SAFETY CONSIDERATIONS ON LIQUID HYDROGEN
(PART 1)

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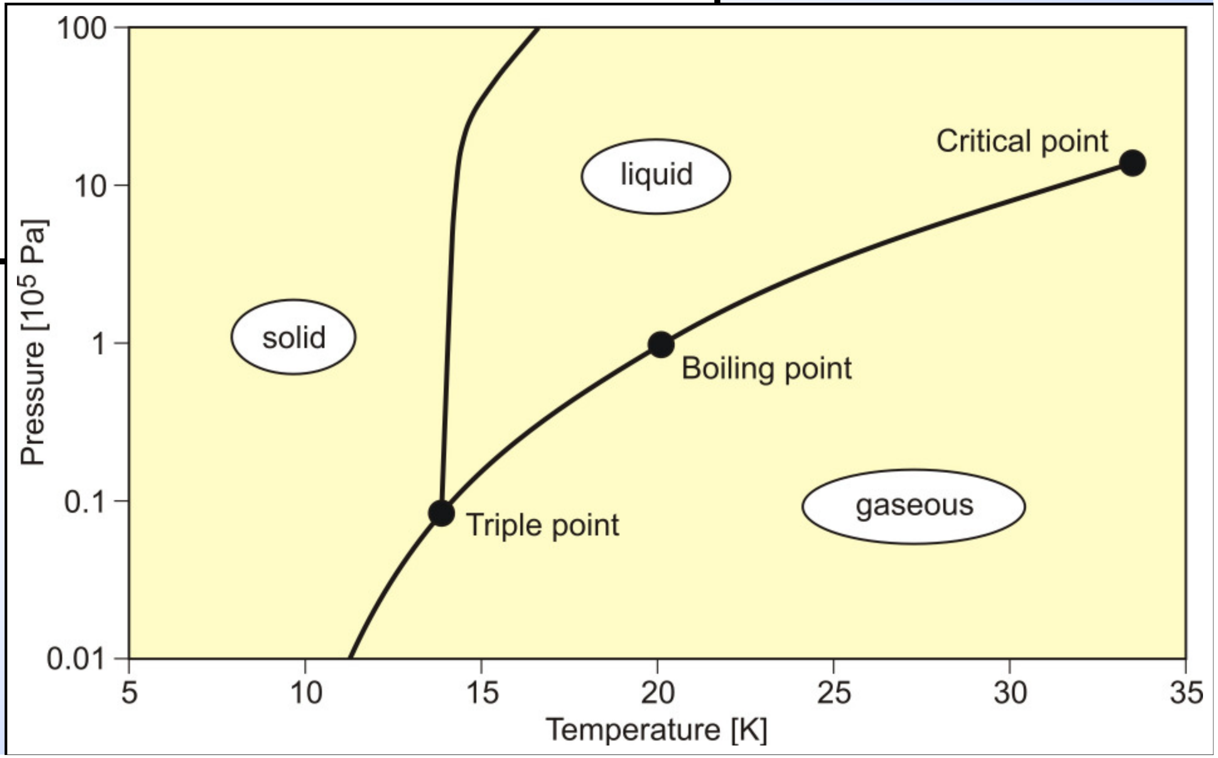
2nd European Summer School on Hydrogen Safety
Belfast, July 30 – August 8, 2007

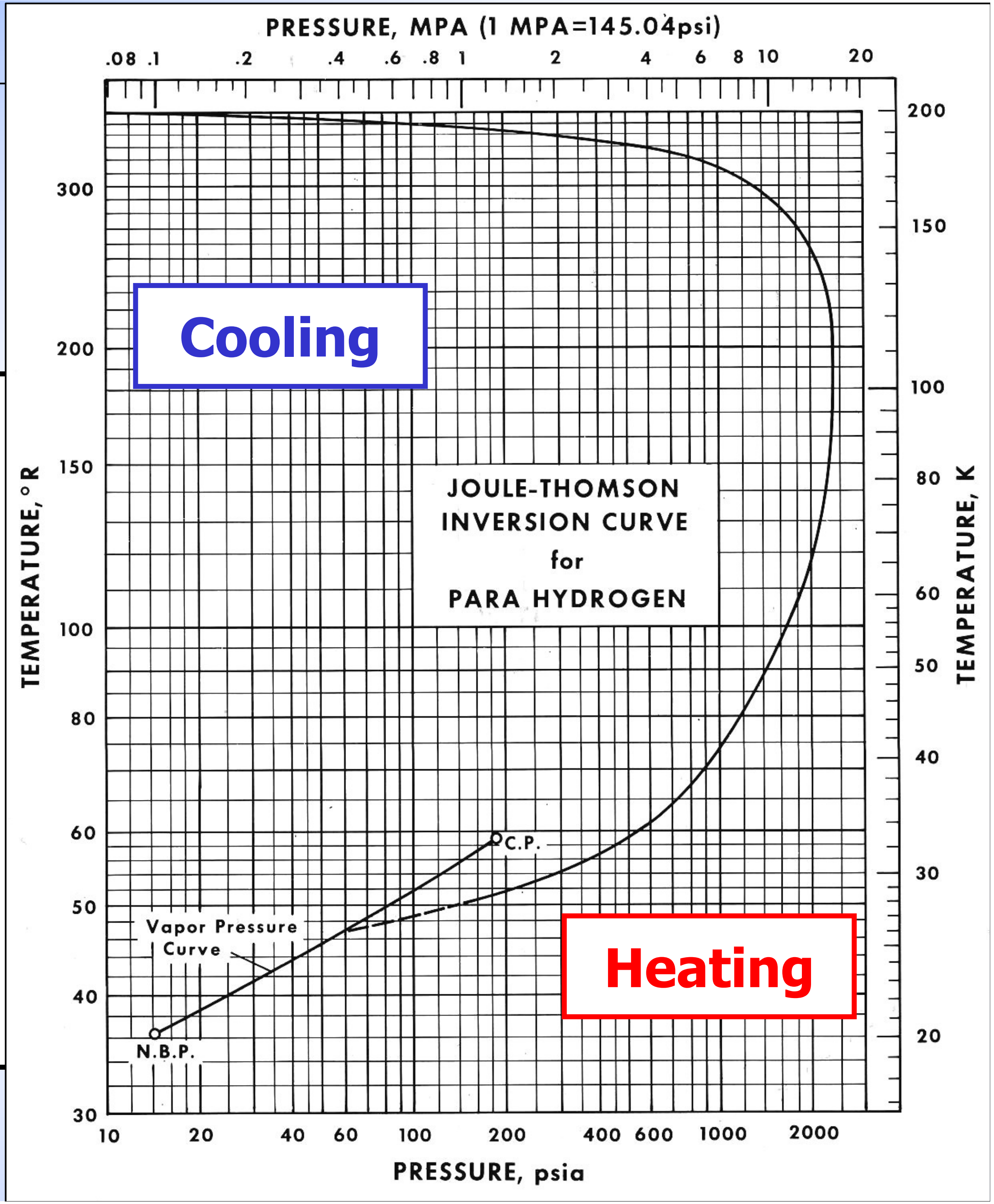
Properties of Liquid Hydrogen (1)

- cold (14-20 K)
  max. BP = 33 K @ 1.3 MPa [critical point]
- light (71 grams per liter)
- high expansion ratio
  (~ 845)



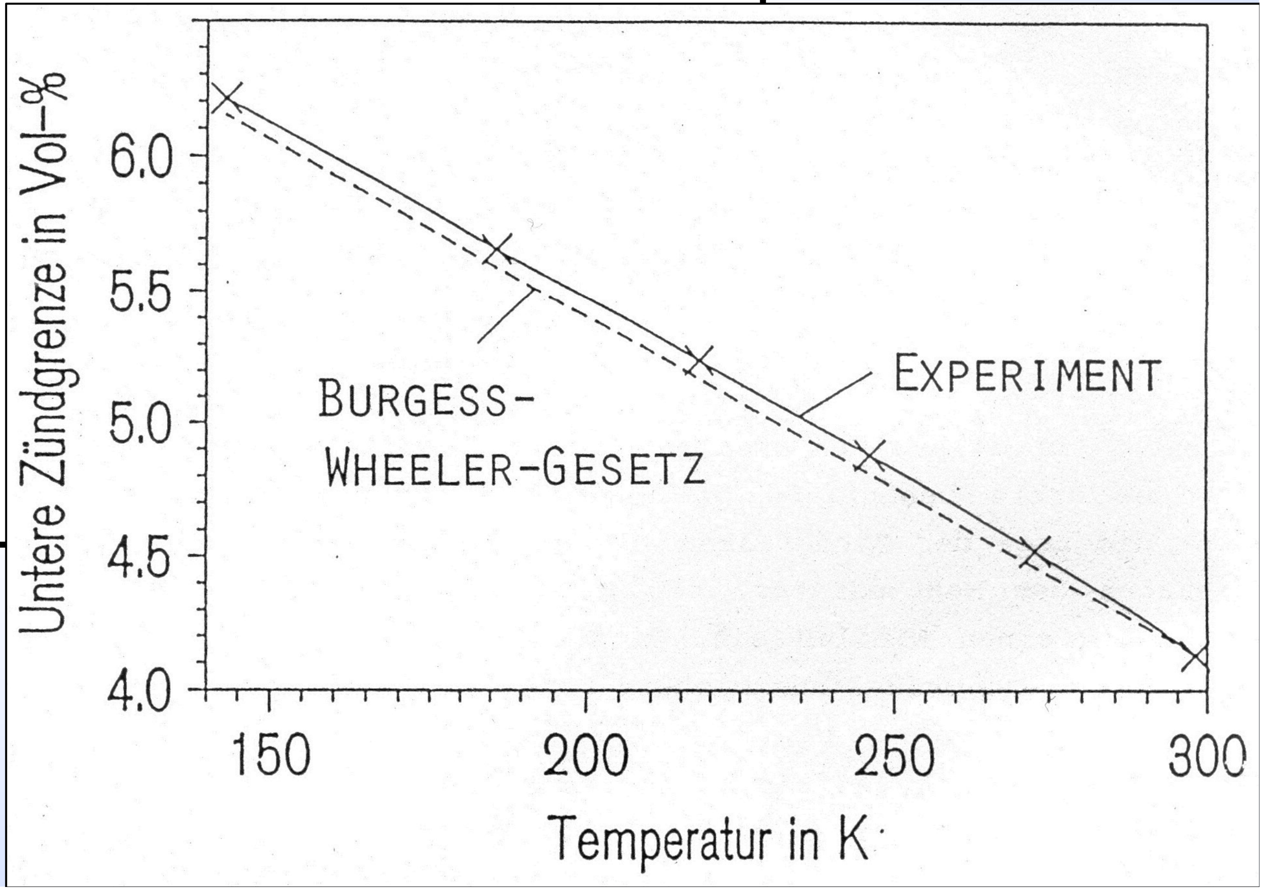
Properties of Liquid Hydrogen (2)

- co-existing in ortho and para form, ($\Delta H_c > \Delta H_v$)
- Thomson-Joule effect negative for T_I=193 K
- thermal contraction, cold embrittlement



Properties of Liquid Hydrogen (3)

- smaller flammability range
  LFL = 7.7 vol% @ BP
- more difficult to ignite
- in open pool, air solidification
  → O_2 enrichment

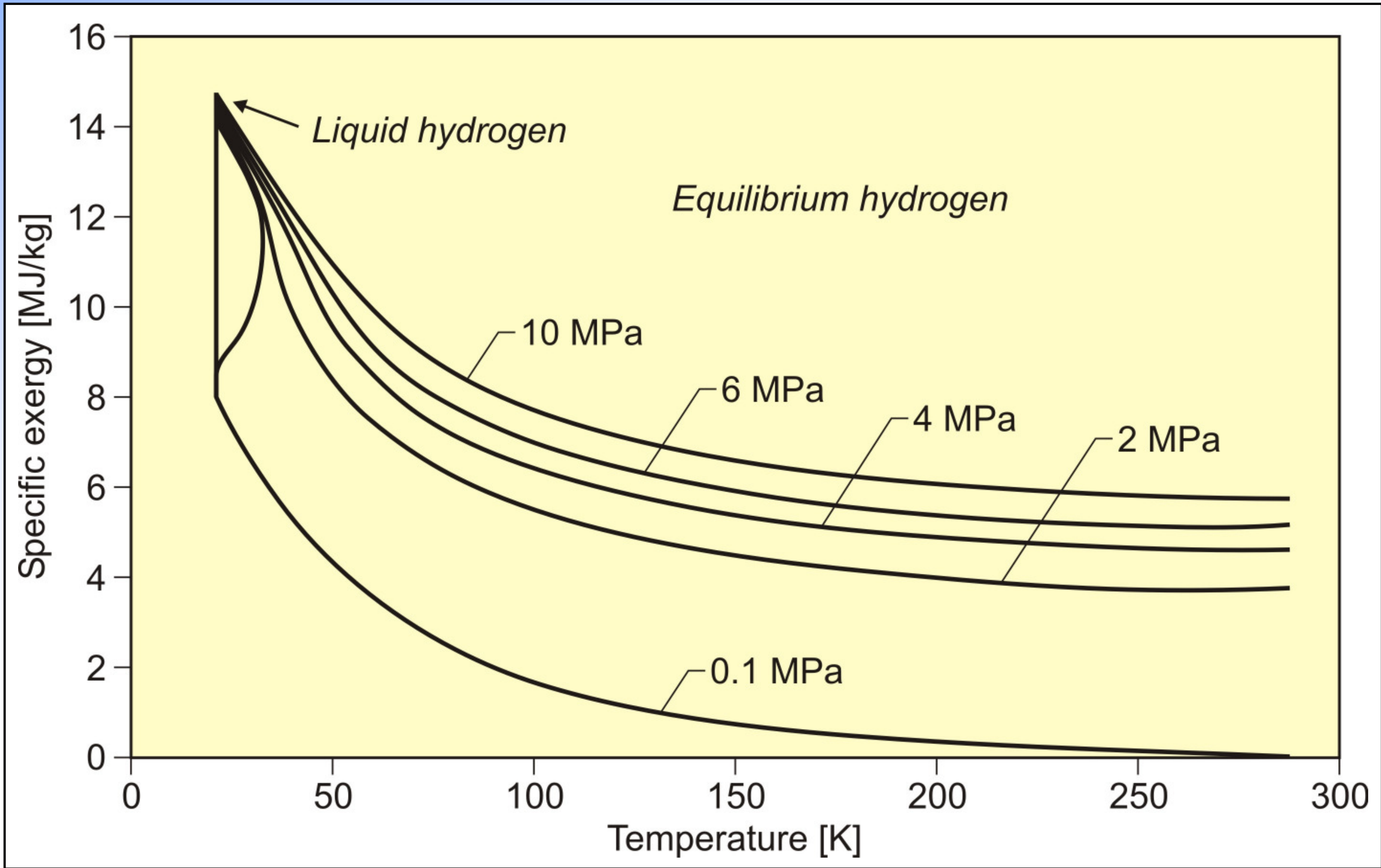


Liquefaction of Hydrogen

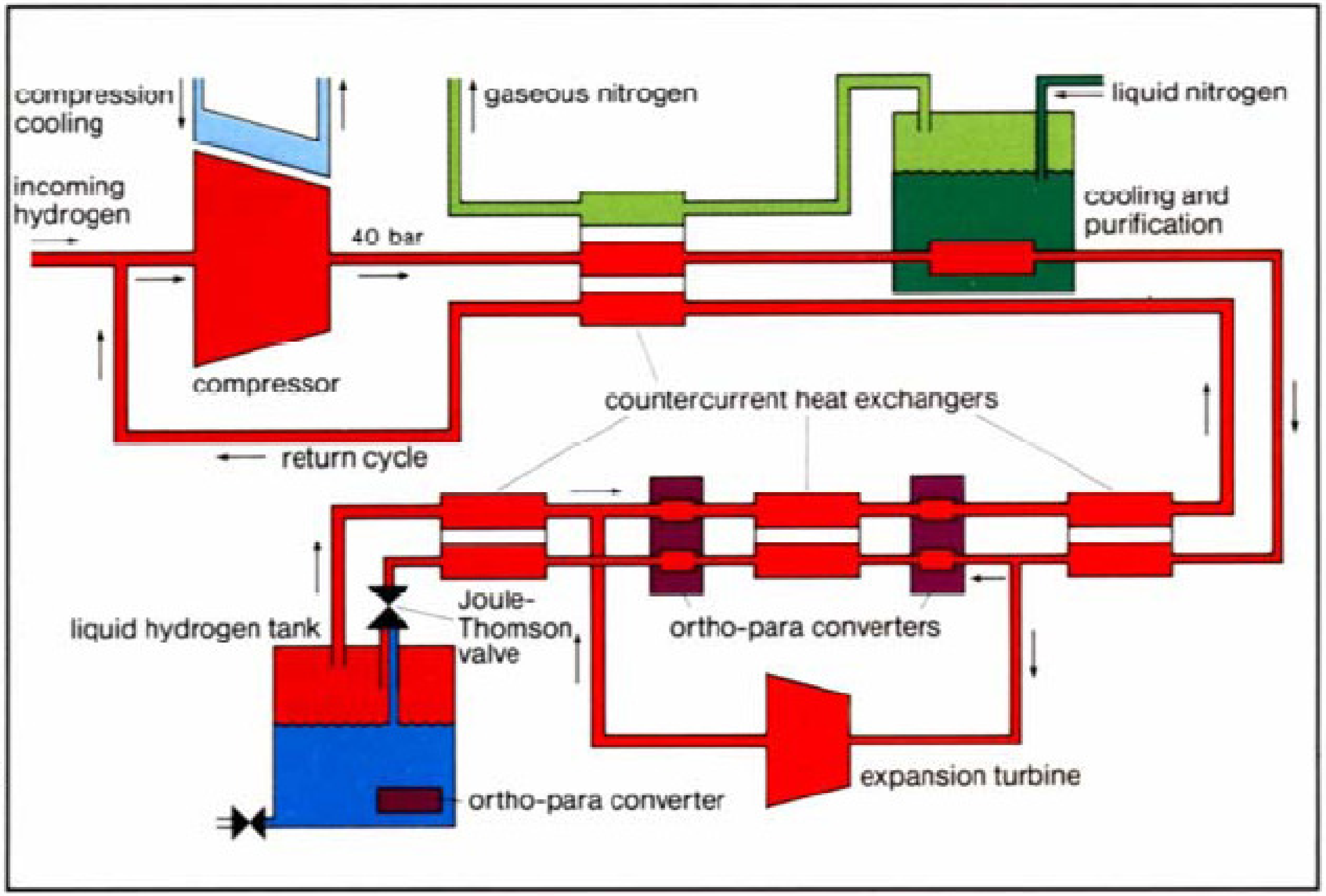
Gas	Boiling Point [K]	Heat of vapori zation [kJ/kg]	Minimum Work [kWh/kg]		
			Cooling NTP → BP	Condensa tion	Total
Hydrogen	20.268	445.59	2.242*	1.666	3.91
Methane	111.632	509.88	0.077	0.230	0.31
Nitrogen	77.34	201.	0.055	0.156	0.21
Helium	4.216	20.9	1.917	0.398	2.32

