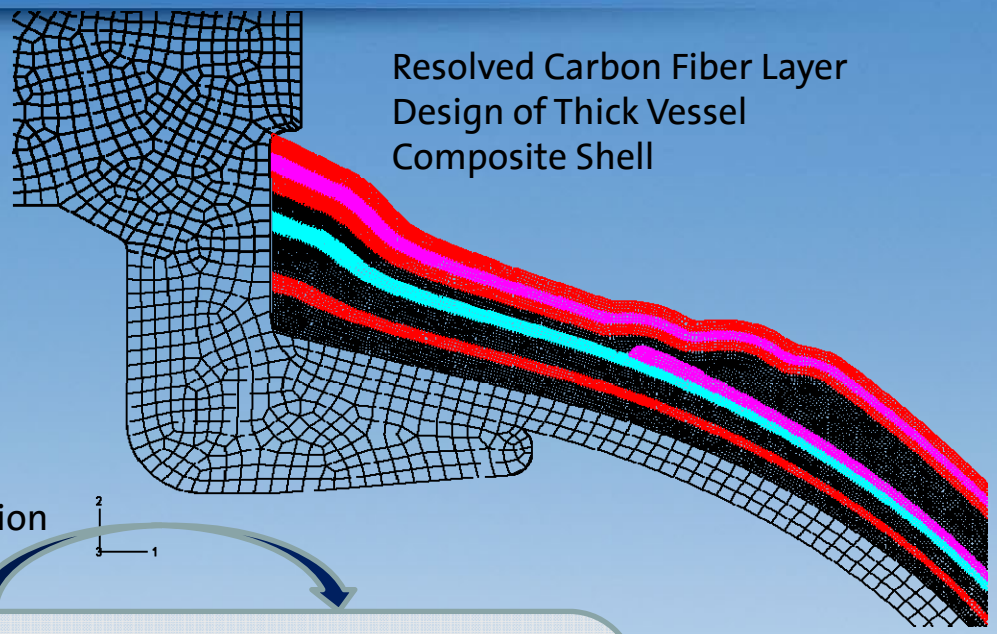
Compared to Type III Vessels, **Type IV Vessels** have

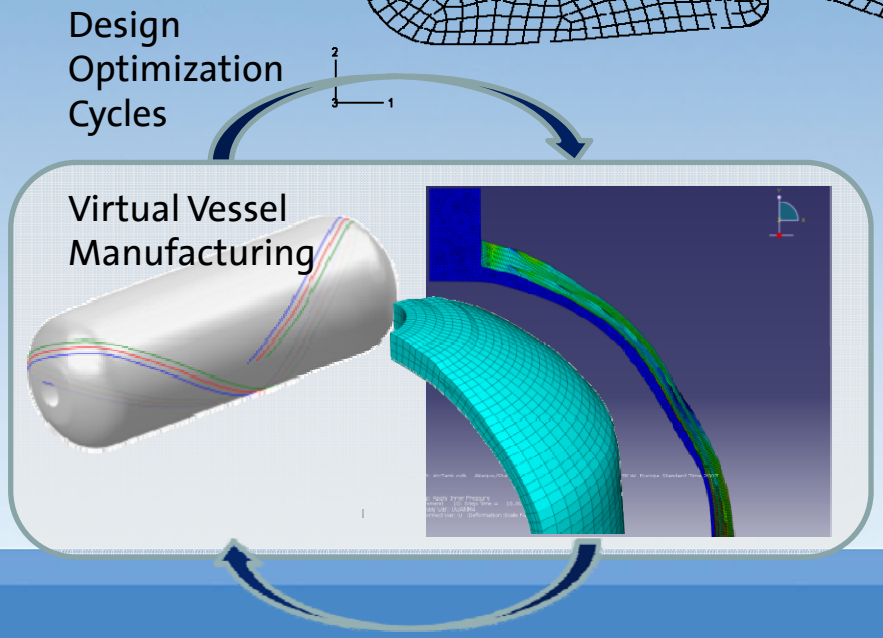
- 20% lower **weight** with identical volumetric storage density
- higher potential regarding long term fatigue and **durability** (little/no liner cracking)
- lower **cost** carbon fibers (lower E-module)