* includes ortho-para conversion

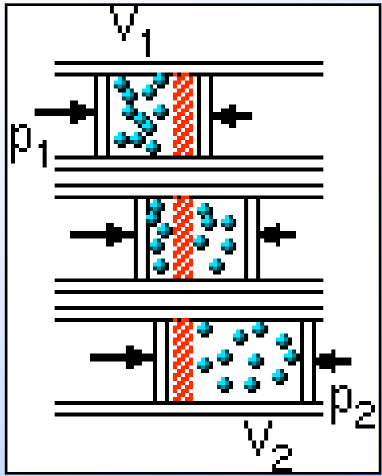
Liquefaction of Hydrogen



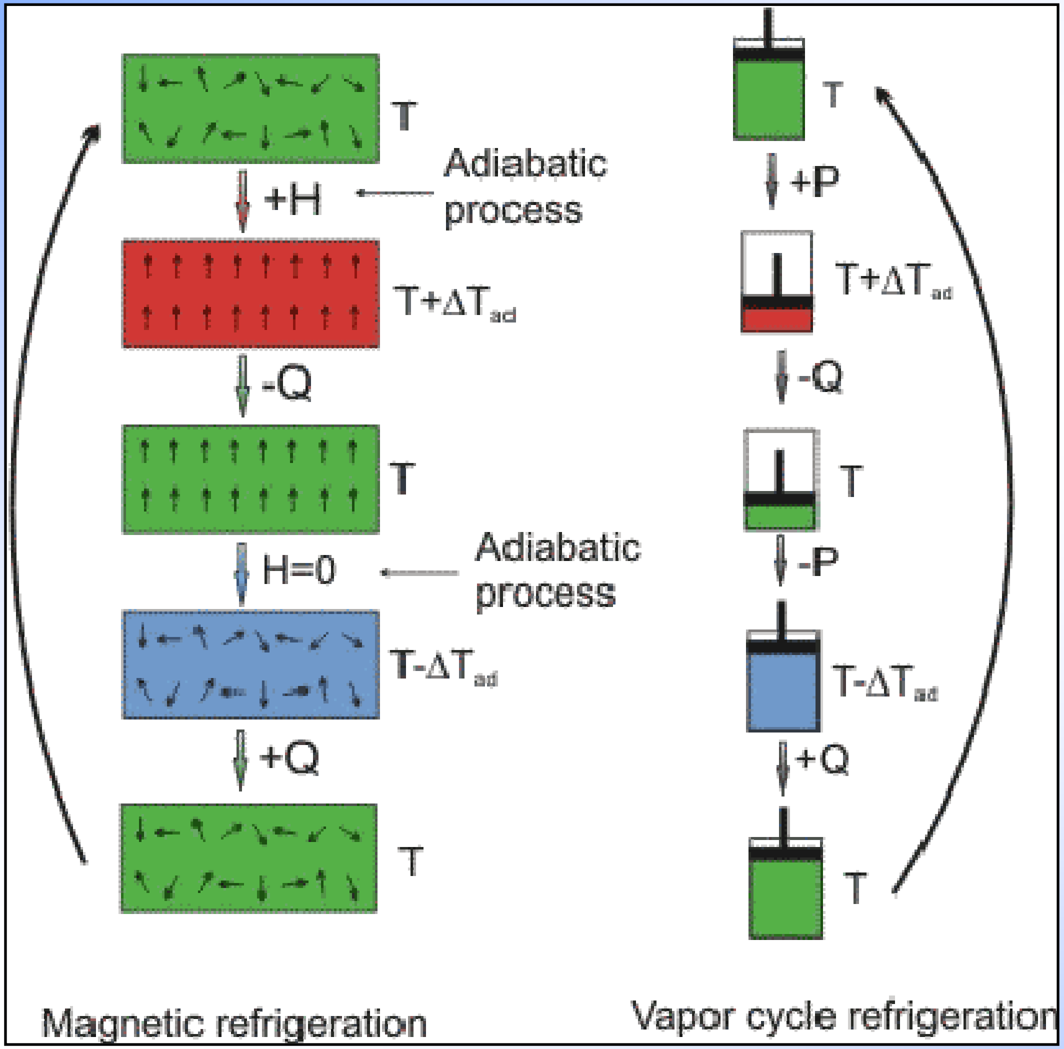
Claude Process



Thomson-Joule Expansion



Magnetic Refrigeration Process



Magnetization

Heat removal

De-magnetization

Heat transfer from gas to be cooled

Ideal: Gd materials

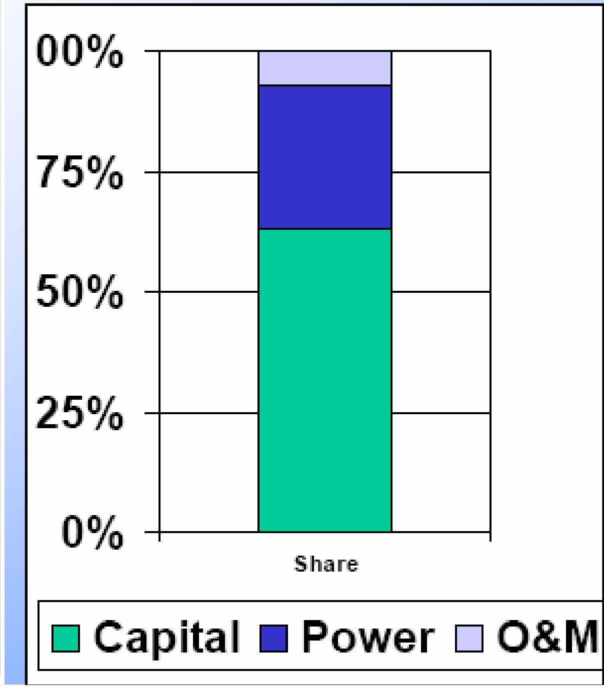
Place	Operator	Capacity [t/d]	Operation since
America			
Sarnia, ON, Canada	Air Products, USA	29	1962
New Orleans, LA, USA	Air Products, USA	68	1977
Pace, USA	Air Products, USA	29	1994
Sacramento, CA, USA	Air Products, USA	6	1986
Magog, QU, Canada	BOC, USA	15	1990
Becancour, QU, Canada	HydrogenAl, Canada	11	1986
Kourou, French Guiana	L'Air Liquide, France	5	1990
East Chicago, IN, USA	Praxair	29	1999
McIntosh, AL, USA	Praxair	29	1995
Niagara Falls, NY, USA	Praxair	38	1981 /1989
Ontario, CA, USA	Praxair	22	1962
	Total America	**281**	
Europe			
Rozenburg, Netherlands	Air Products, USA	5.0	1987
Lille, France	L'Air Liquide, France	10.5	1987
Ingolstadt, Germany	Linde, Germany	4.4	1991
Leuna, Germany*	Linde, Germany	5.0	2007
	Total Europe	**24.9**	
Asia			
Amagasaki, Japan	Iwatani Gas, Japan	1.2	1978
Ooita, Japan	Pacific Hydrogen Co., Japan	1.4	1986
Kimitsu, Japan	Nippon Steel Corp., Japan	0.2	2004
Sakai, Japan	Iwatani Gas, Japan	1.1	2006
	Total Asia	**3.9**	
	Total World	**316.8**	

gszentrum Jülich
in der Helmholtz-Gemeinschaft

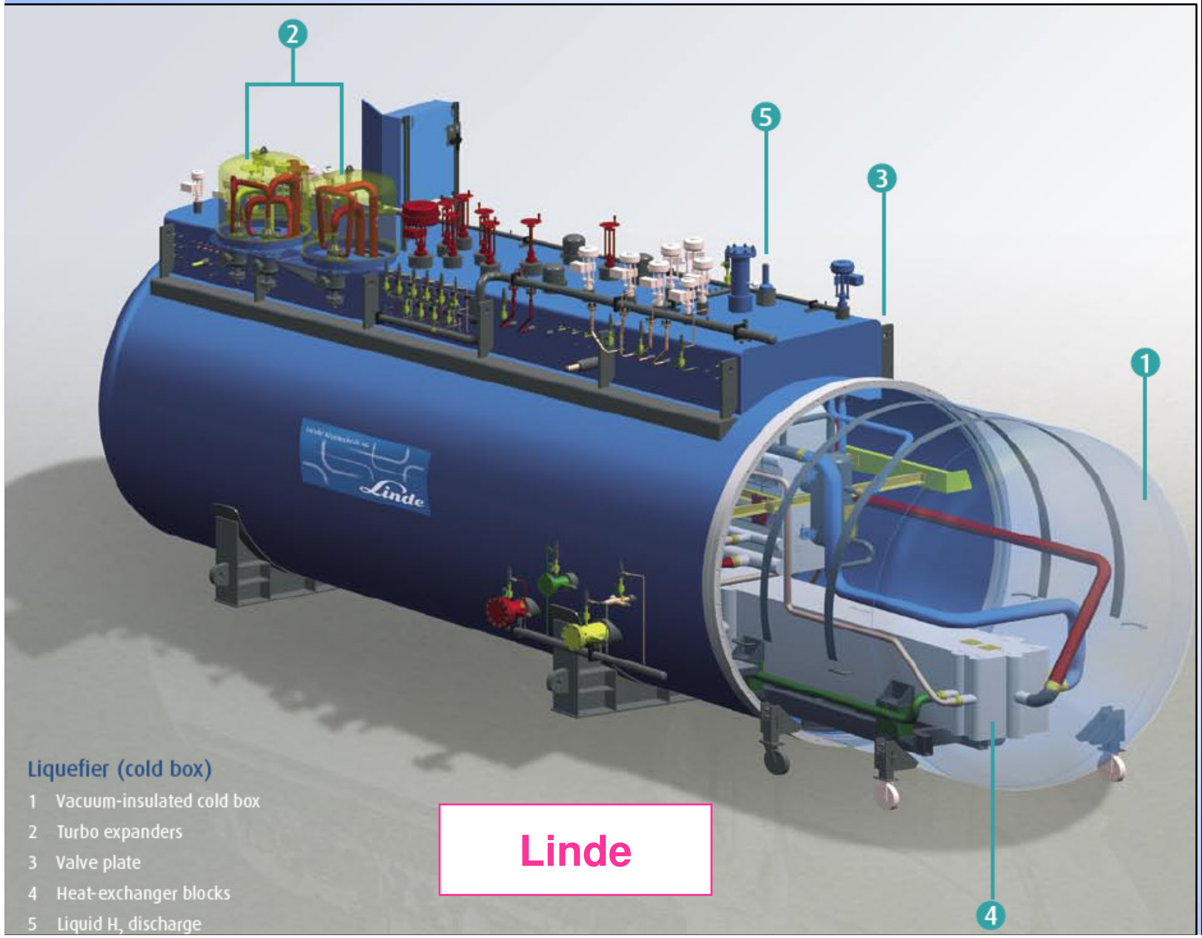
50 Jahre / Zukunft

H_2 Liquefaction Capacity in the World

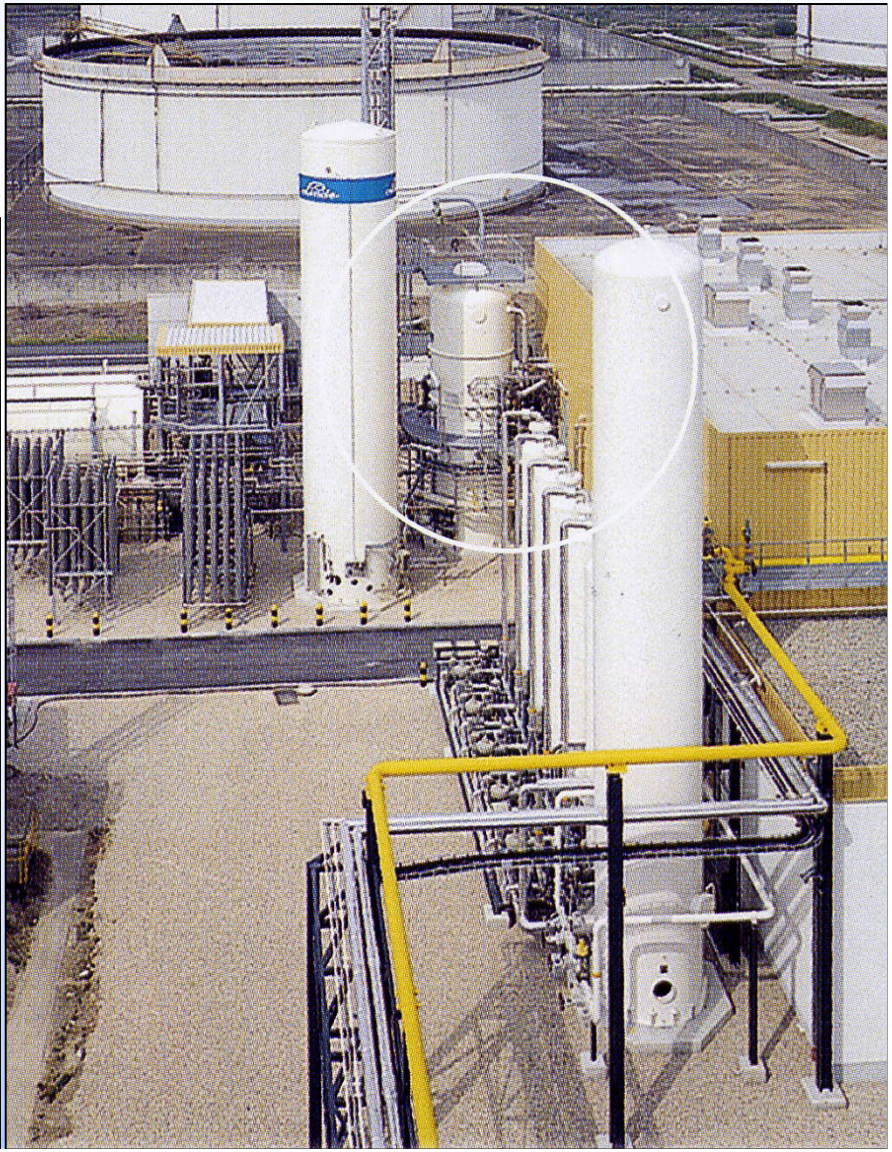
Cost Stack



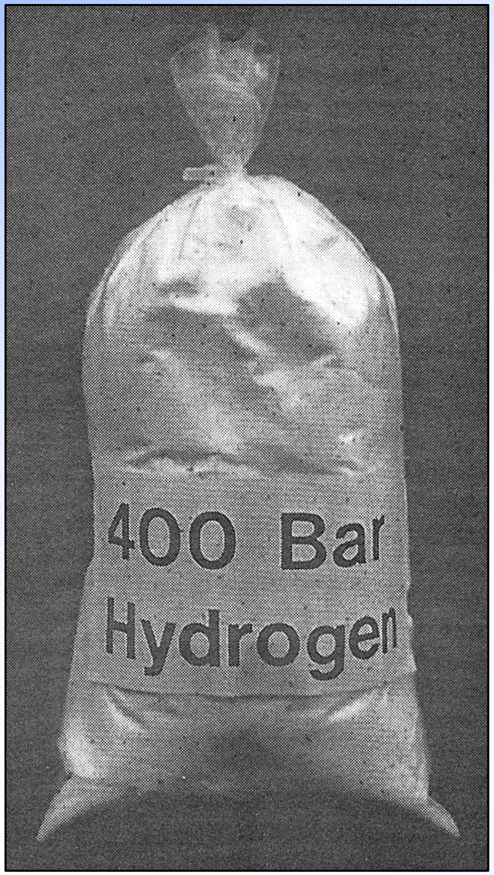
4.5 t/d LH_2 Liquefaction Plant in Ingolstadt



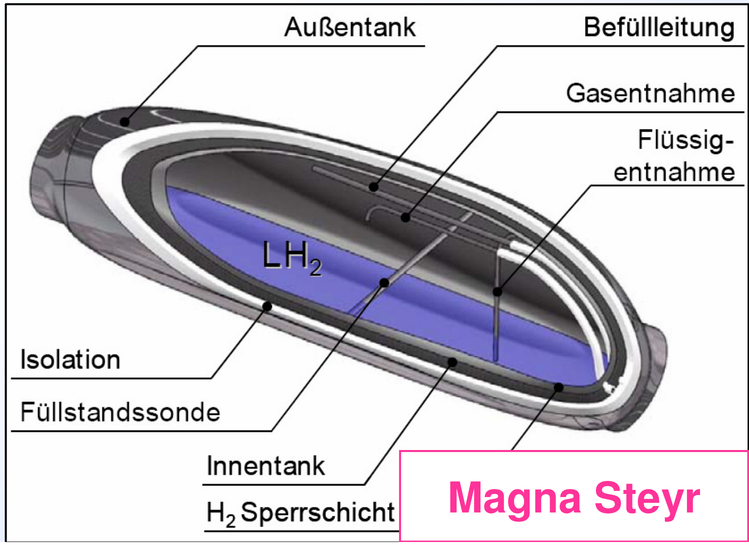
Linde



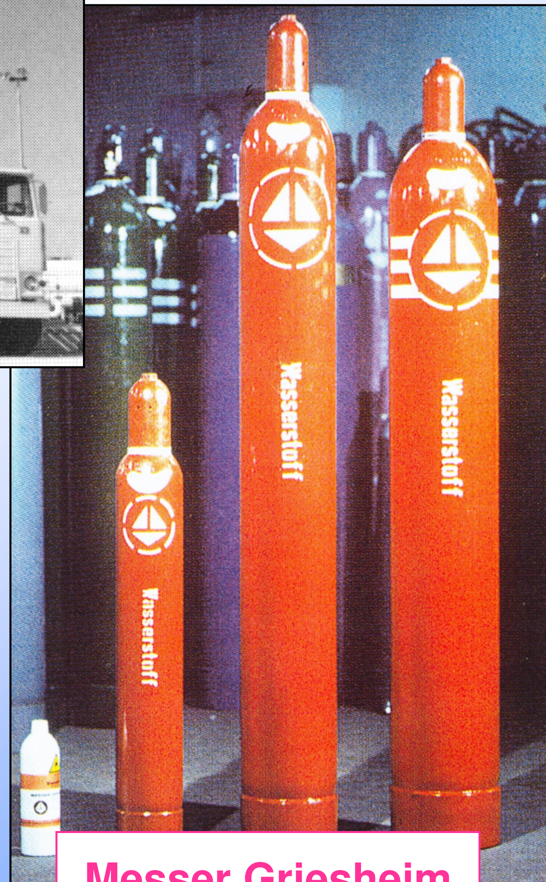
Storage



NASA

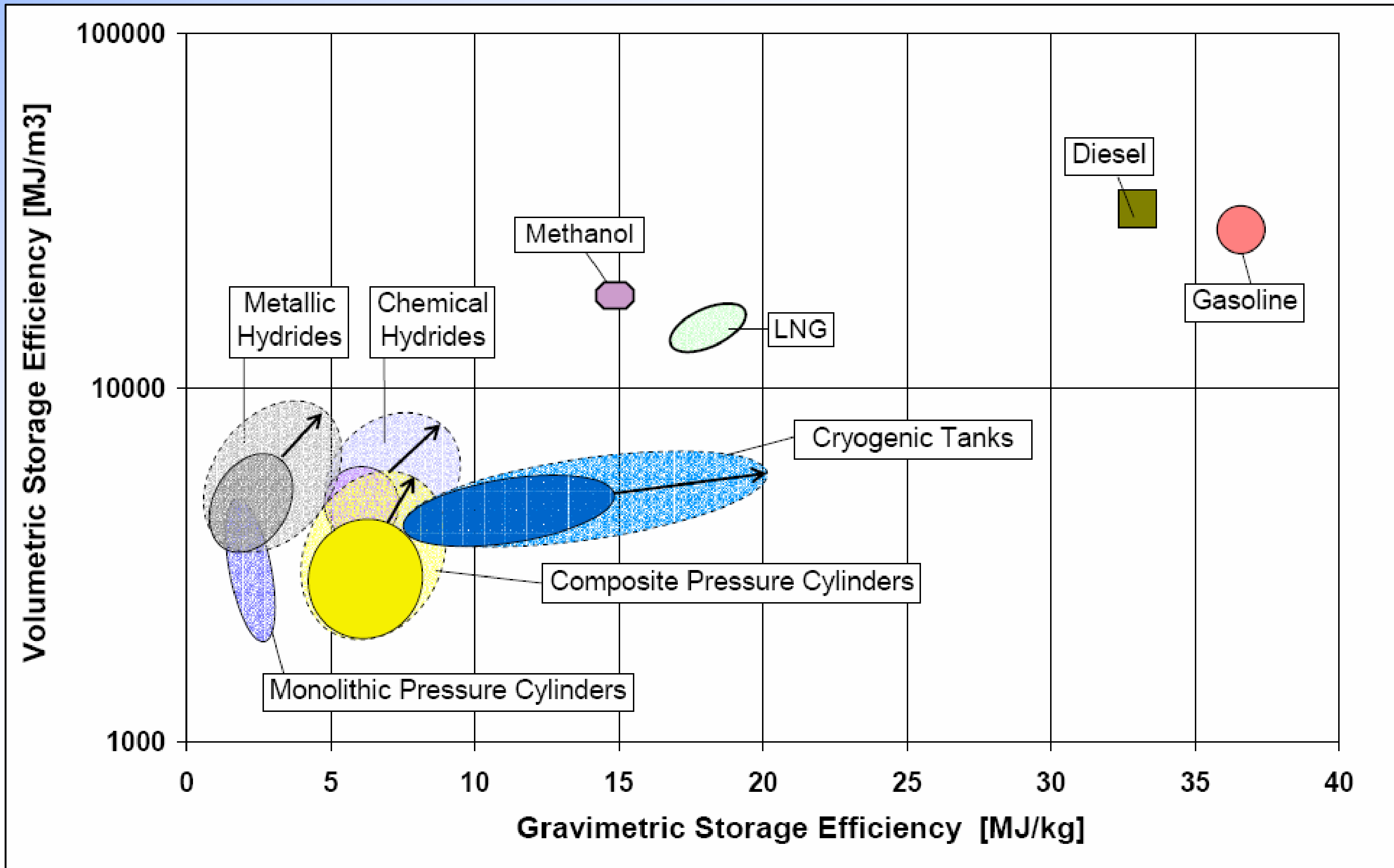


Magna Steyr



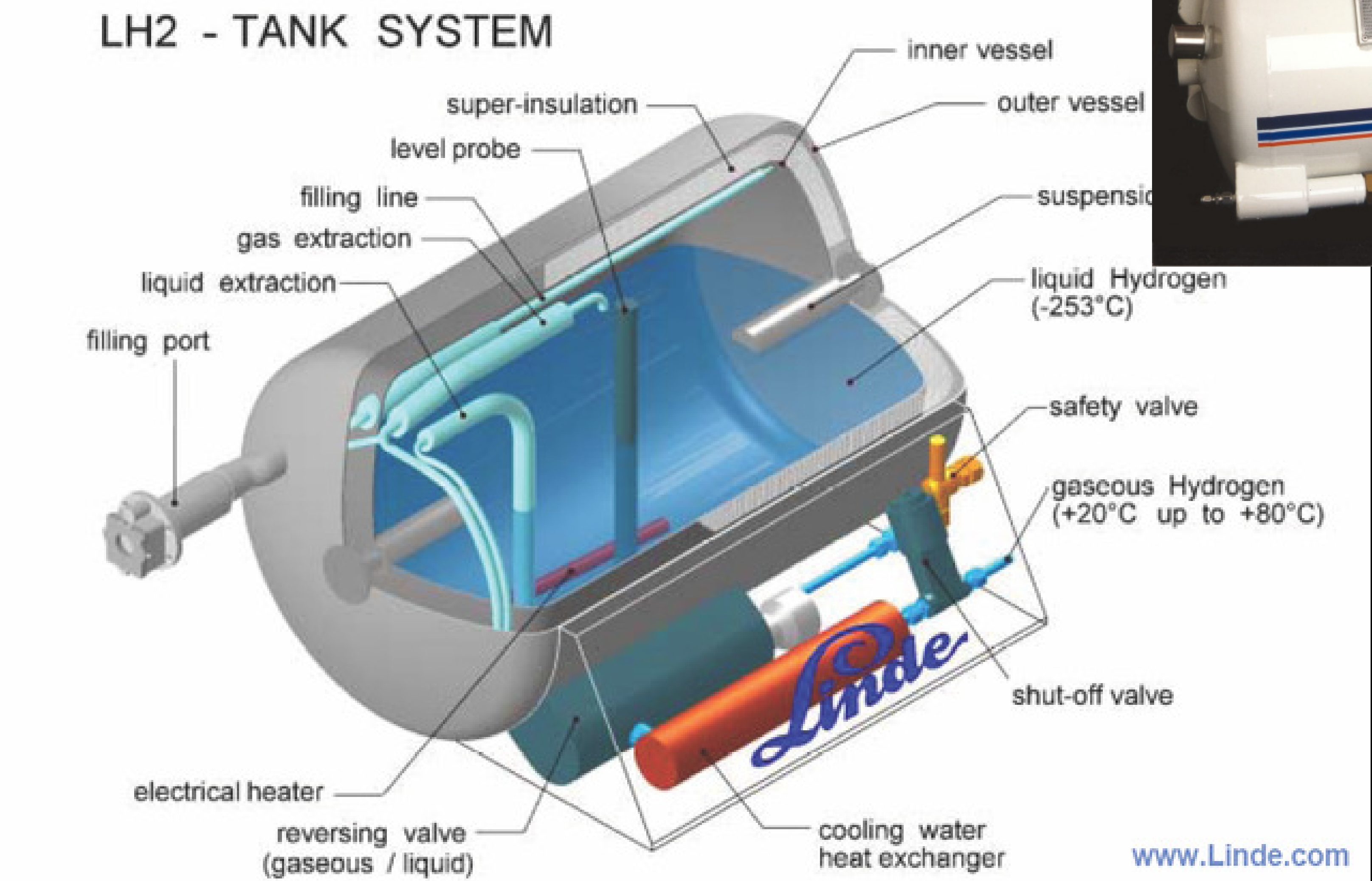
Messer Griesheim

Storage of Liquid Hydrogen



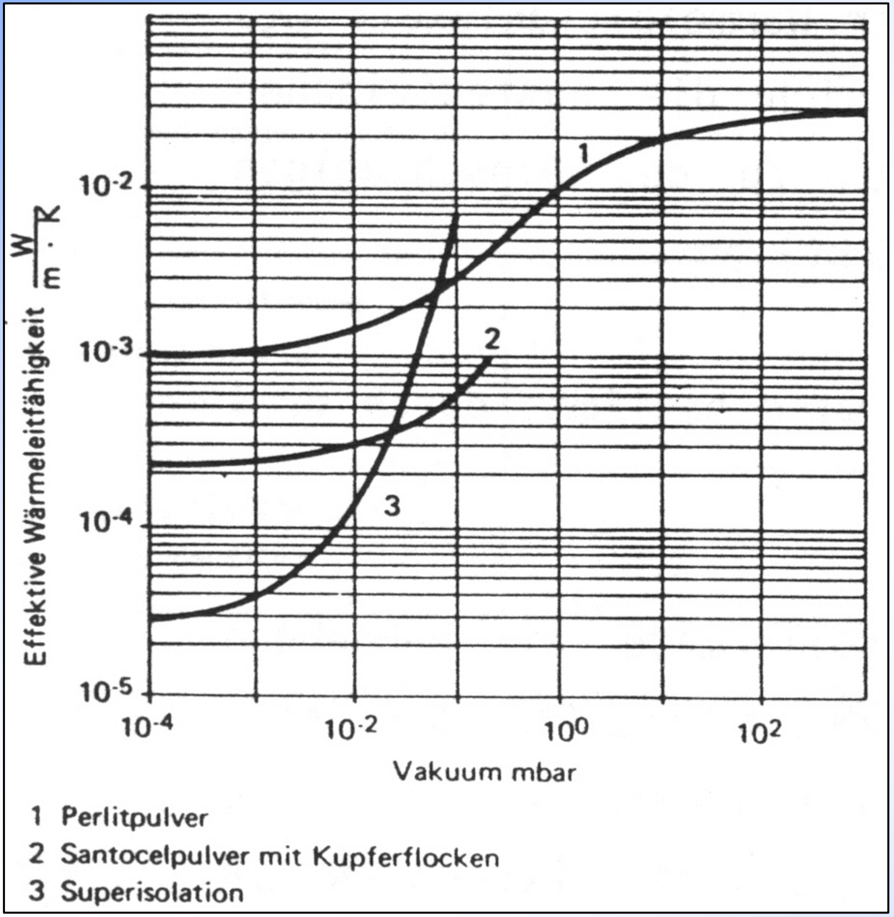
Volumetric-Gravimetric Tank Characteristics

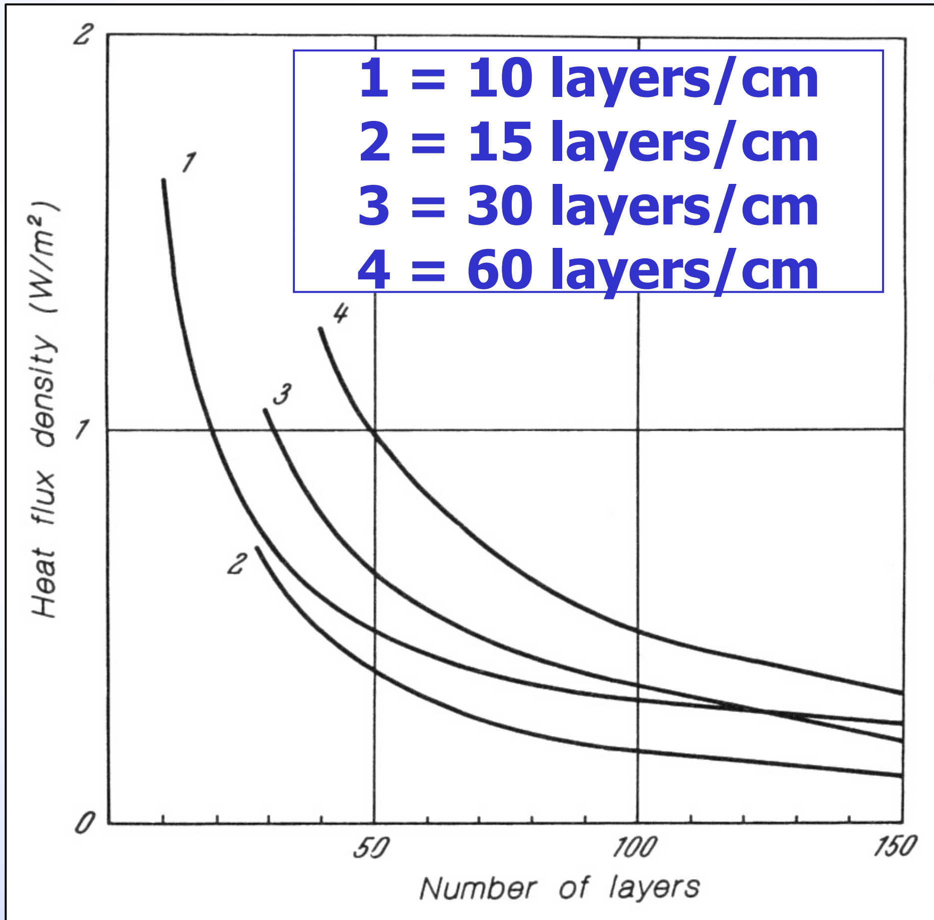
LH_2 Tank for Passenger Car



Messer Griesheim

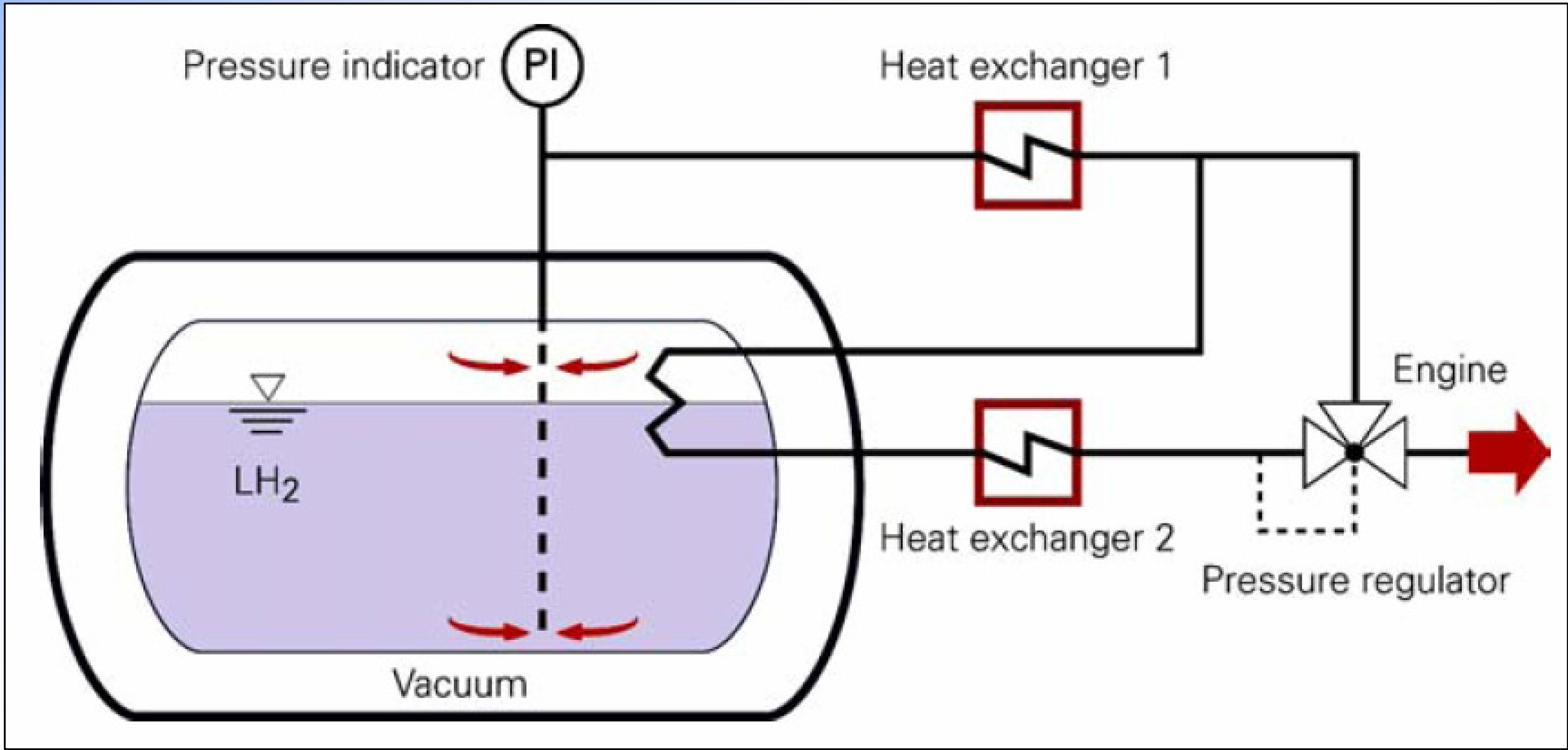
Superinsulation





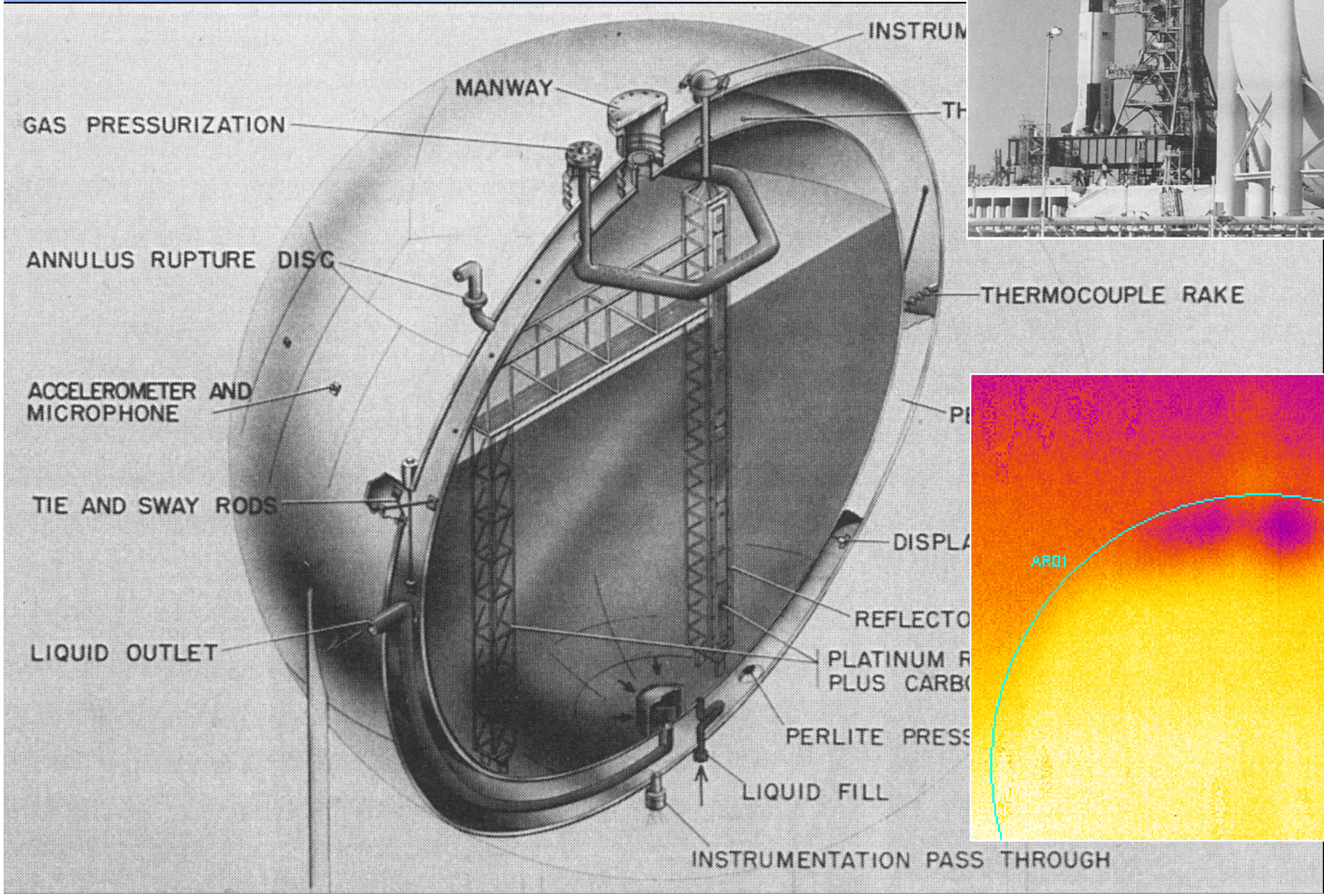
Peschka 1992

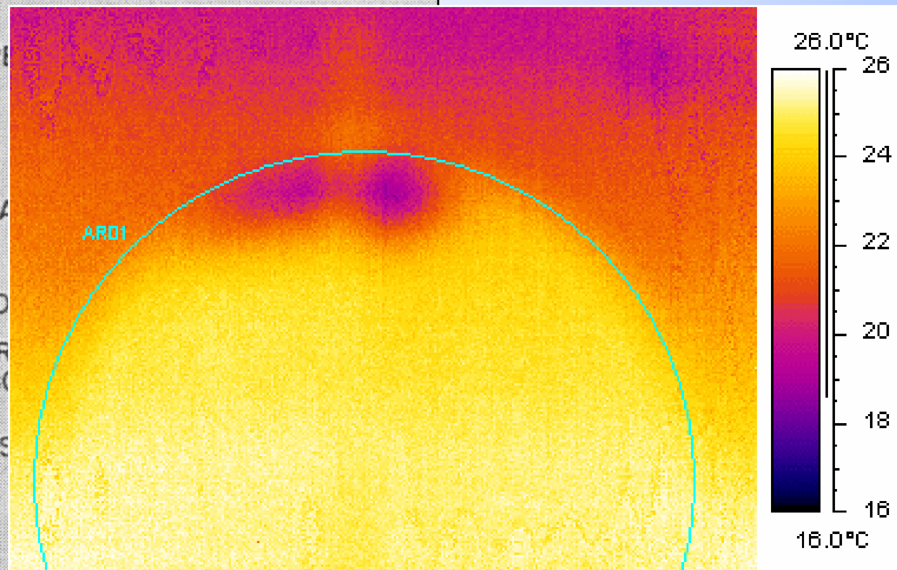
New Pressure Management System



Air Liquide 2006

Stationary LH_2 Tank at KSC

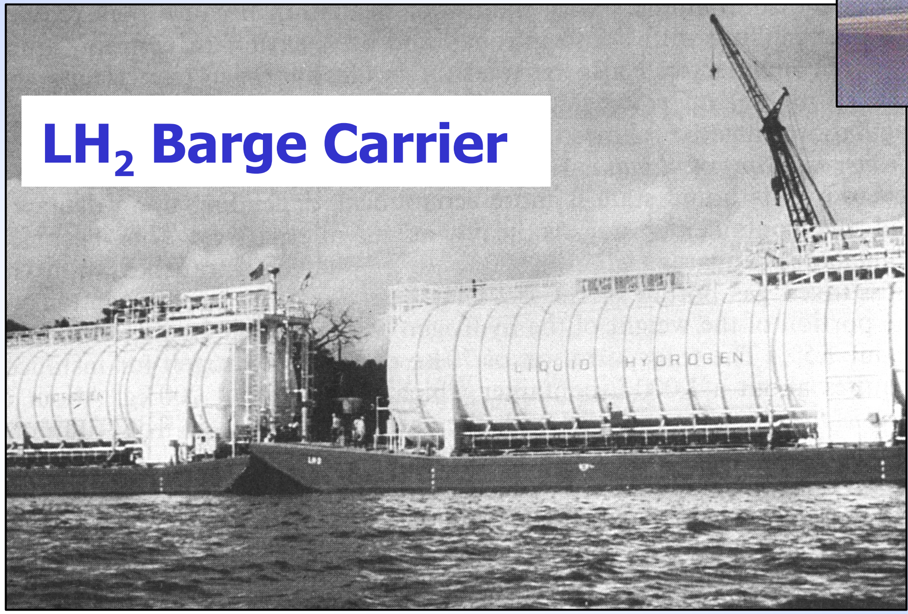




Transportation

Natural Gas, low pressure, 2005

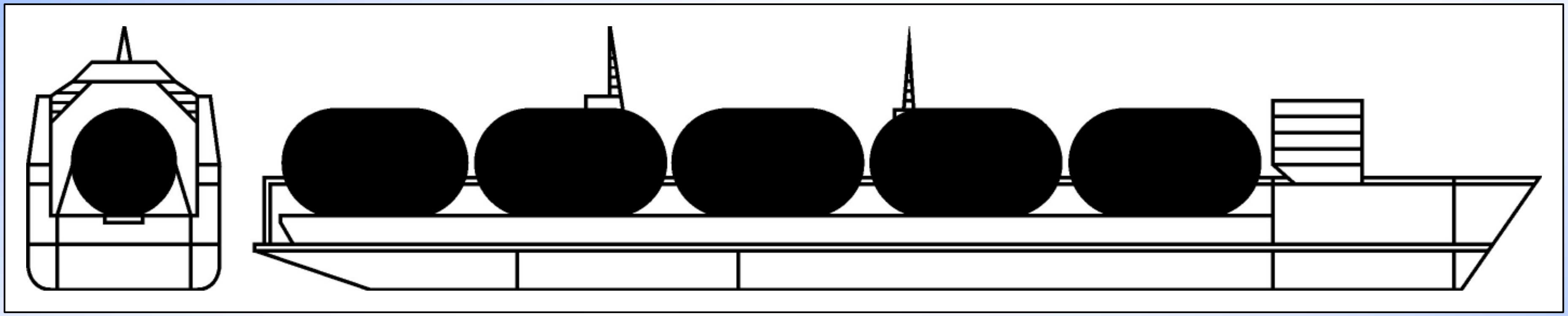
LH$_2$ Barge Carrier

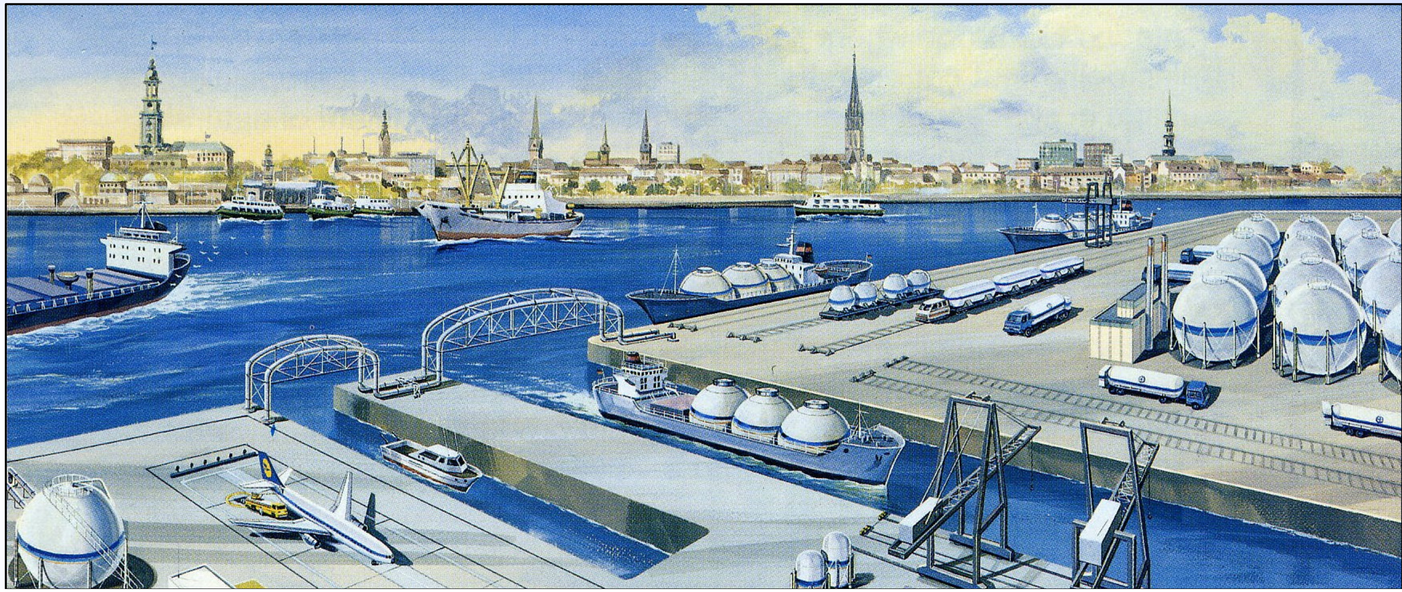


LOX, medium pressure, 1960s

Euro-Quebec Barge Carrier

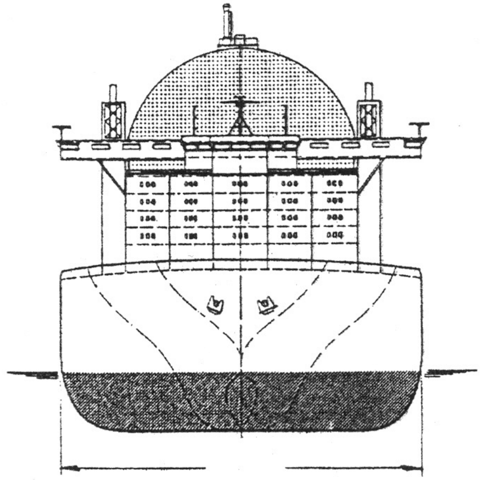
Dock ship
Length: 180 m, Width: 29 m
5 barges with 3000 m^3 of LH_2 each