Hydrogen Storage System cost reduction - Finite Element modeling

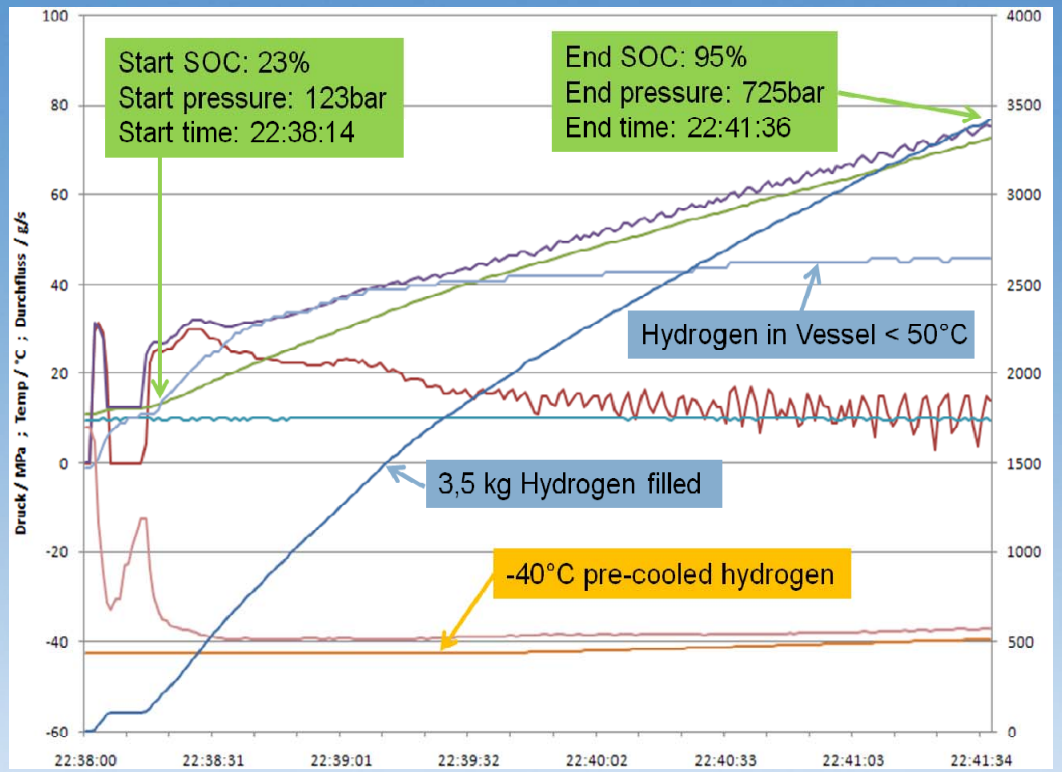
- Predictive FE models generate material-cost optimized designs and manufacturing processes
- Composite material experiments feed virtual design optimization cycles
- Virtual design cycles reduce build and test time of vessel prototypes





Project Driveway Learning – Refueling Time

"The fueling process is lengthy, though the staff are EXCELLENT and make the time seem short with healthy conversation and great interaction"



- Project Driveway refueling time < 4 min validated at GM proving ground station
- All stations in Germany with -40°C precooling: 4 current, 3 add. in 2010

Refueling Time: SAE J2601 A (-40°C) vs. B (-20°C)

A-70 1-7kg	Actual Fueling Duration (min) Add intermediate leak check times: up to 10 sec after every 2.5MPa increase in fueling pressure										
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)										
	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	6.3	6.0	5.5	5.1	4.6	3.7	2.8	1.9	1.0	0.2	no fueling
45	4.6	4.4	4.0	3.7	3.4	2.7	2.1	1.4	0.8	0.1	no fueling
40	3.6	3.5	3.2	2.9	2.7	2.1	1.6	1.1	0.6	0.1	no fueling
35	3.1	2.9	2.7	2.5	2.2	1.8	1.4	0.9	0.5	0.1	no fueling
30	2.6	2.5	2.3	2.1	1.9	1.5	1.1	0.8	0.4	0.0	no fueling
25	2.5	2.4	2.2	2.0	1.8	1.4	1.1	0.7	0.3	no fueling	no fueling
20	2.5	2.4	2.2	2.0	1.8	1.4	1.0	0.7	0.3	no fueling	no fueling
10	2.5	2.4	2.1	1.9	1.8	1.4	1.0	0.6	0.2	no fueling	no fueling
0	2.4	2.3	2.1	1.9	1.7	1.3	0.9	0.5	0.1	no fueling	no fueling
-10	2.4	2.3	2.1	1.8	1.6	1.2	0.8	0.4	no fueling	no fueling	no fueling
-20	2.4	2.2	2.0	1.8	1.6	1.1	0.7	0.3	no fueling	no fueling	no fueling
-30	2.3	2.2	2.0	1.7	1.5	1.1	0.6	0.2	no fueling	no fueling	no fueling
-40	2.3	2.2	1.9	1.7	1.5	1.1	0.6	0.2	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