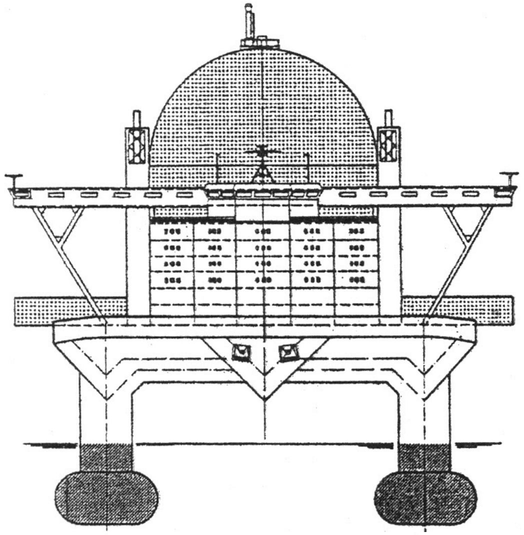




Dockship

Capacity	8 150	t
	115 000	m^3
Length (l_{pp})	318	m
Breadth (WL)	62	m
Draught (CWL)	10	m
Displacement	134 400	t
Power (mcr)	36 000	kW
trial speed	16	kn



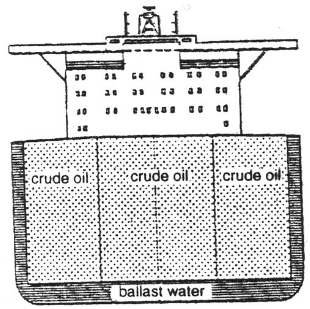


SWATH carrier

Capacity	8 150	t
	115 000	m^3
Length (l_{pp})	322	m
Breadth (WL)	65	m
Draught (CWL)	14	m
Displacement	104 000	t
Power (mcr)	36 000	kW
trial speed	17,5	kn

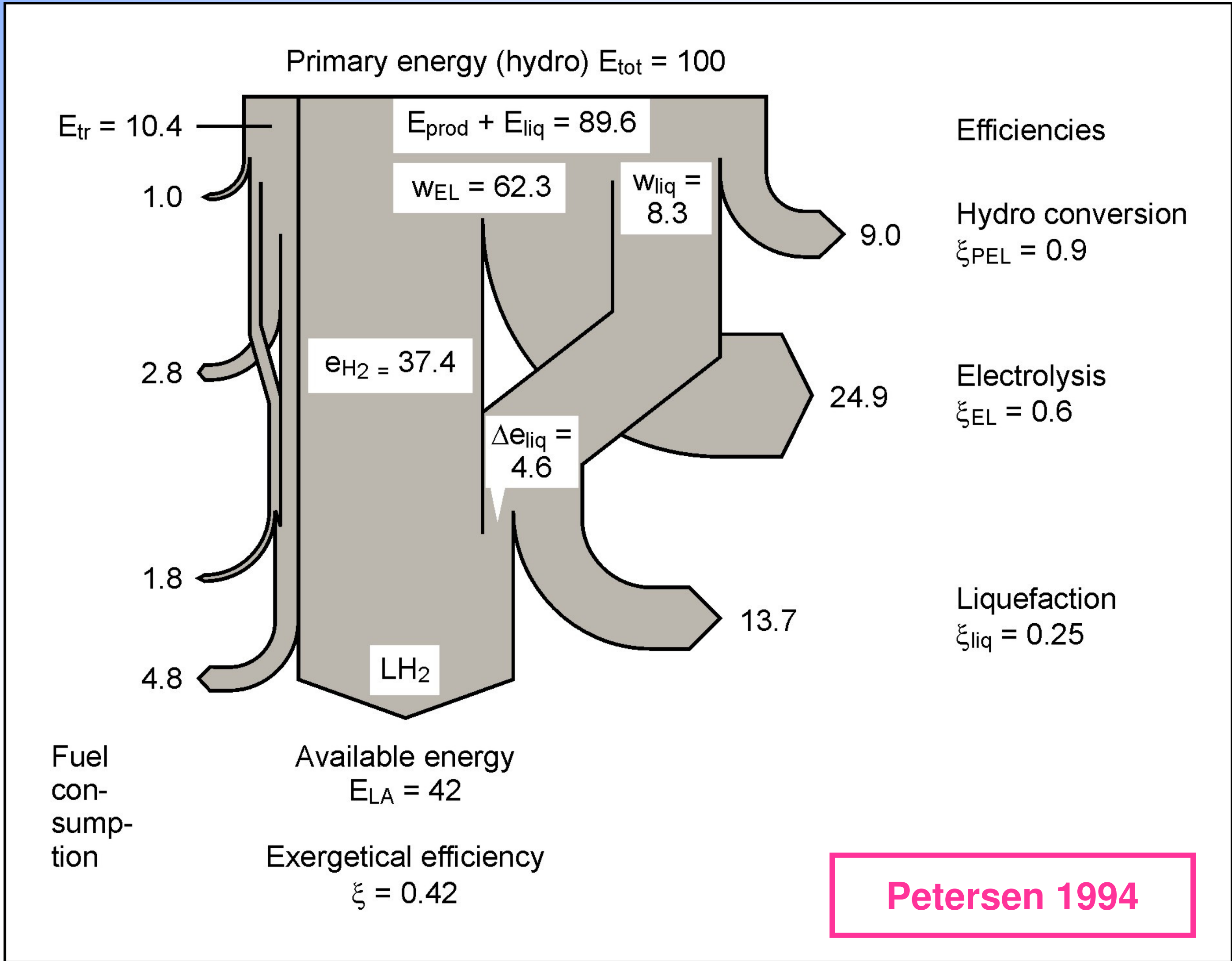
Double hull tanker

Capacity	273 000	t
	300000	m^3
Length (l_{pp})	330	m
Breadth (WL)	58	m
Draught (CWL)	20,6	m
Power (mcr)	22 450	kW
trial speed	14,5	kn



Germanischer Lloyd
Howaldtswerke Deutsche Werft AG

Exergy Analysis for Sea-Borne LH_2-Transport

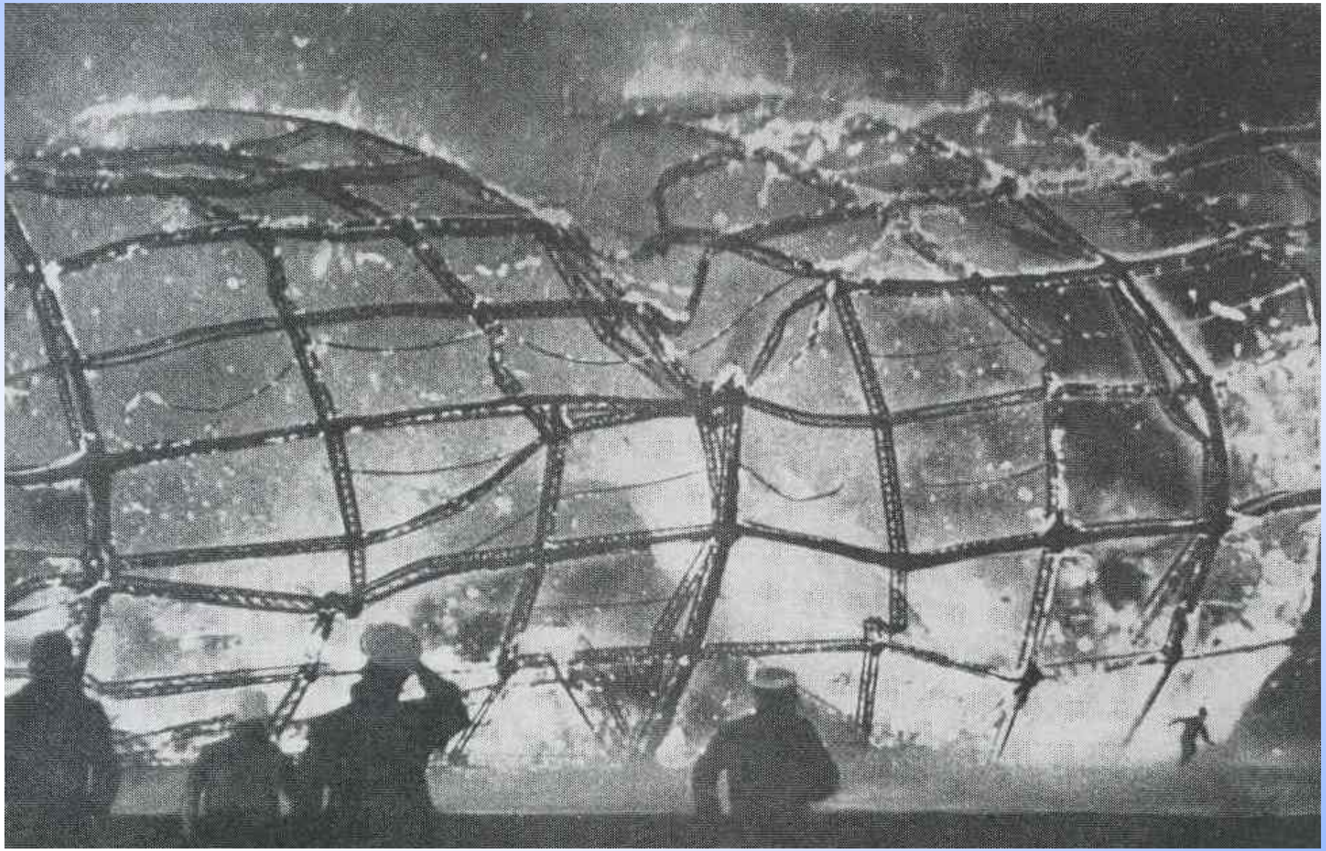


SWATH ship

WE-NET Design of Maritime LH_2-Transport

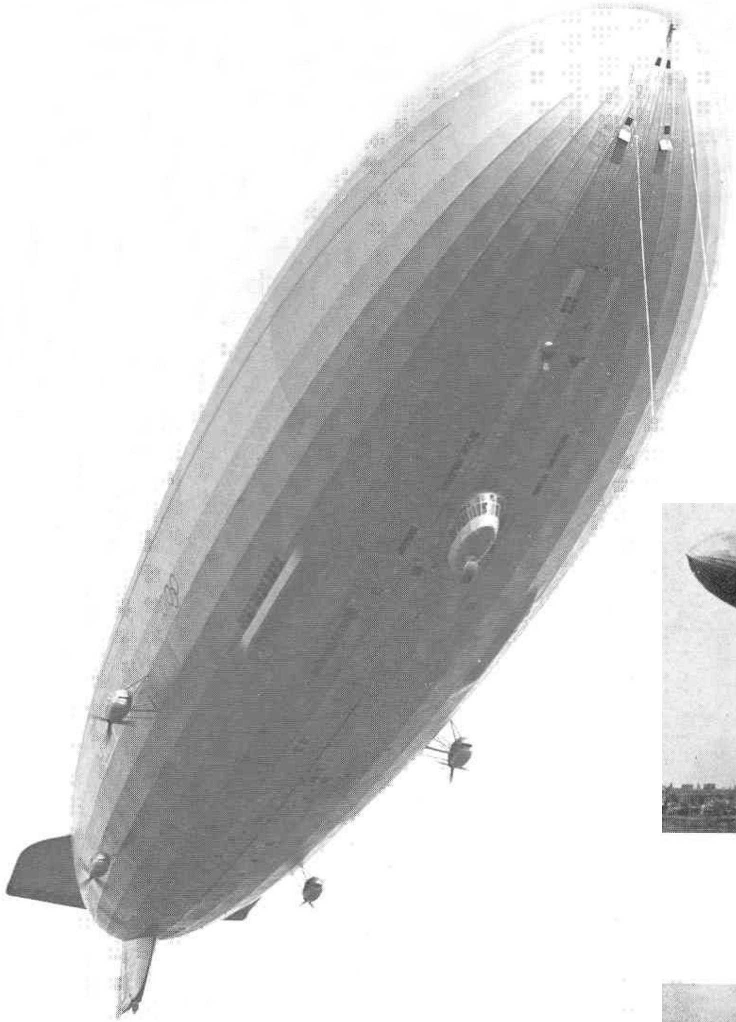
Hijikata 2002

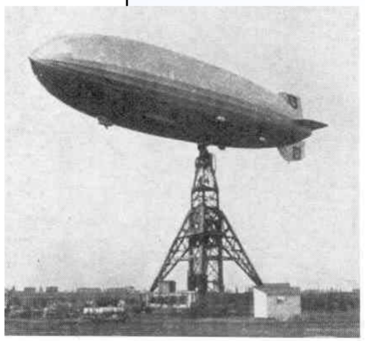
Accidents

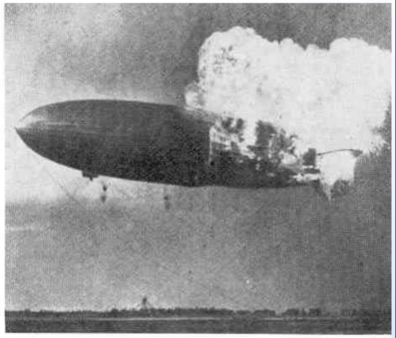


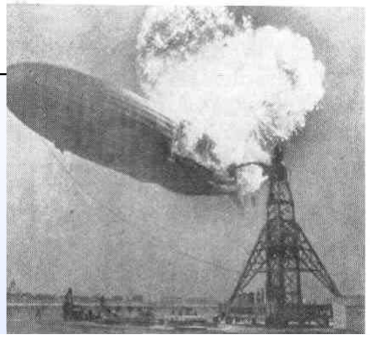
German Newspaper, 1937

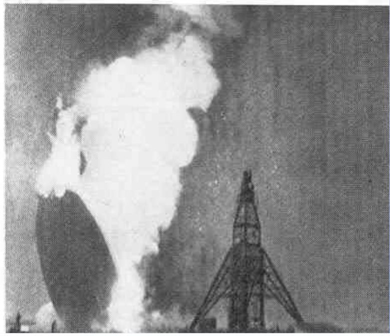
Hindenburg 1937

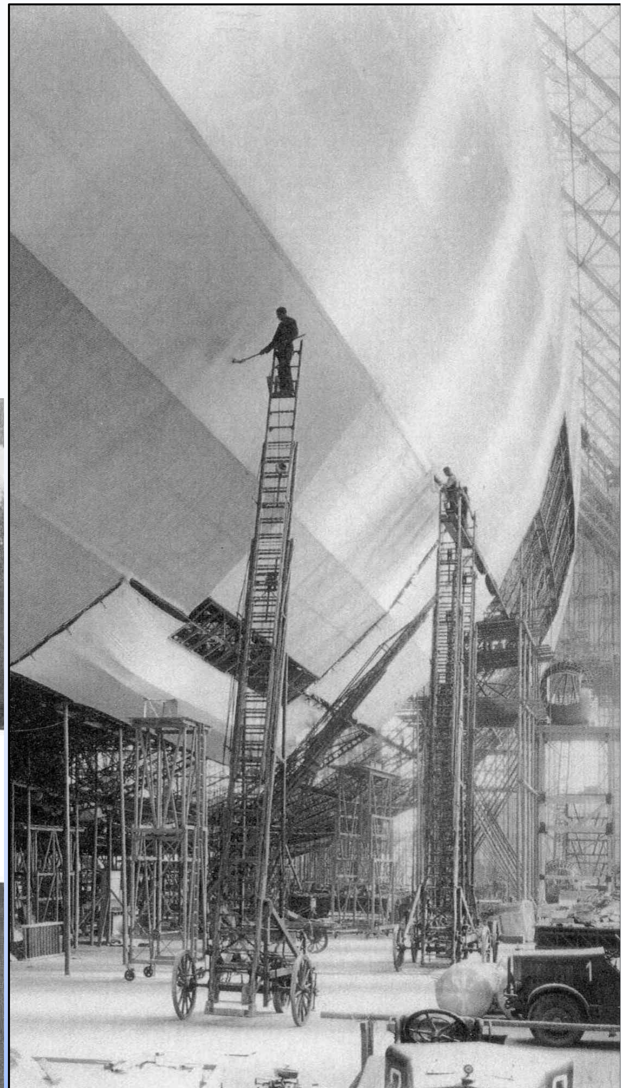












Car Accidents

Truck after LOX tank explosion

UCLA car overturn, rapid LH_2 boil-off

Accident with H_2 Truck

June 2006, H_2 Tube Trailer Accident, Germany

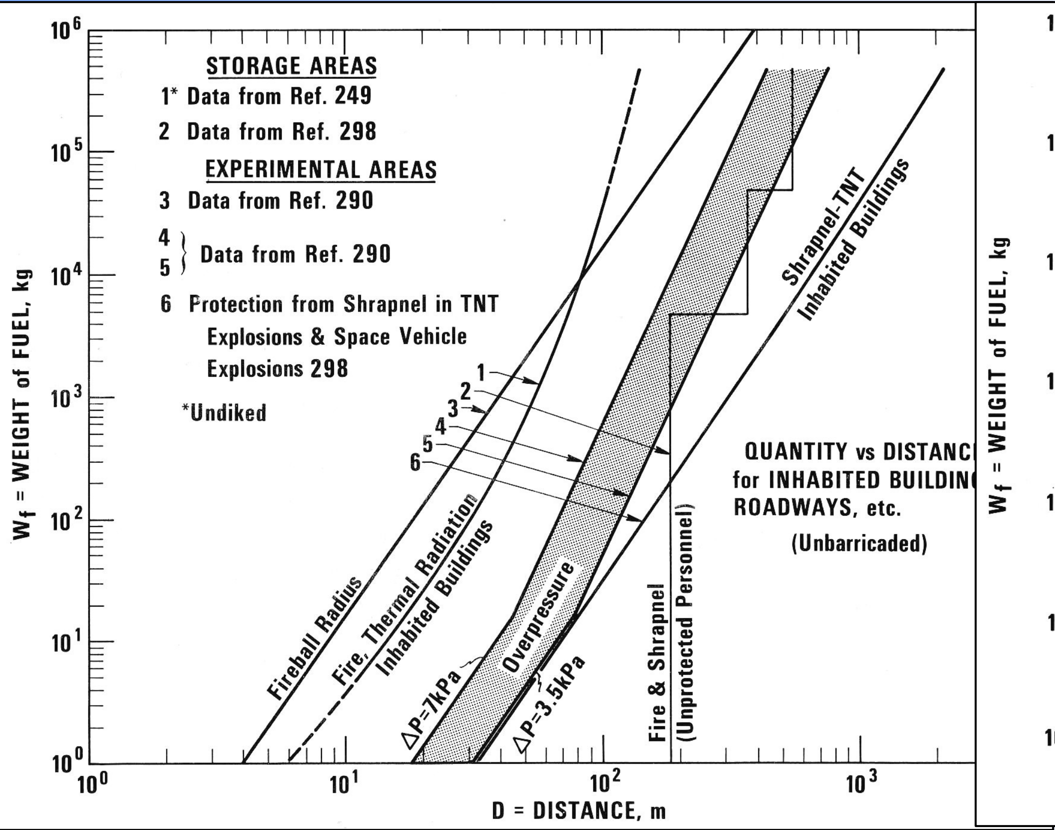
Accident Simulation Test

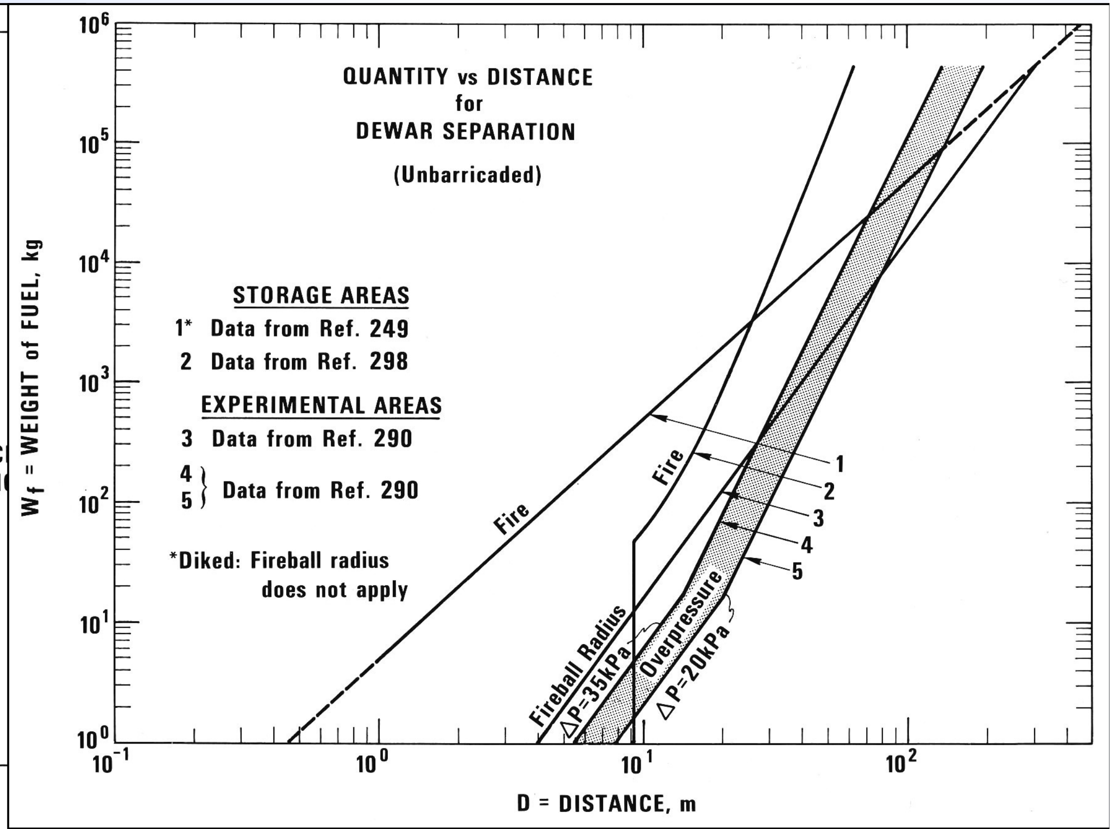
Comparison of fuel behavior after leakage and ignition

hydrogen vs. gasoline

Quantity-Distance Relationships

Hord 1978



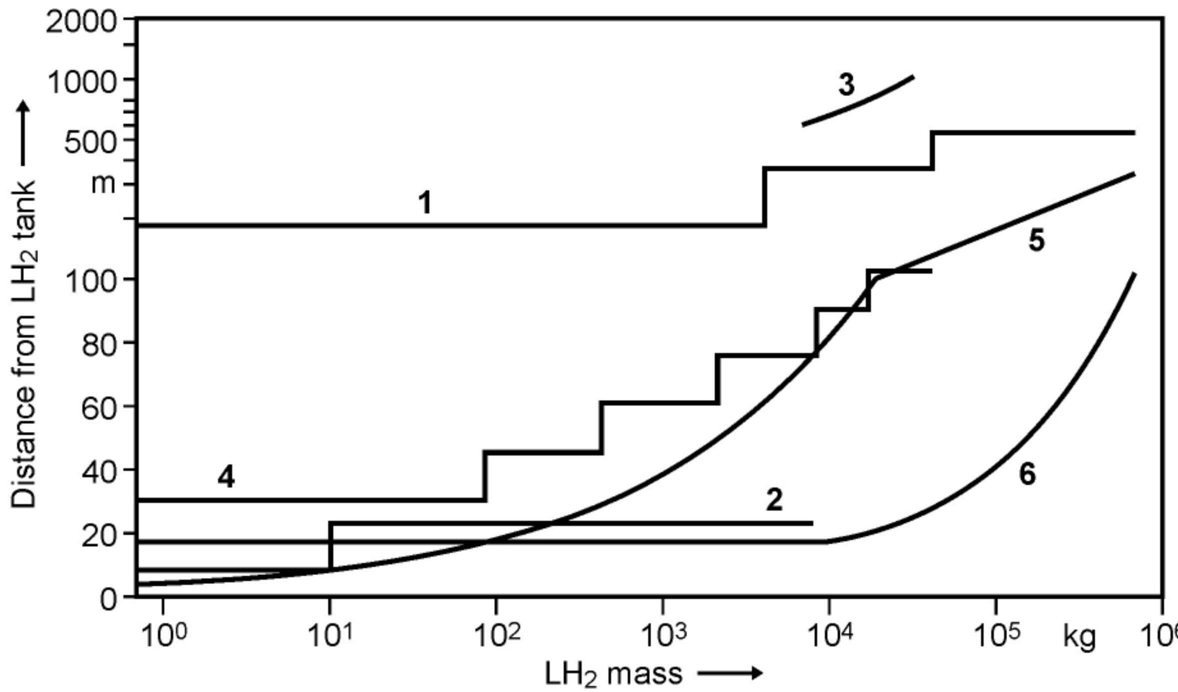


Protection of adjacent LH_2 tanks

Protection of personnel and residential area near LH_2 tanks

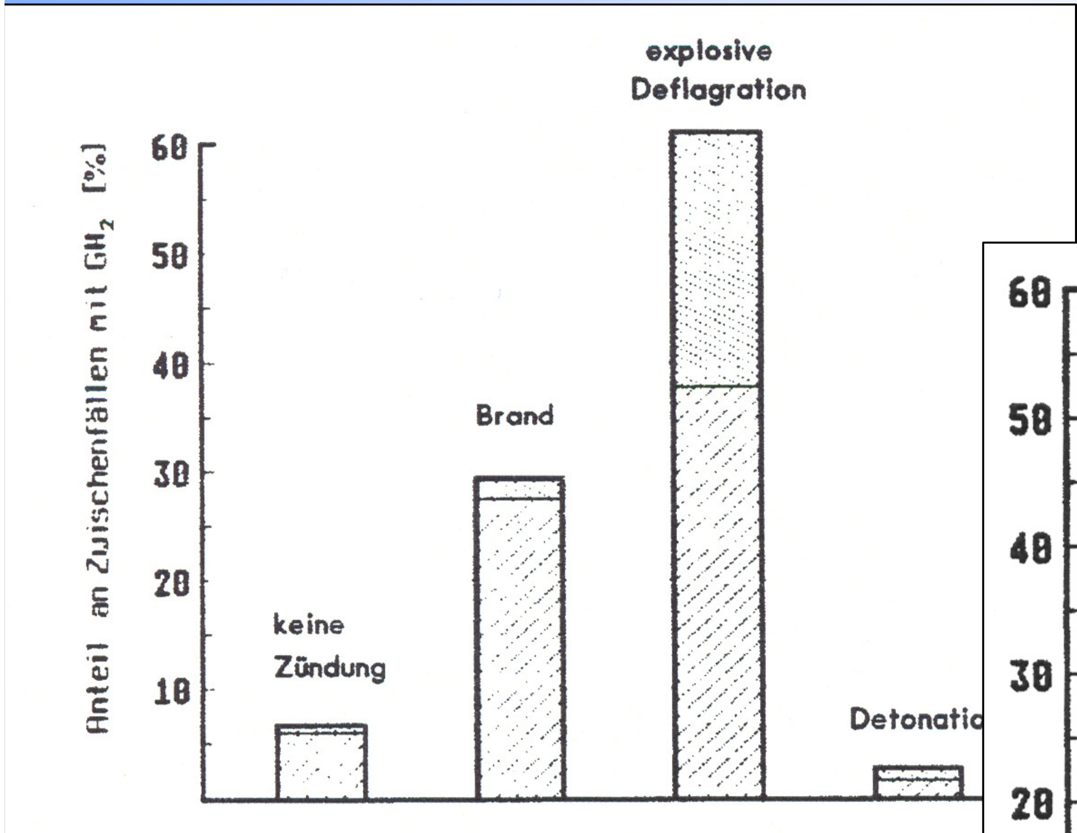
Safety Distances in Different Countries

1 US Dep. Defense Instruction No. 4145.21 (1964)
2 National Fire Protection Association (NFPA), Boston (1973)
3 US Army Material Command Safety Manual No. 385-224 (1964)
4 Burean of Mines, Pittsburgh (1961)
5 German Fed. Ministry of the Interior, Bonn (1974) (nuclear power plants) for liquefied gases
6 High-Pressure Gas Control Legislation, Japan (category I)



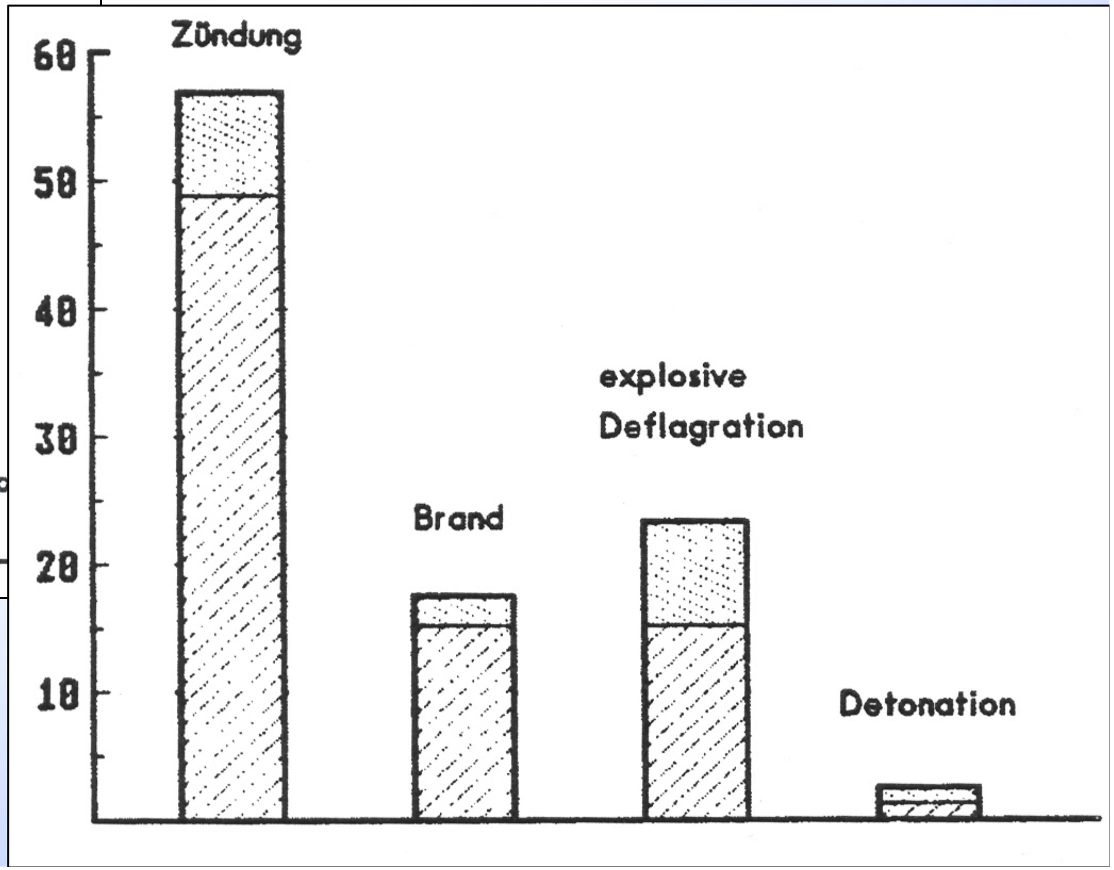
Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

Accident Statistics (Kreiser)



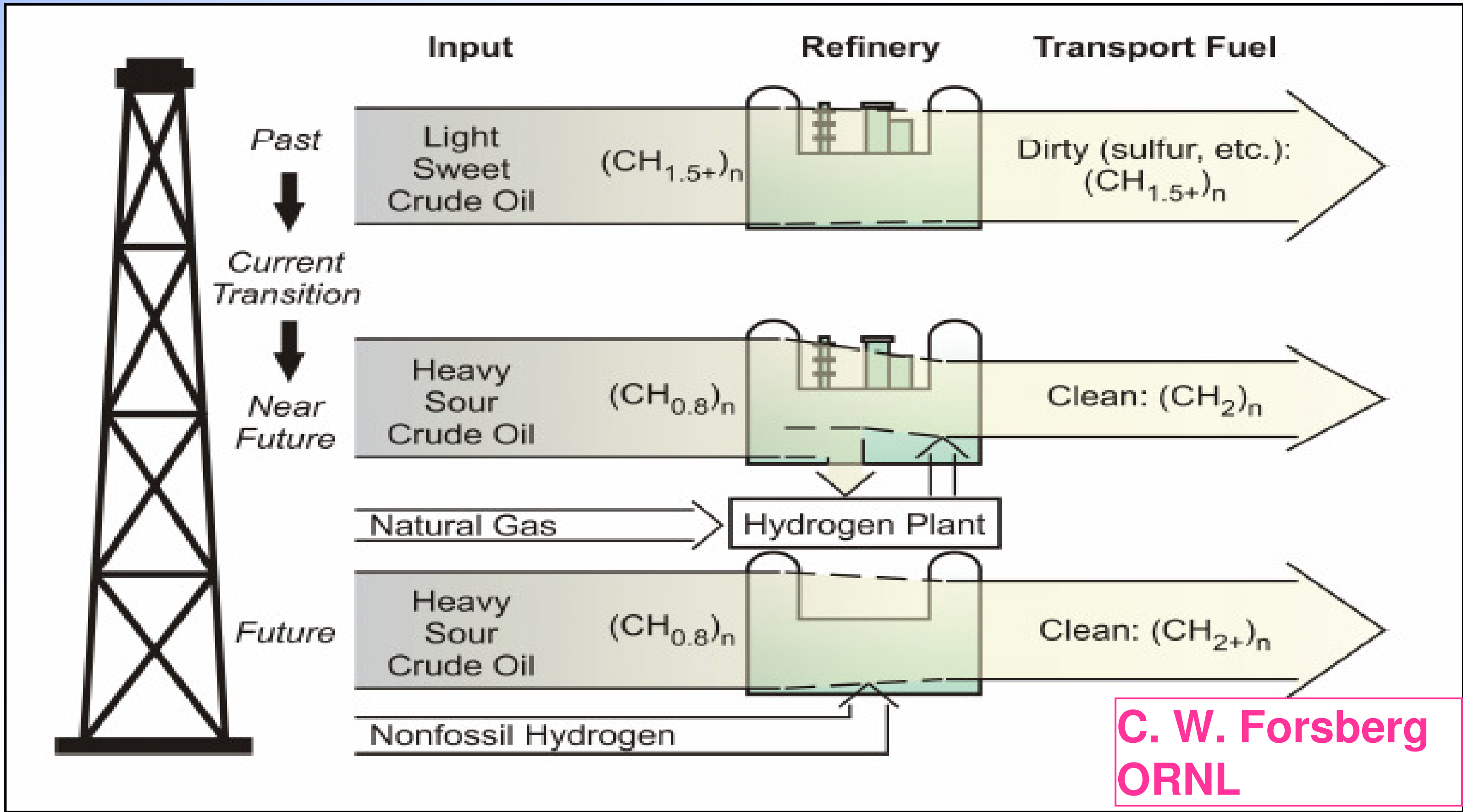
Gaseous Hydrogen

Liquid Hydrogen



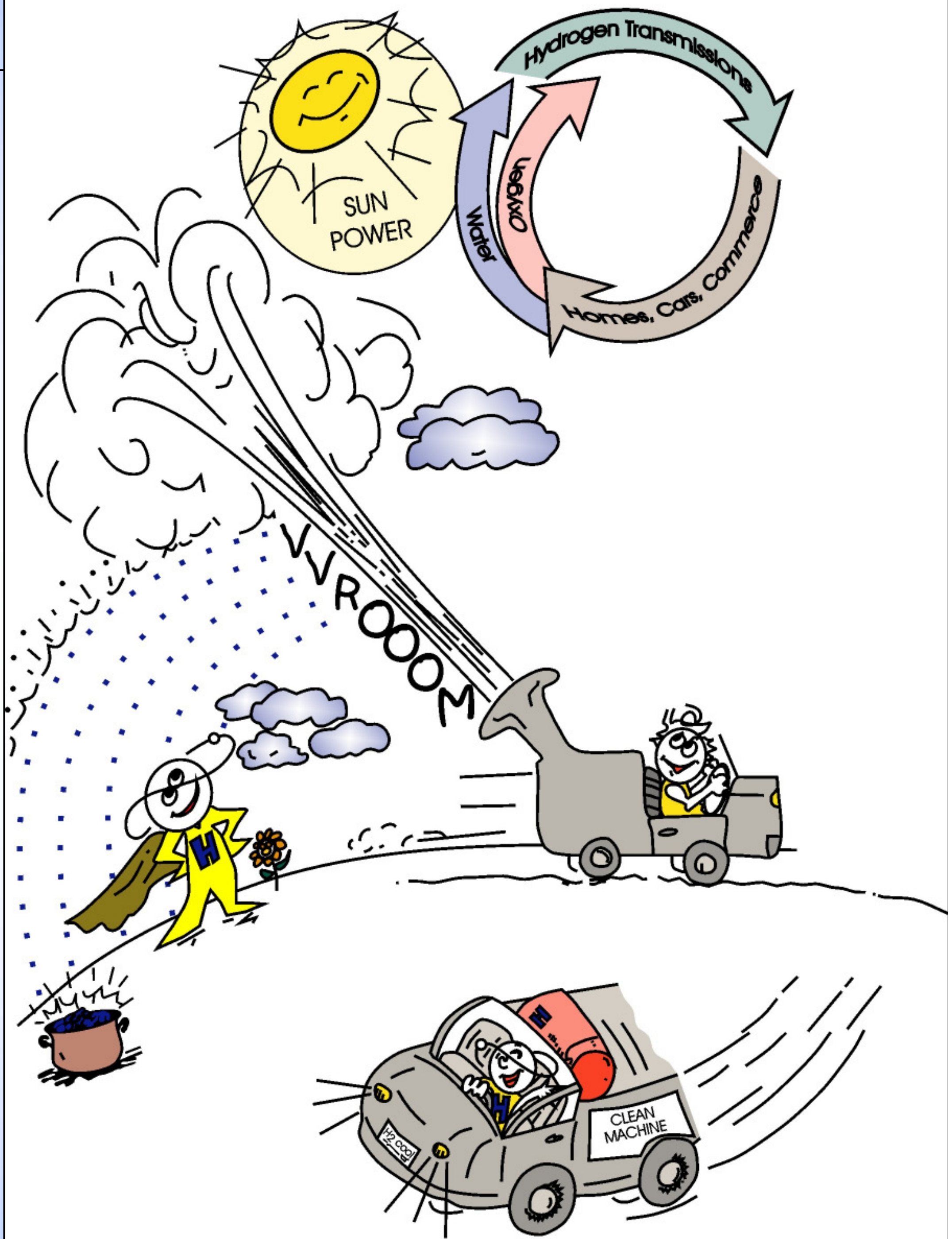
Applications of Liquid Hydrogen

Crude Oil Quality Change



„Dirty fuels“ requiring even more H_2 and process steam

Hydrogen-Driven Vehicles



First Hydrogen Vehicles

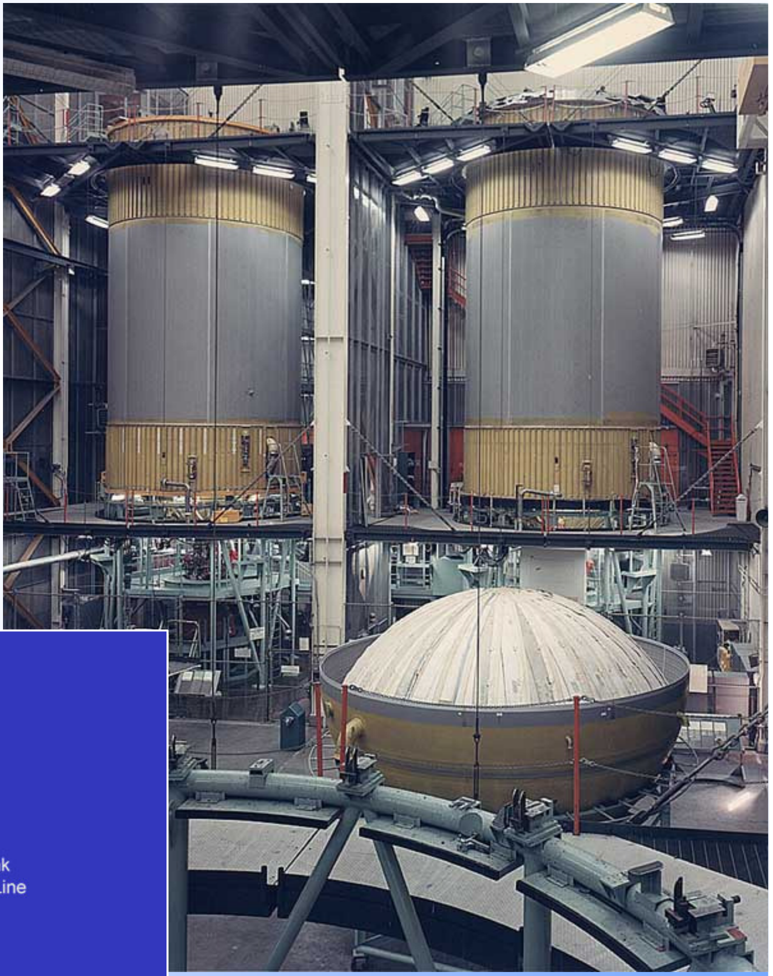
NASA Space Program

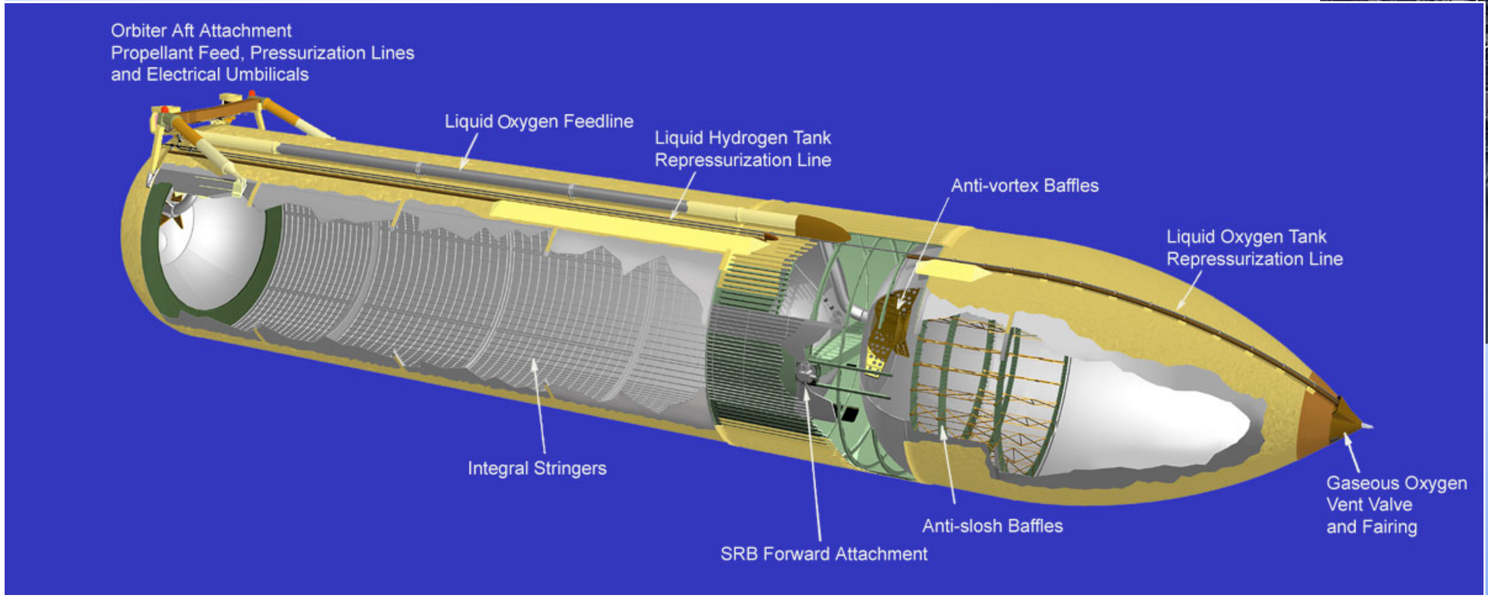
Space Shuttle

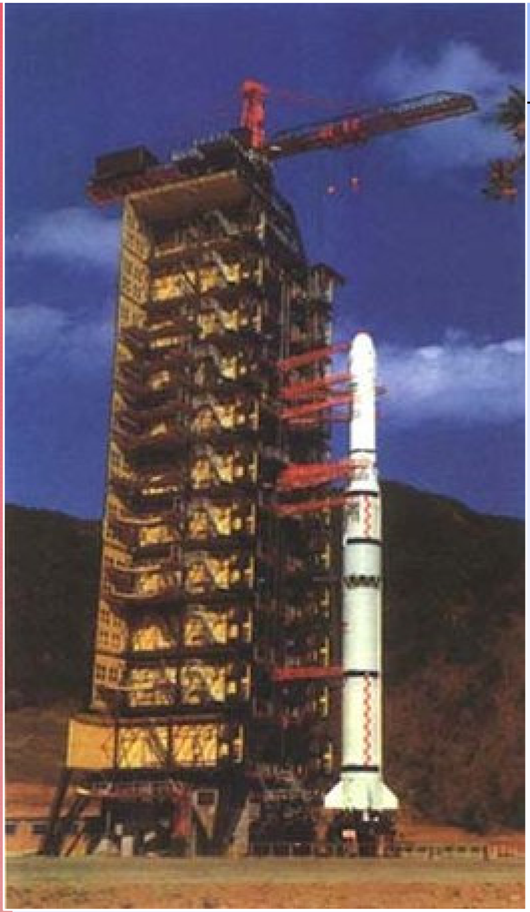
Saturn / Apollo

Space Shuttle External Tank

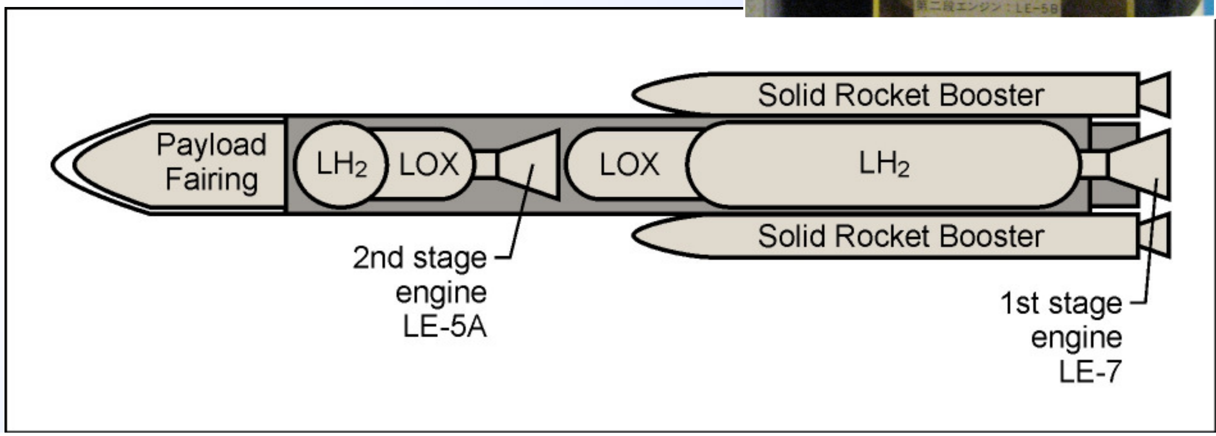
Length: 46.9 m
Diameter: 8.4 m
Gross weight: 762.1 t
LOX: 629.3 t
LH_2: 106.3 t