-40°C:
1.8 – 2.9 min

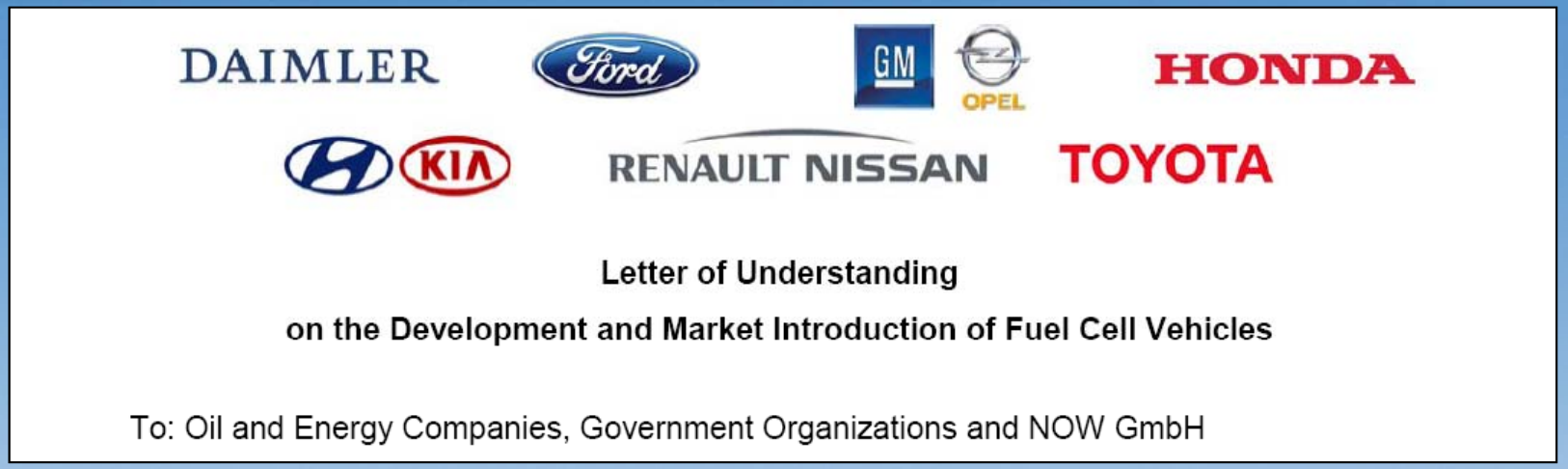
B-70 1-7kg	Actual Fueling Duration (min) Add intermediate leak check times: up to 10 sec after every 2.5MPa increase in fueling pressure										
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)										
	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	41.0	39.1	36.0	33.0	30.0	24.1	18.3	12.6	7.0	1.3	no fueling
45	28.9	27.5	25.3	23.2	21.1	17.0	12.9	8.9	4.9	0.9	no fueling
40	21.3	20.3	18.7	17.2	15.6	12.6	9.6	6.6	3.7	0.7	no fueling
35	16.4	15.7	14.4	13.2	12.0	9.7	7.4	5.1	2.8	0.5	no fueling
30	13.0	12.4	11.4	10.5	9.5	7.6	5.8	3.9	2.0	no fueling	no fueling
25	10.7	10.1	9.3	8.5	7.7	6.2	4.6	3.1	1.5	no fueling	no fueling
20	8.9	8.5	7.8	7.1	6.4	5.1	3.8	2.4	1.1	no fueling	no fueling
10	6.6	6.2	5.7	5.2	4.6	3.6	2.6	1.6	0.6	no fueling	no fueling
0	5.1	4.8	4.4	4.0	3.6	2.7	1.9	1.1	0.3	no fueling	no fueling
-10	5.0	4.7	4.3	3.9	3.4	2.6	1.7	0.9	0.1	no fueling	no fueling
-20	4.9	4.6	4.2	3.7	3.3	2.4	1.6	0.7	no fueling	no fueling	no fueling
-30	4.8	4.5	4.1	3.6	3.1	2.3	1.4	0.5	no fueling	no fueling	no fueling
-40	4.8	4.5	4.0	3.6	3.1	2.3	1.4	0.5	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