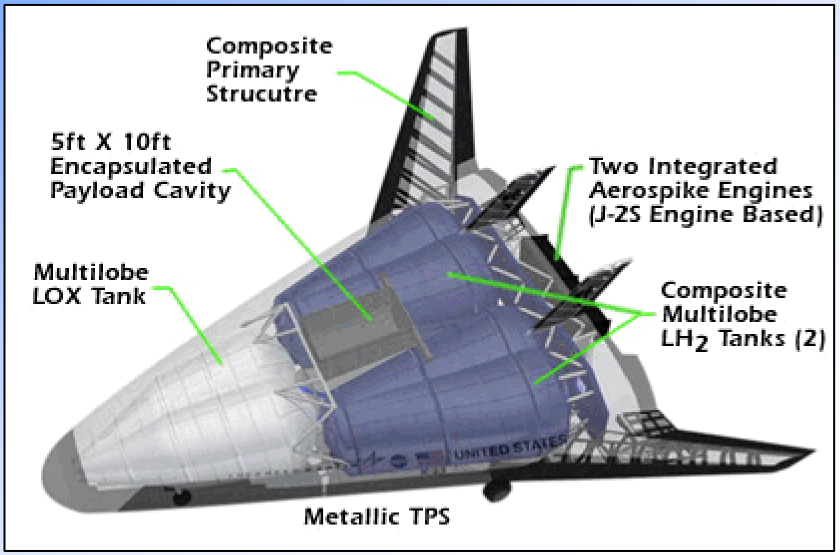




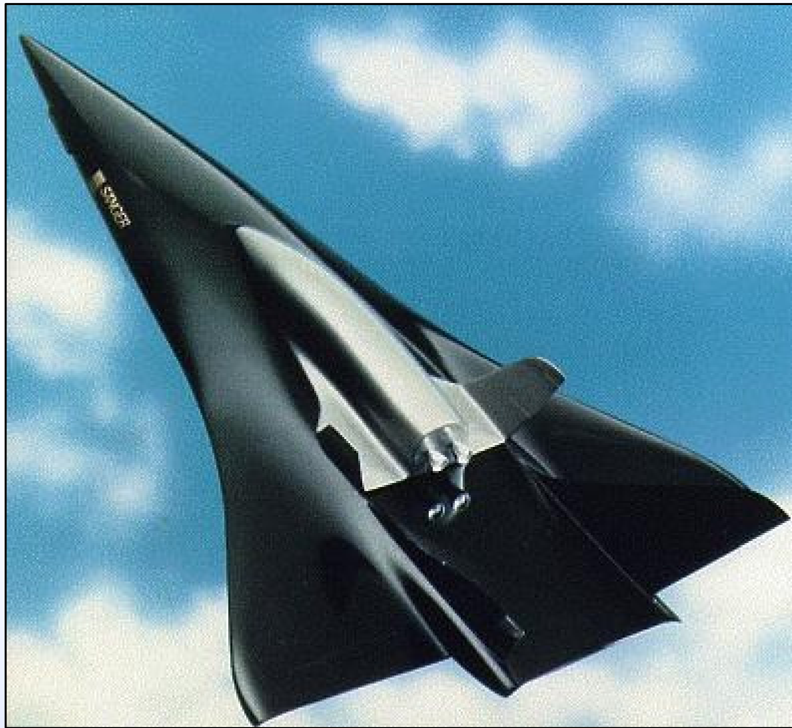
Rockets with LH_2/LOX Fueling System



Future Space Planes

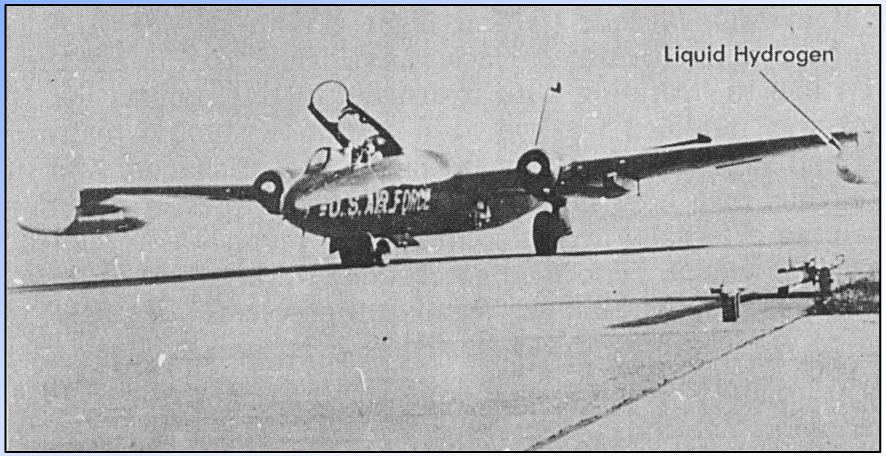


X-33

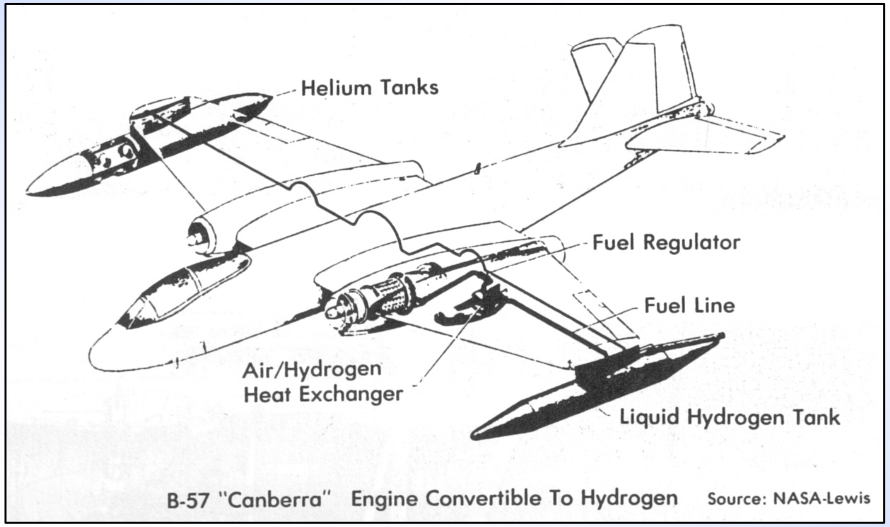


Saenger

Airplanes to Fly with LH_2



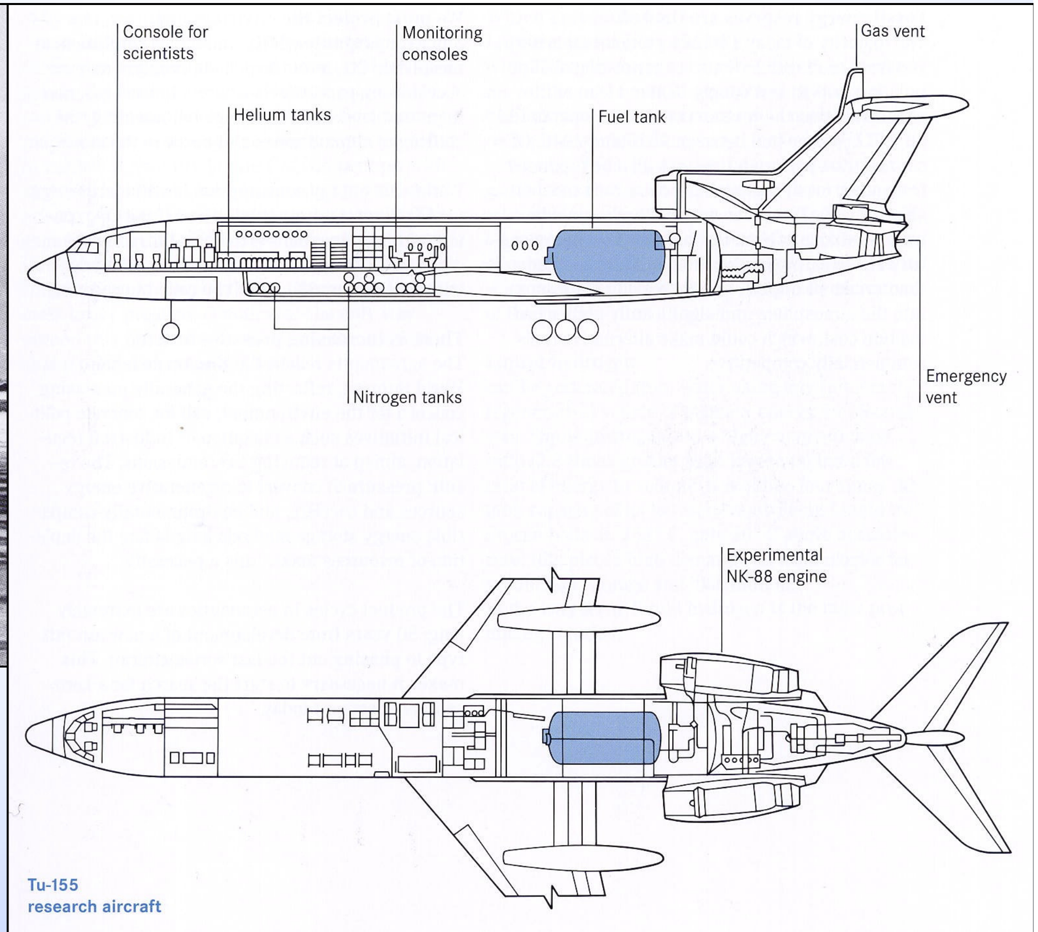
1956
Twin-jet B-57 Canberra with one H_2 engine



B-57 "Canberra" Engine Convertible To Hydrogen Source: NASA-Lewis

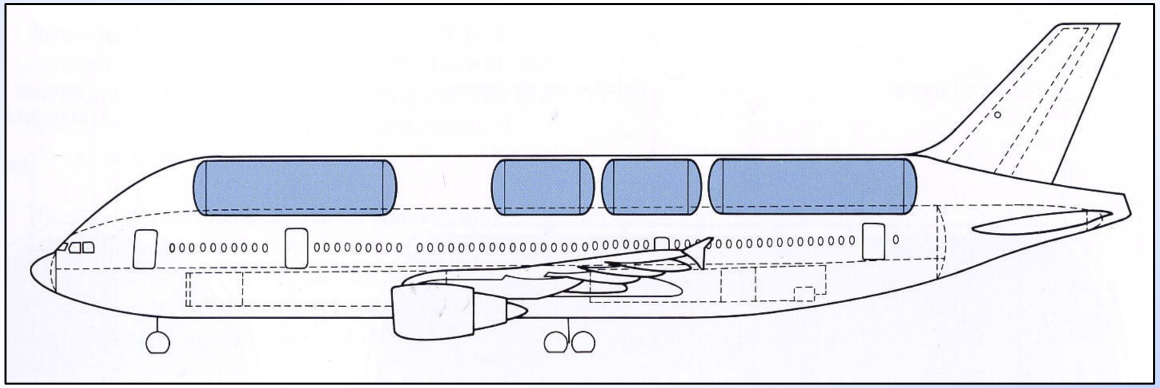
1988
Grumman Cheetah

Russian Tupulev 155 „Flying Laboratory“



1988
Central engine converted to H_2/CH_4

Project CRYOPLANE



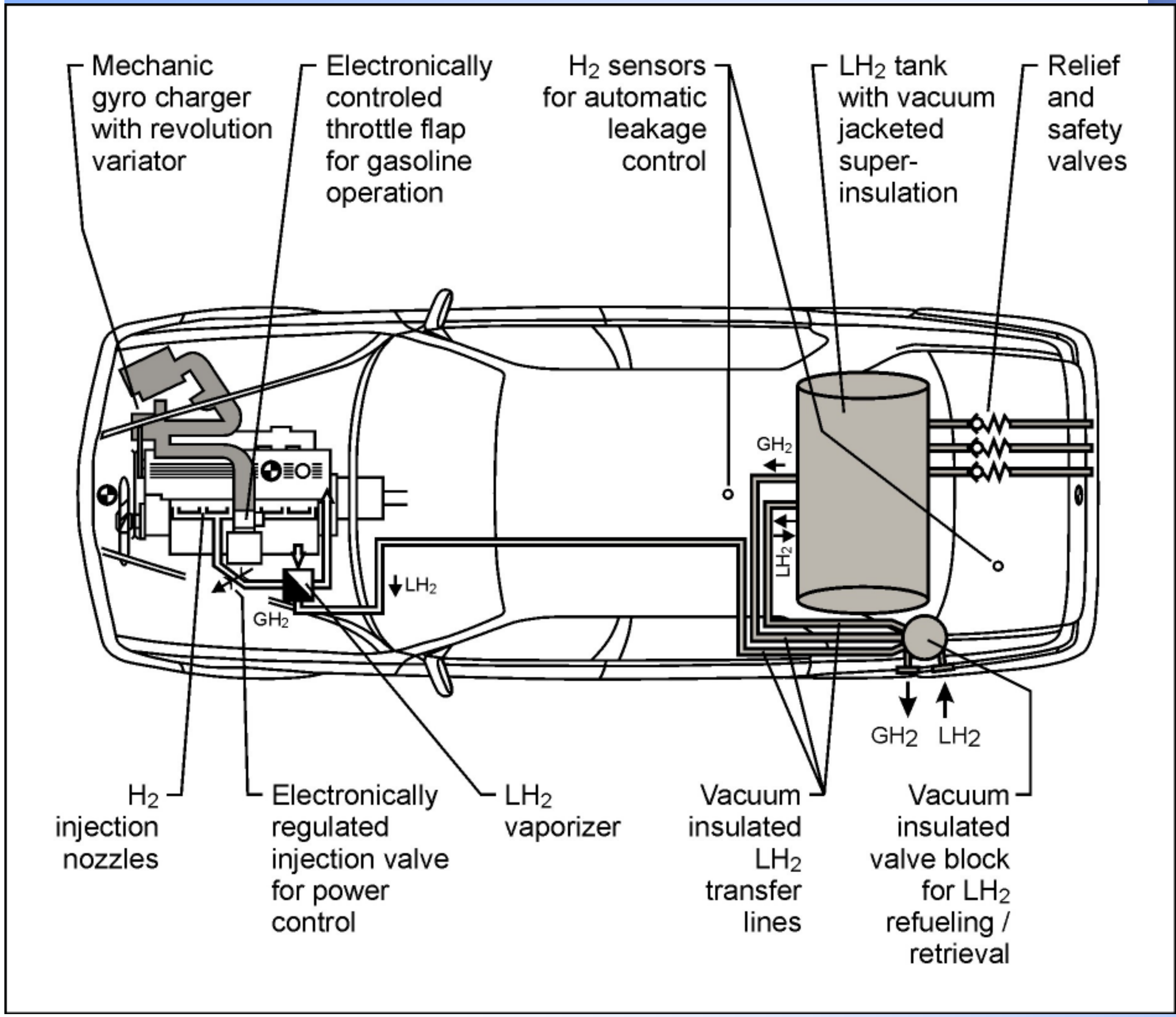
2 x 40 m^3 LH_2 tanks
2 x 80 m^3 LH_2 tanks

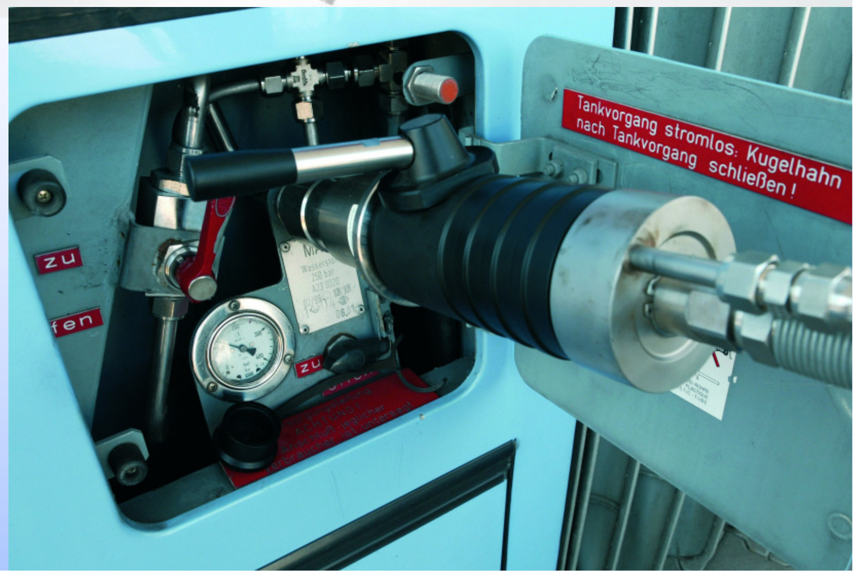
LH_2 Cars

1973

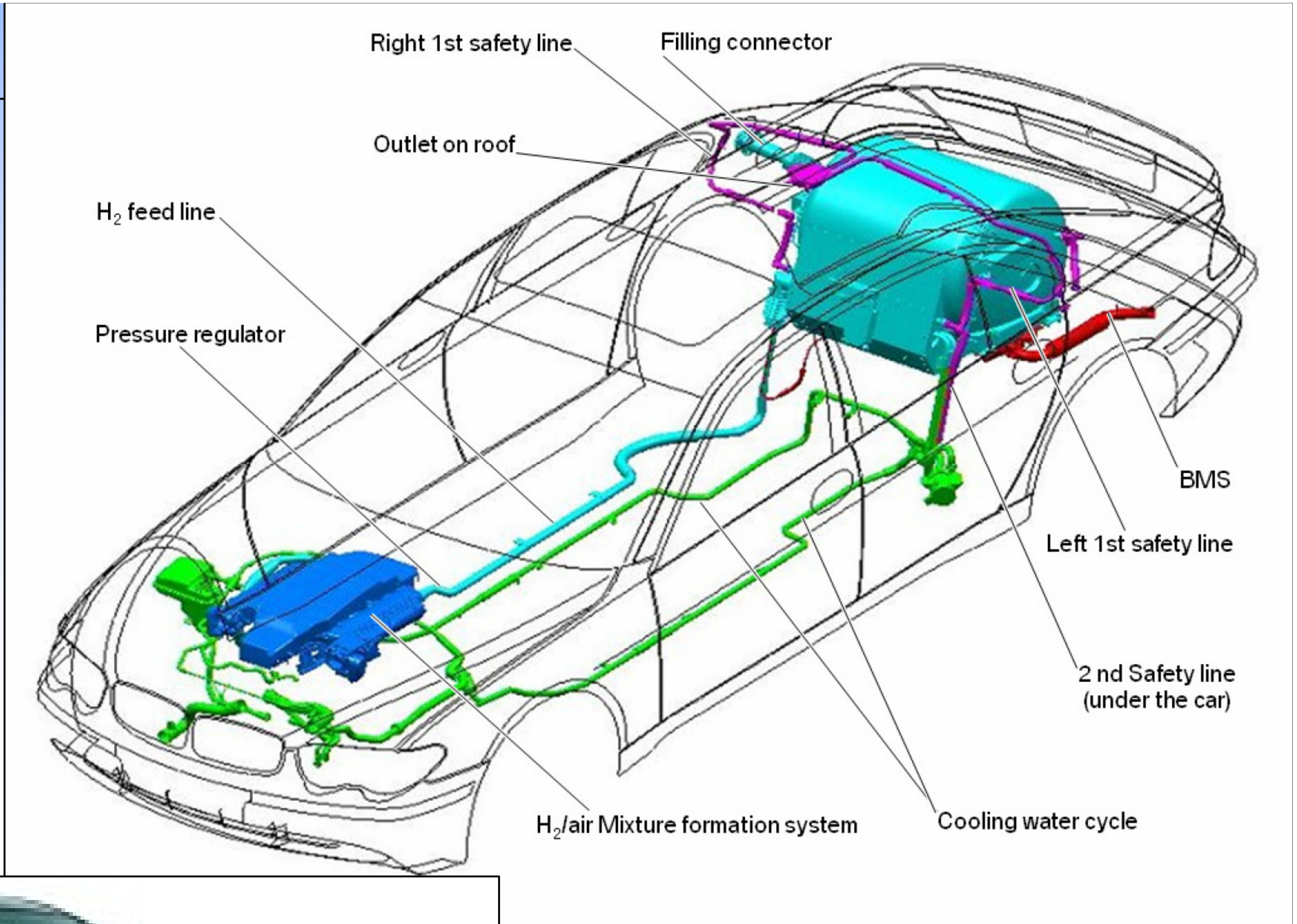
**One of the First!
(LANL-DFVLR)**

7 Generations of BMW





BMW Hydrogen 7



Buses using LH_2

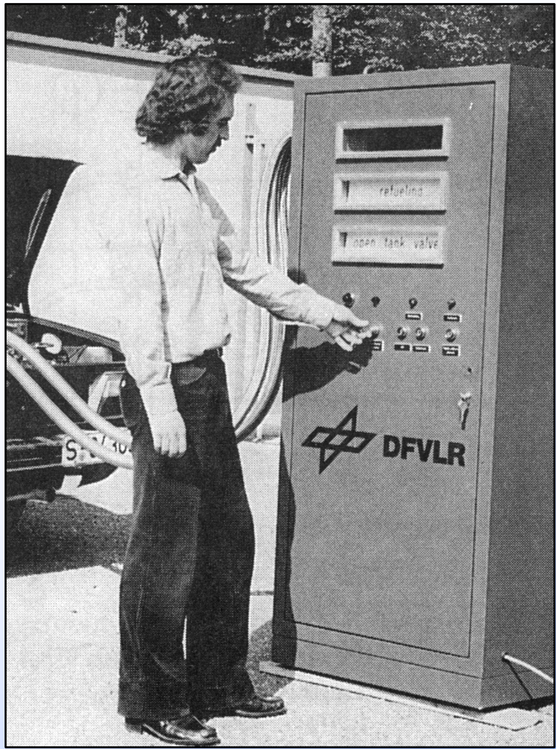
2001
MAN Hydrogen FC Bus
2 x 350 l LH_2 tanks

1995 (Euro-Quebec)
Van Hool ICE Bus
125 l LH_2 tank
experimental demonstrator

LH_2 Refueling Station

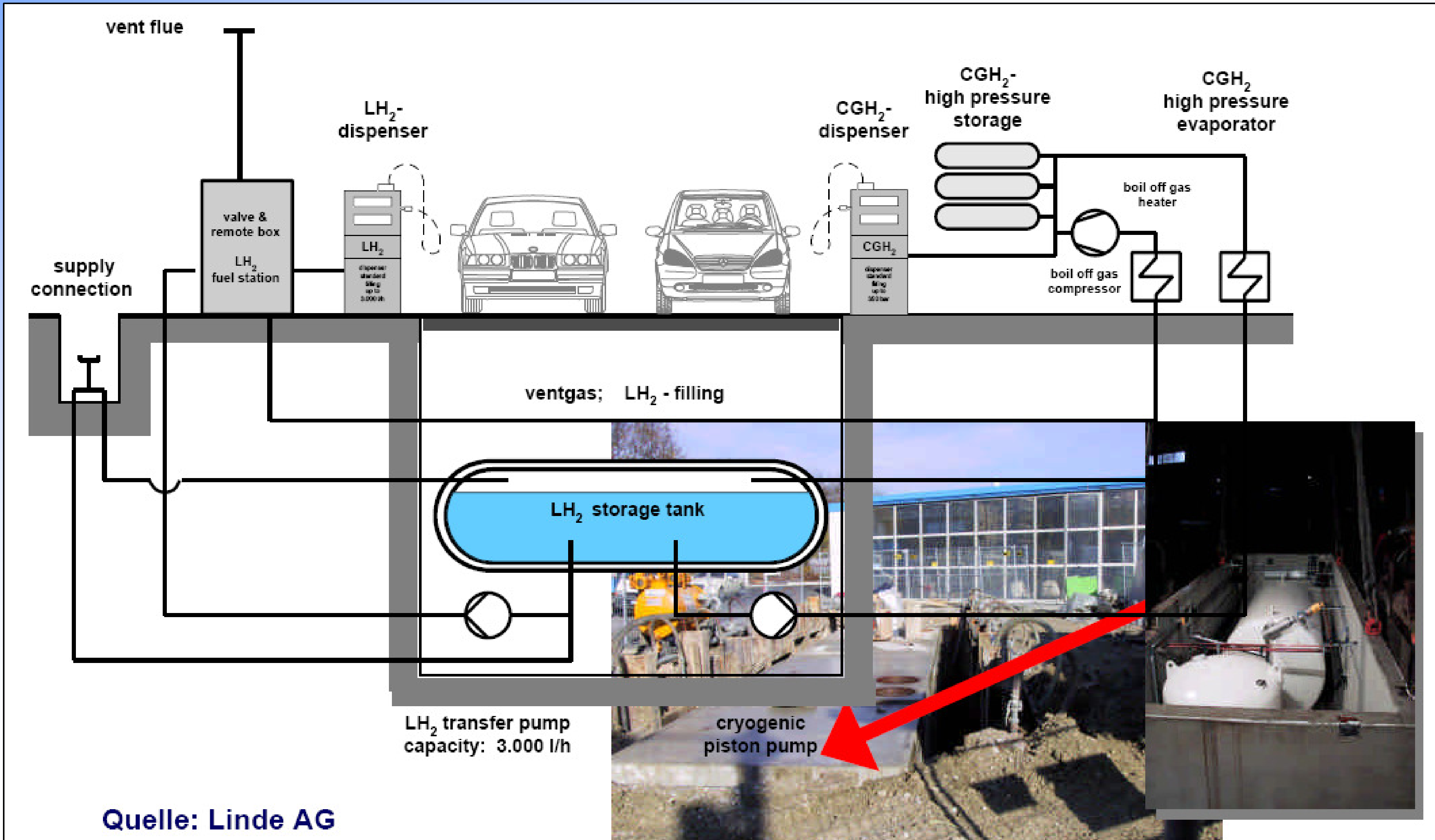
Total 2006

DFVLR/LANL 1979



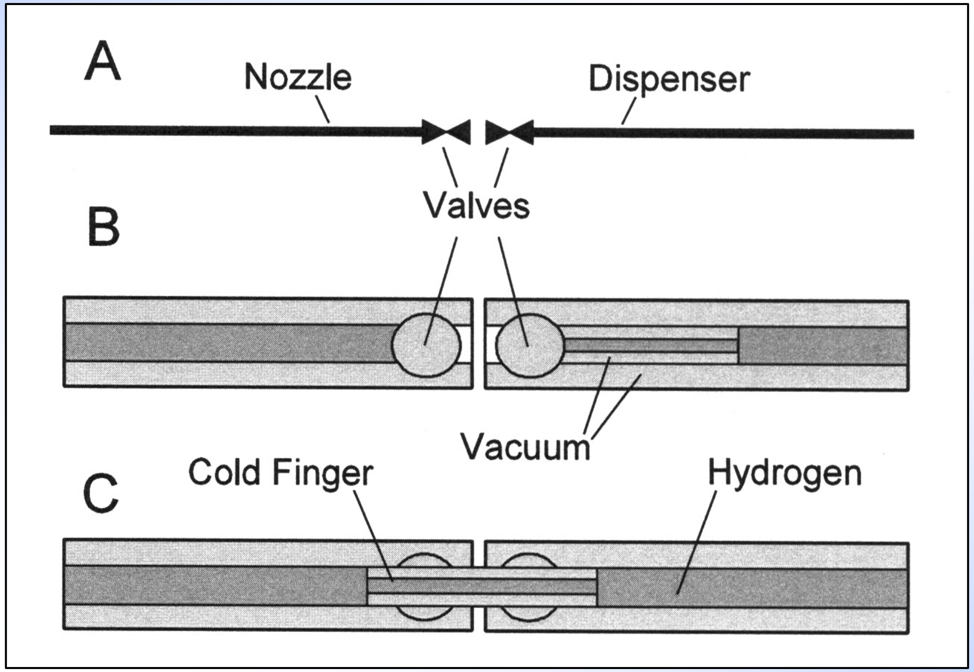
ARGEMUC 1999-2006

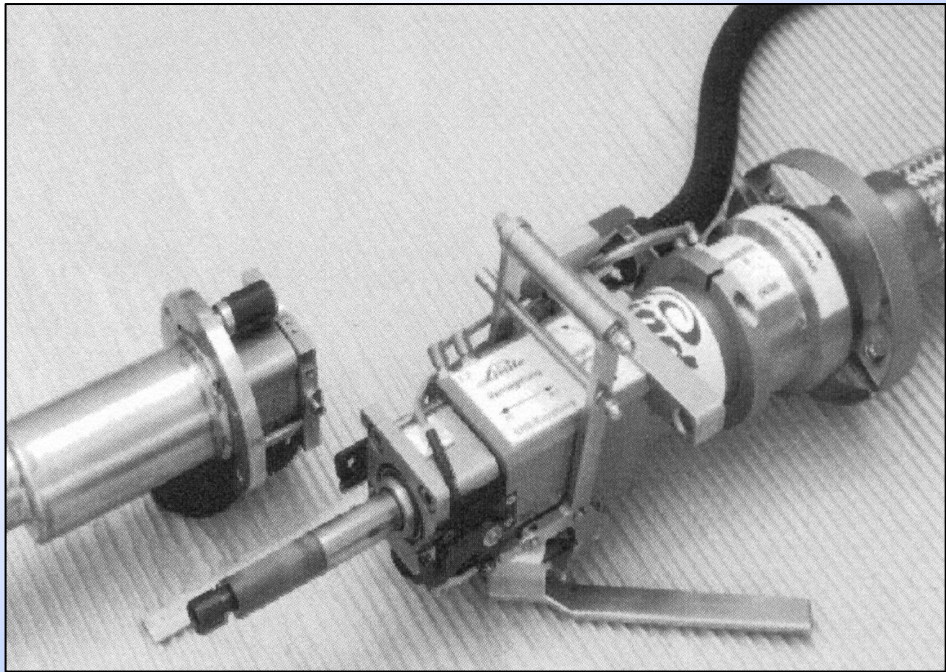
LH_2 Tank to supply both liquid as gas



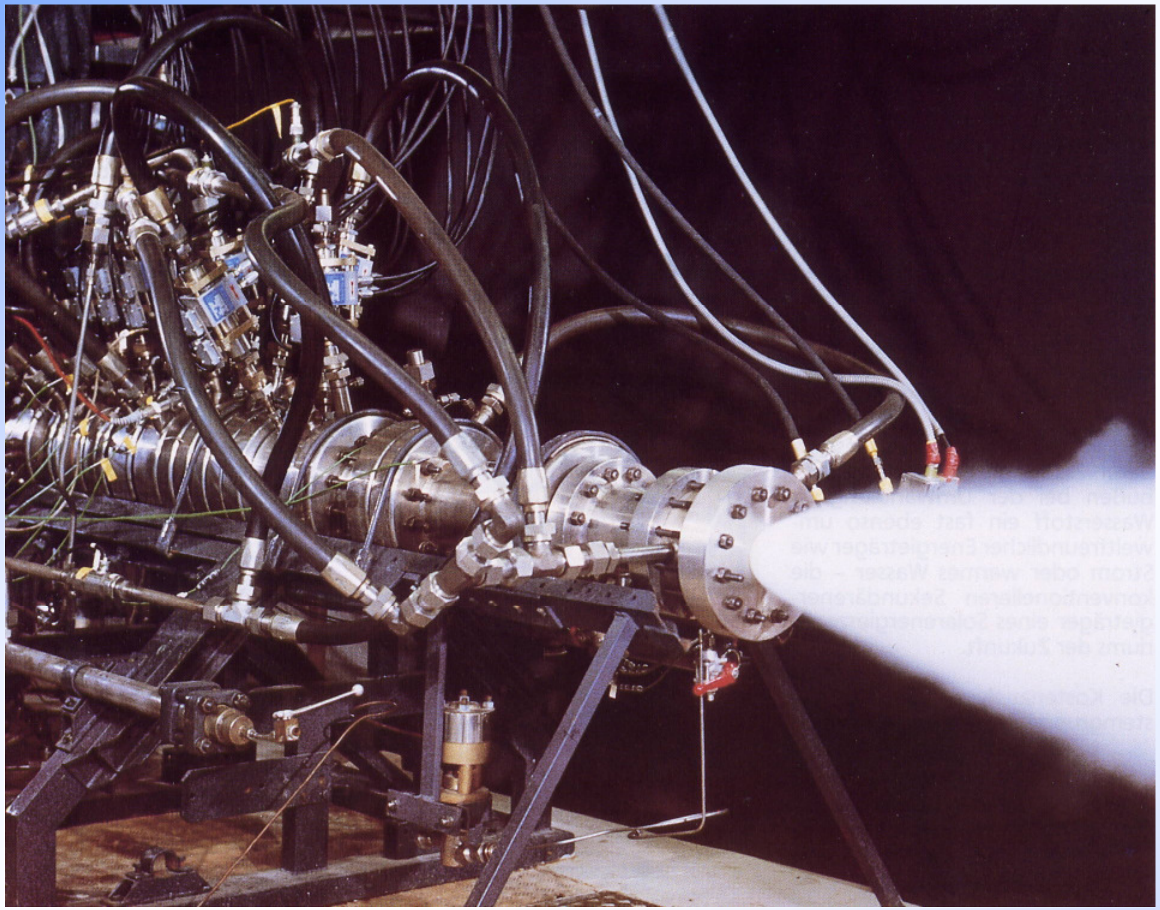
Quelle: Linde AG

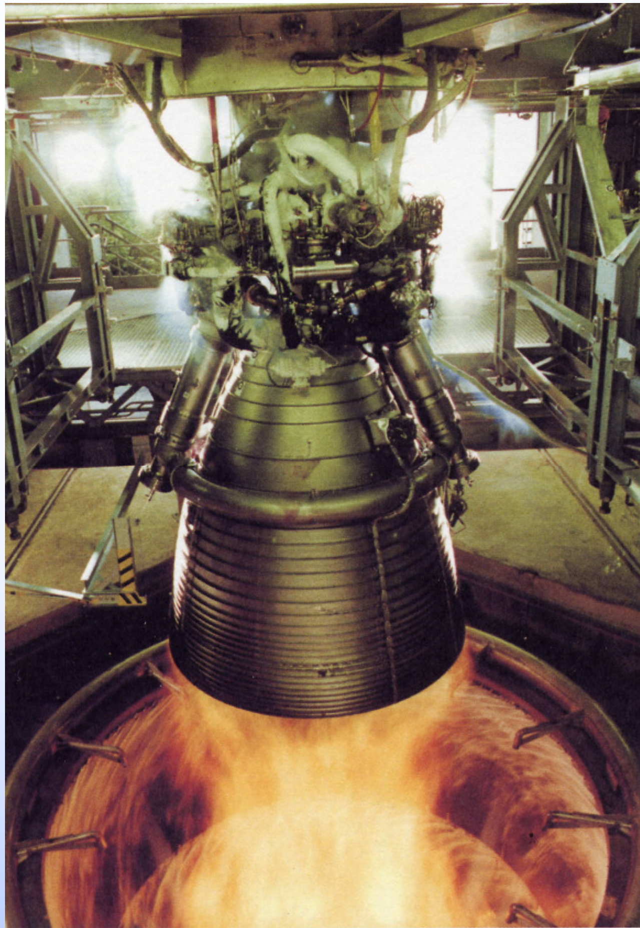
Refueling Process





DLR H_2/O_2 Steam Generator

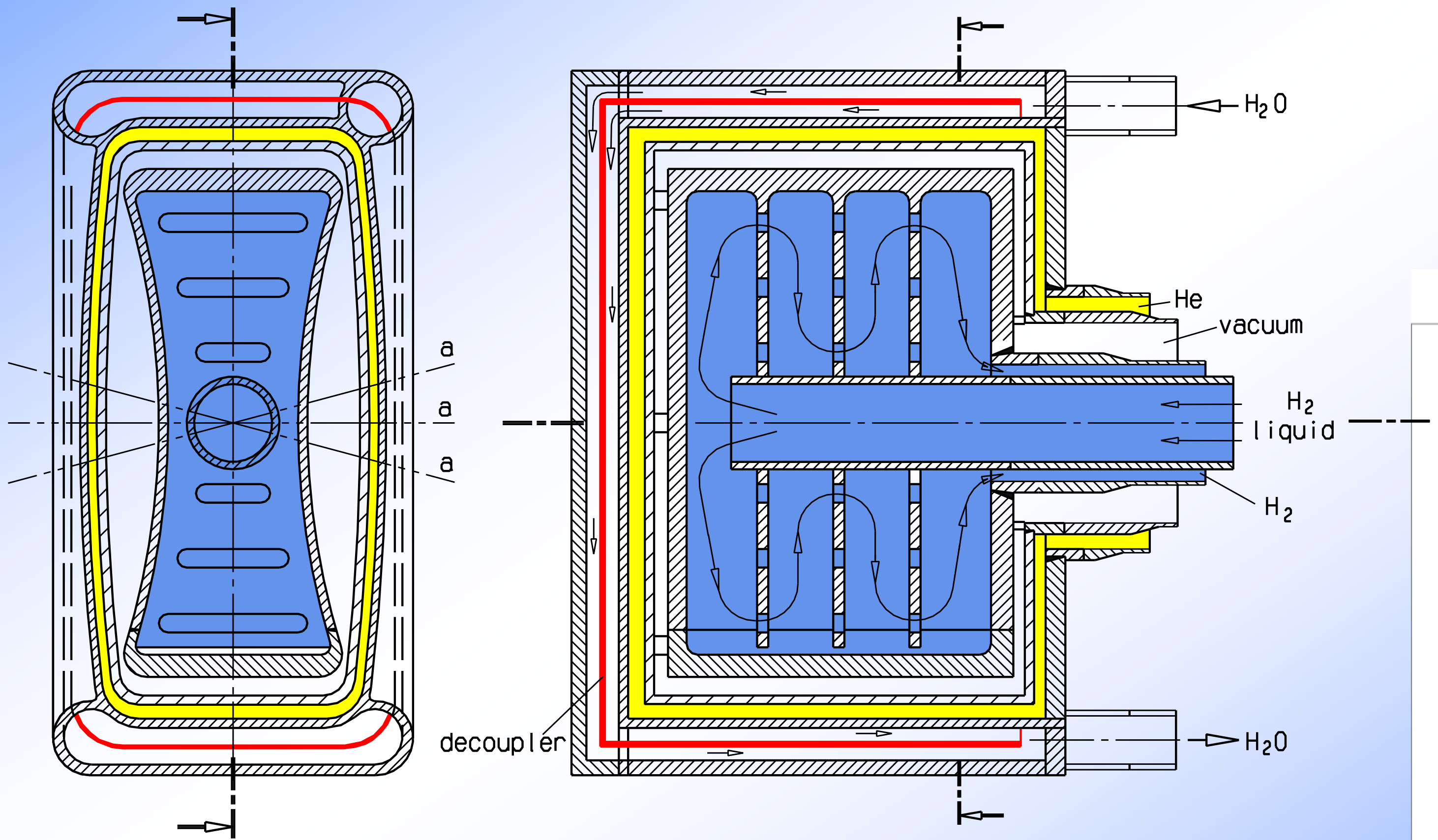




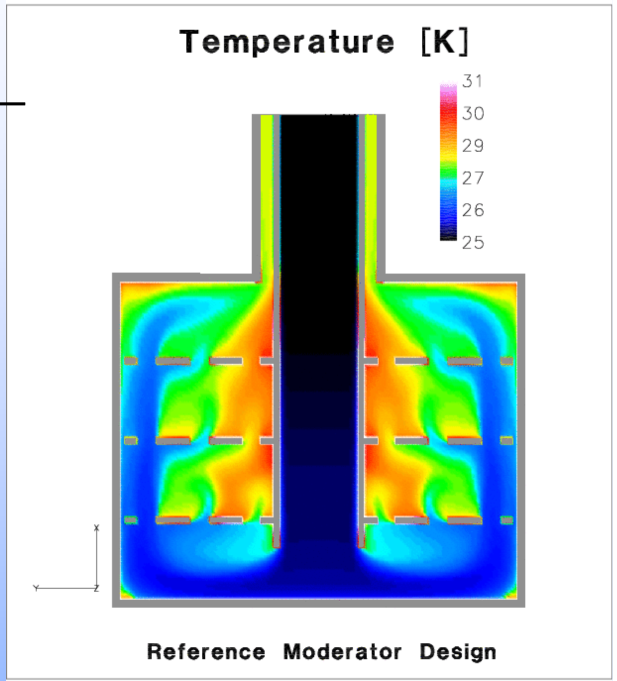
DLR Testing of Vulcain Engine

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

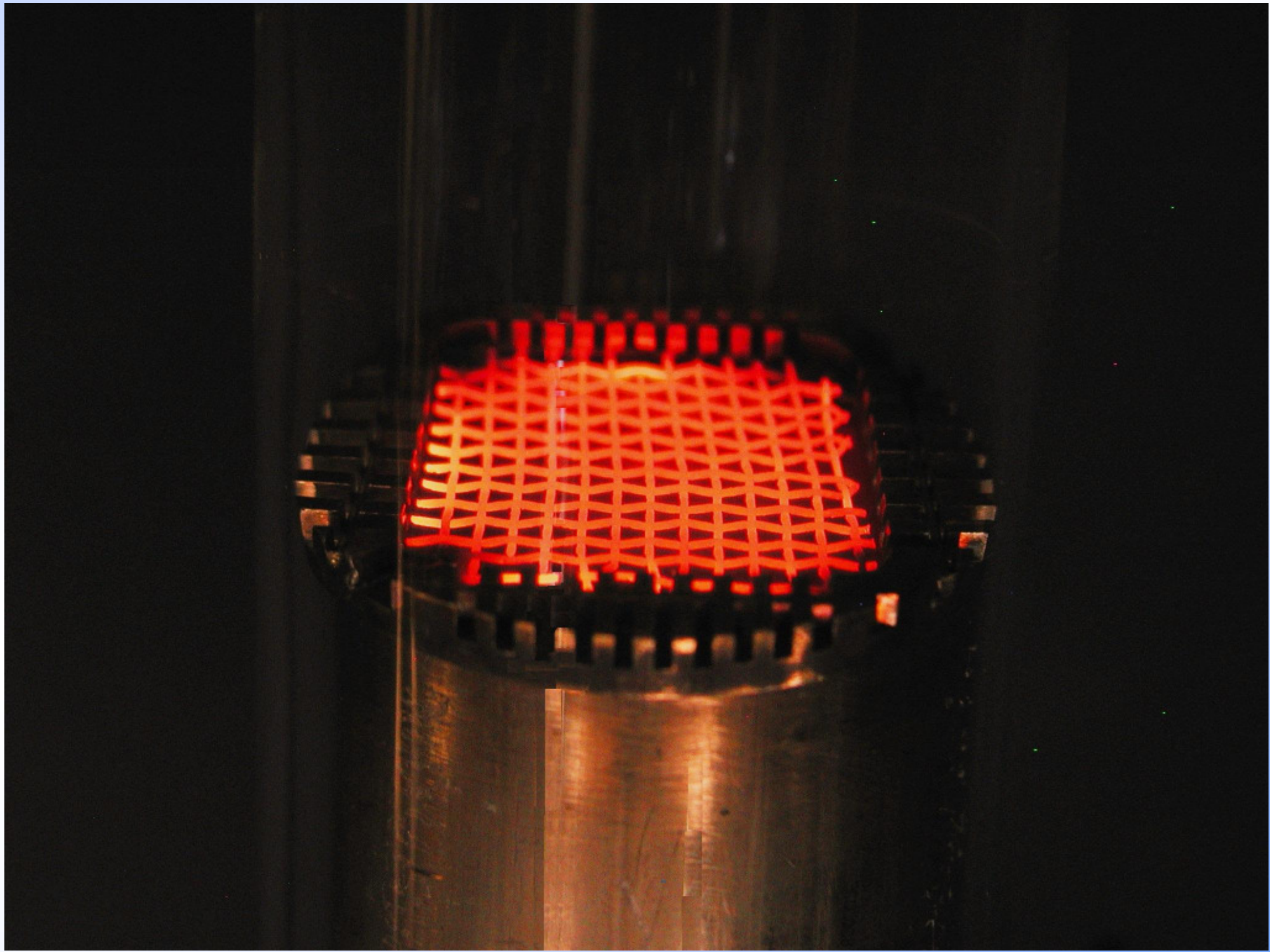
Supercritical H_2 als Cold Neutron Moderator