-20°C:
3.9 – 15.7 mi

- -40°C is a significant enabler for customer acceptance of Hydrogen refueling

Letter of Understanding Signed – 08SEP09

Automotive Industry Support for Battery & Fuel Cell Technology



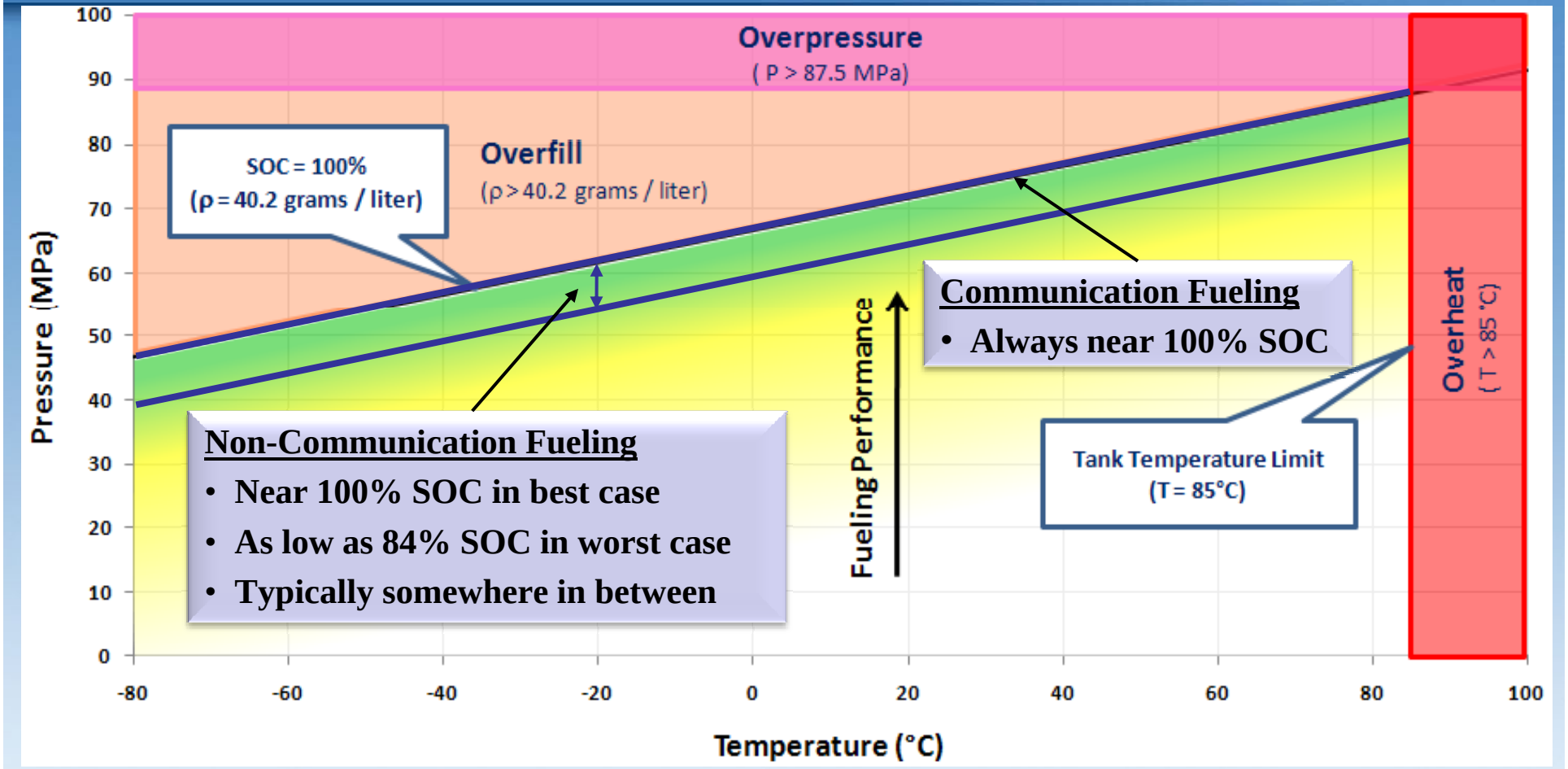
- Battery and fuel cell vehicles complement each other
- 2015 FCEV commercialization anticipated
- Hydrogen infrastructure with sufficient density required by 2015
- Built up from metropolitan areas via corridors into area-wide coverage
- Stations integrated into branded conventional stations, **meet SAEJ2601 requirements**, and offer hydrogen at a reasonable price to the customers