Horizontal (left) and vertical (right) cuts through the chamber for the supercritical H_2 moderator (gaps and walls enlarged), a: center line of beam tubes



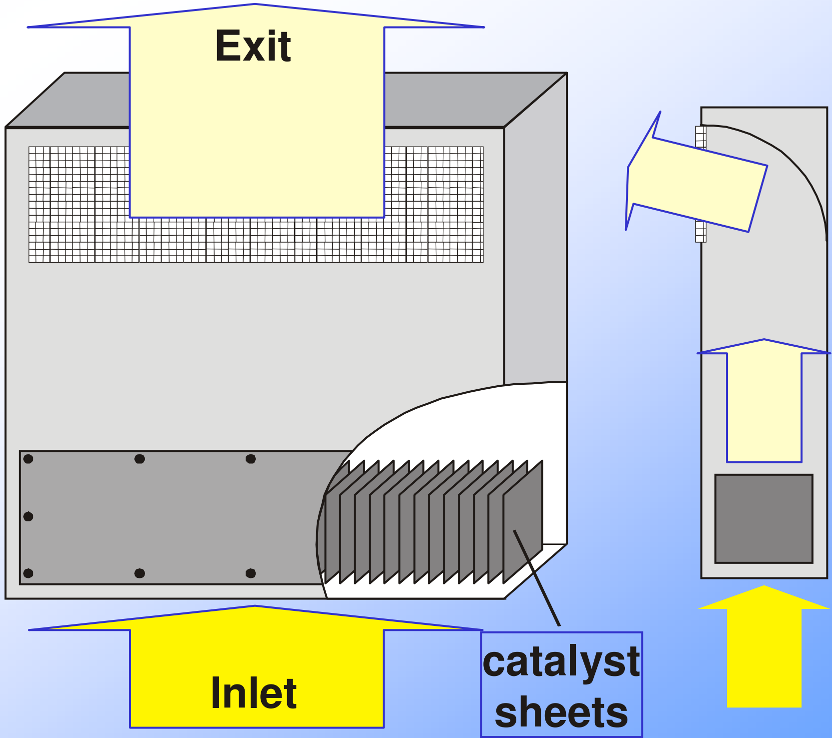
Passive Auto-Catalytic Recombiners



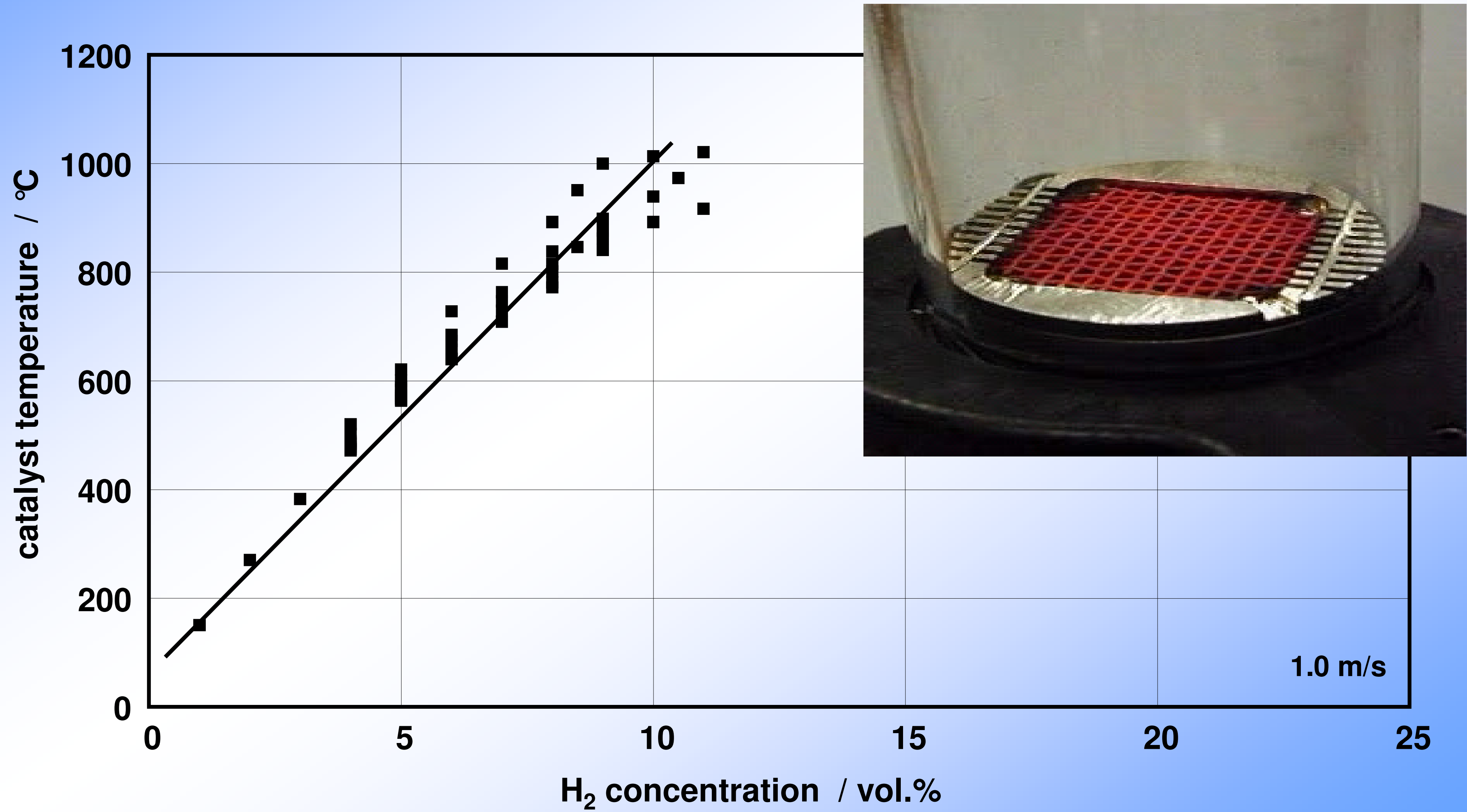
Reinecke et al.

Passive Auto-Catalytic Recombiner (PAR)

- PAR: flameless conversion of H_2 even at concentrations as low as 1-2 vol.% at ambient temperatures
- Installation in numerous European LWR since the 1990s

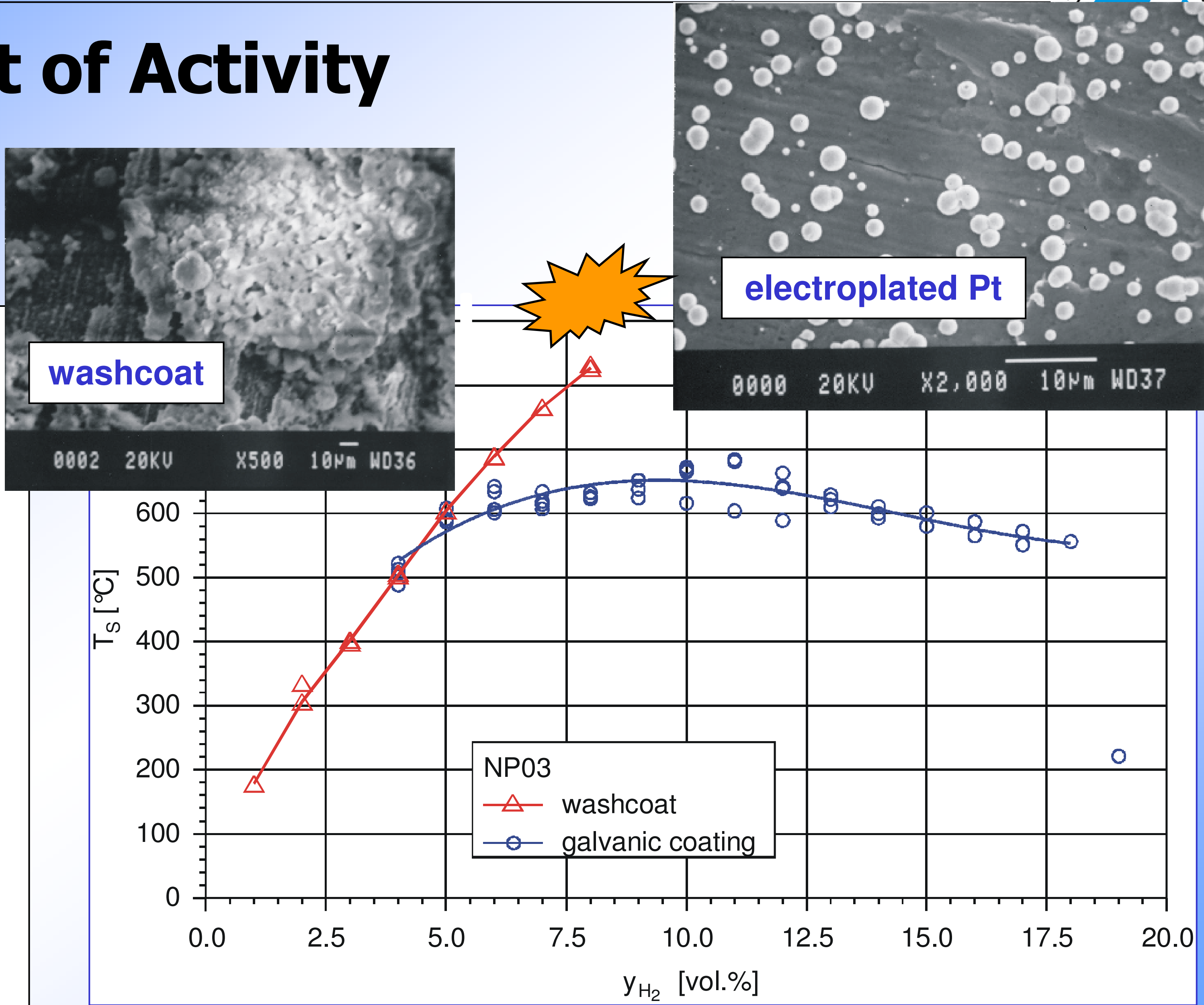


Catalyst Temperature on Washcoat Meshes



Adjustment of Activity

- Limitation of catalyst temperature
- Adjustment of catalytic activity
- Combination with passive cooling elements

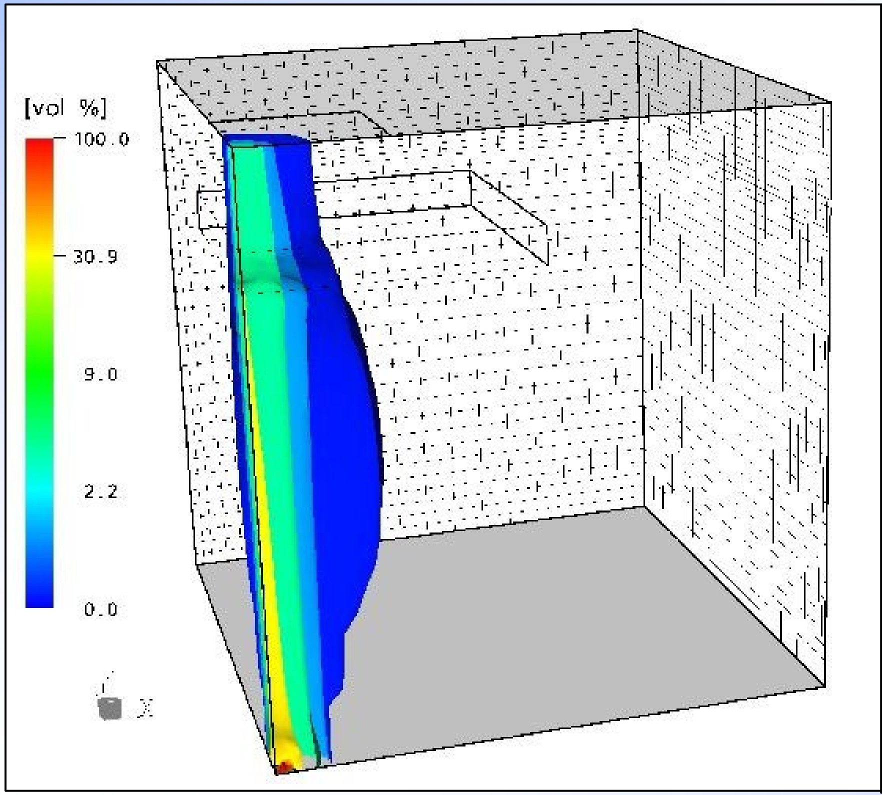


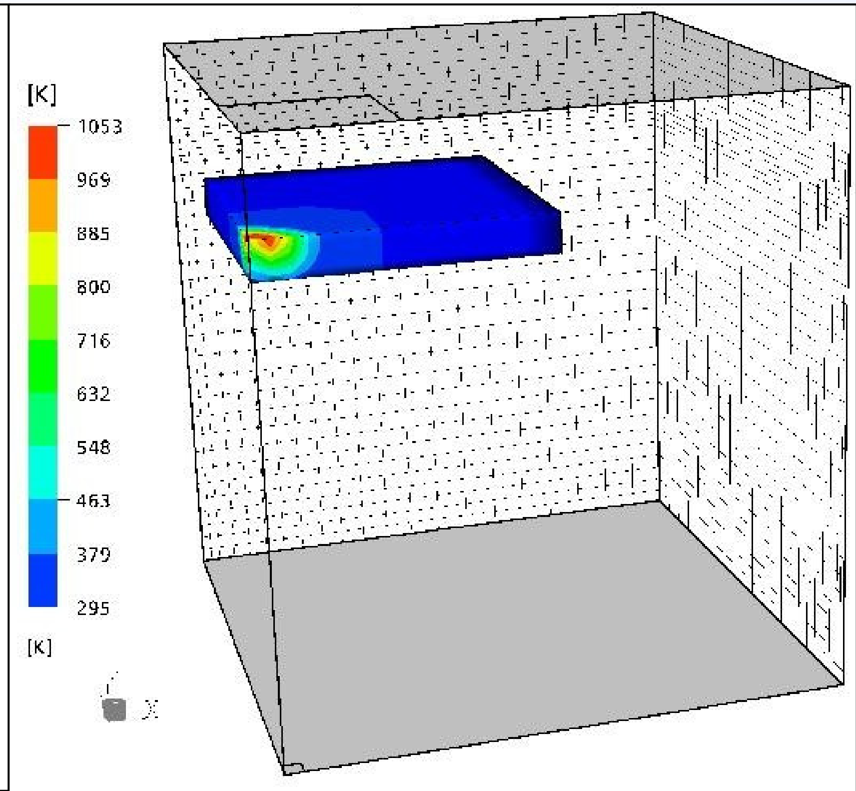
Catalyst Temperature vs. H_2 Concentration

CFX Application: Recombiner in a Garage

H_2 concentration

Temperature distribution

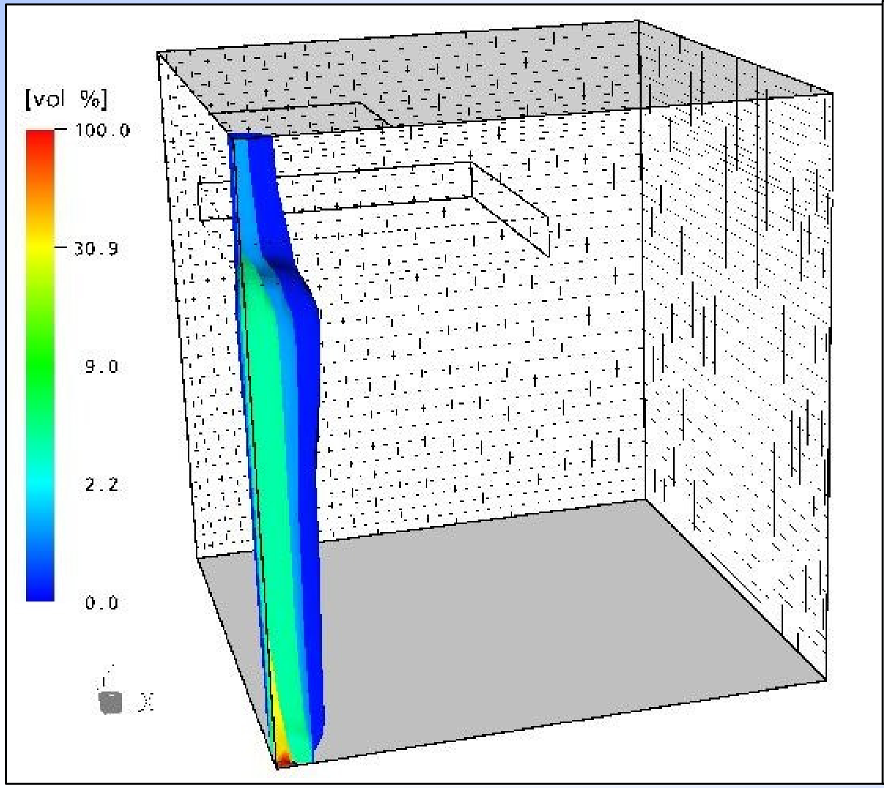


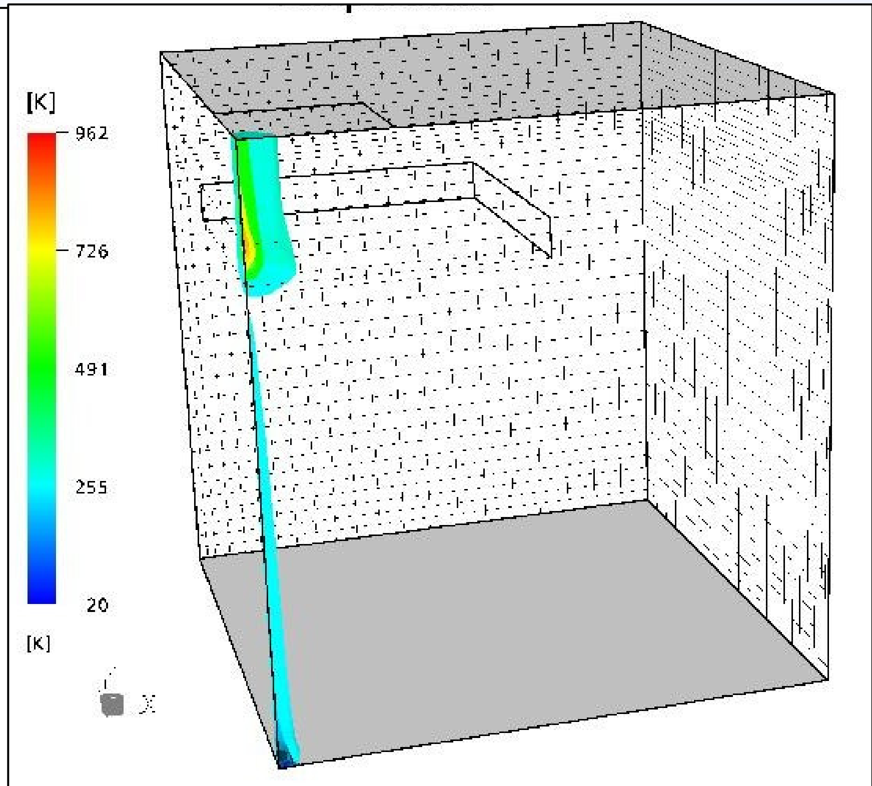


Source: H_2 gas @ 300 K

CFX Application: Recombiner in a Garage

H_2 concentration **Temperature distribution**





Source: H_2 gas @ 20 K

End
Part 1