GM

OPEL

Increased Range through Communication Fill

Hydrogen Storage System Fueling Window and SOC range (700 bar)



Vehicle data allows station to target 100% SOC, increasing real-world range of the fuel cell vehicle

700 bar type IV vessels - refueling

Equinox FC Refueling

Customer friendly fueling:

- One single physical connection
- Infrared communication interface (tank pressure/temperature)
- Fast fill: 3 min. at -40°C pre-cooling
- Automatic data transfer via WLAN to Engineering team

700 bar type IV vessels - tests

Equinox FC Testing

- Certification according to Draft ECE Compressed Gaseous Hydrogen Regulation Revision 12b, 12.10.03

- Following test were successfully conducted with 700 bar type IV Vessels:

✓ Tests of raw material
✓ Corrosion test
✓ Hydraulic pressure test
✓ Burst test
✓ Cycle test (ambient temperature)
✓ Cycle test (extreme temperature)
✓ Leak before break test
✓ Chemical exposure test
✓ Bonfire test
✓ Penetration (bullet) test
✓ Composite flaw tolerance test
✓ Accelerated stress rupture test
✓ Impact damage (drop) test
✓ Leak test
✓ Permeation test
✓ Boss torque test
✓ Hydrogen cycle test

700 bar type IV vessels – Equinox statistics

Equinox FC Statistics

(status: Sep. 8th, 2010)

- Start of operation: Mid of 2007
- Current fleet: 117 vehicles
- Total mileage of Equinox vehicles: 1,665,602 miles
- Total refueling counter: **20,404**

700 bar type IV vessels – standards and regulations

Standards / Regulations for next Vessel Generation

Next generation of Type VI Vessel shall be certified / tested according to following standards / regulations:

- EC 79-2009 EU H2 Regulation
  REGULATION (EC) No 79/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC
- EC 406-2010, Implementation Regulation
  COMMISSION REGULATION (EU) No 406/2010 of 26 April 2010 implementing Regulation (EC) No 79/2009
- HGV 2 Draft
  COMPRESSED HYDROGEN GAS VEHICLE (HGV) FUEL CONTAINERS
- ISO 15869
  Gaseous hydrogen and hydrogen blends — Land vehicle fuel tanks
- SAE J 2579
  COMPRESSED HYDROGEN VEHICLE FUEL CONTAINERS

Open items China, Global

- Type IV vessel operation
- 700bar pressure
- Test facilities which deliver same results around the globe
- Globally harmonized codes and standards for on-vehicle H2 storage
- Globally harmonized filling protocols and interfaces
- Globally harmonized H2 vehicle certification and process

Ideal solution from automotive company perspective

Goal:

•tank systems certified in one country to be allowed in other countries

•supplier based development on global basis

- Test protocols and requirements to be harmonized with global standards, ISO, SAE and Global Technical Regulations (GTR) for on-board vessel, interface, filling protocols, etc.
- Established testing facilities that are fully efficient in performing tests and validation.
    - Test data to be interchangeable with data performed in other countries
- Need special process to permit small volume operation (demo, pre-commercial phase).
- Trigger discussion of requirements for Infrastructure to meet vehicle level requirements