Long Term ZBO(Zero-boil-off) Liquid Hydrogen Storage Tanks

Task 2. Hydrogen Storage Systems

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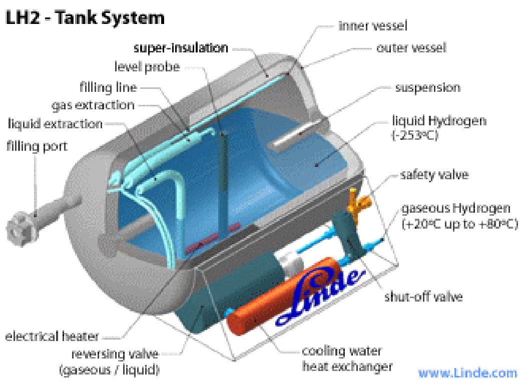
Start Date =January 2003
Planned Completion = December 2006

Research Goals and Objectives

- To develop a long-term ZBO (zero-boil-off) LH_2 storage system combining **densified liquid hydrogen and passive/active cooling** technologies.
  - Development of a 150 L capacity densified liquid hydrogen test facility which is capable of liquefying, densifying hydrogen through a GM cryocooler and unique heat pipe design.
  - Development of vapor cooled shield(VCS) with inline para-to-ortho hydrogen converter to minimize boil-off loss from LH2 storage tank.
  - Development of a Joule-Thompson expansion system to increase densification rate in the densifier, and to expand boil-off gas in the VCS of storage tank.

Relevance to Current State-of-the-Art

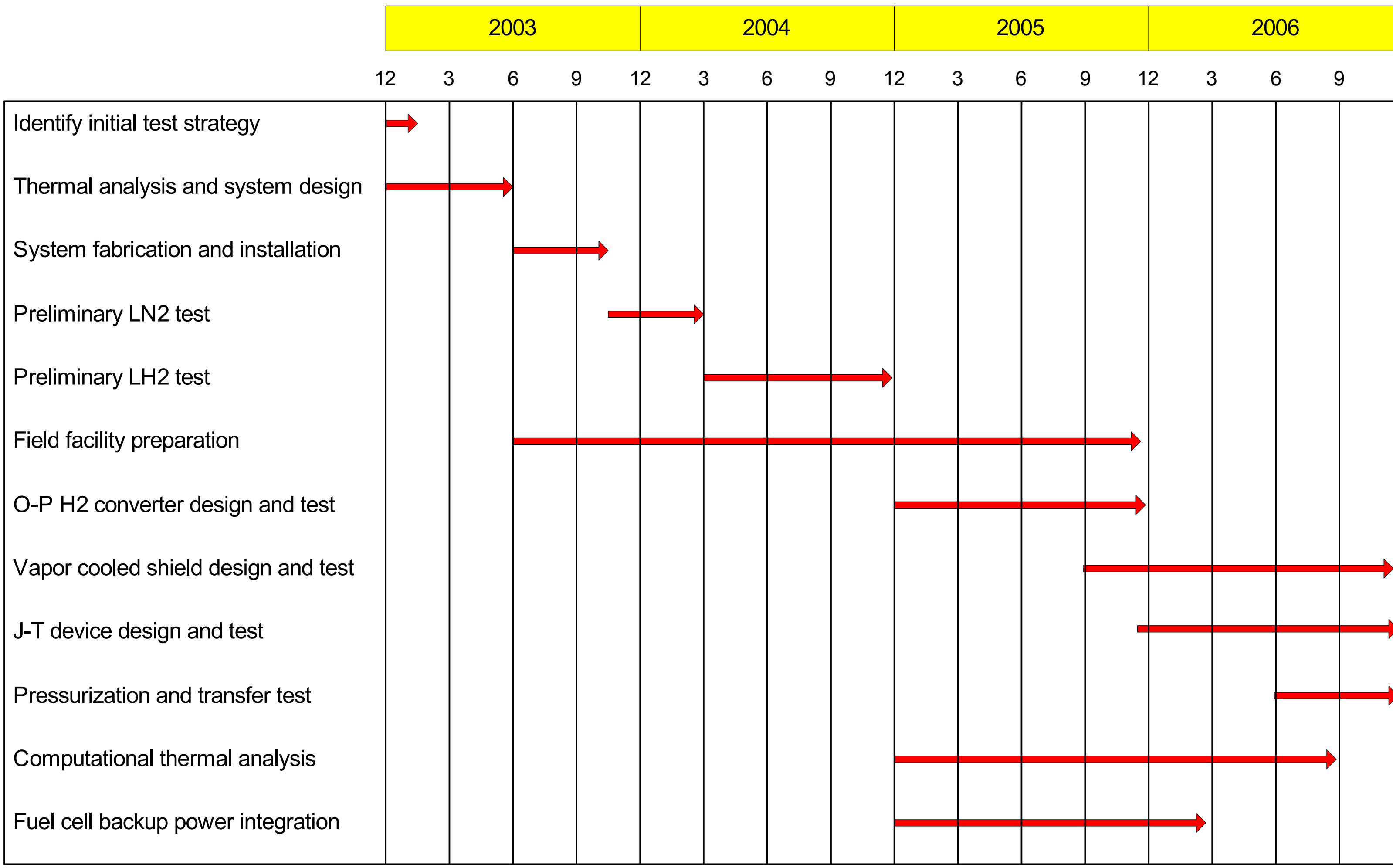
- On-board hydrogen fuel storage for transportation : DOE, BMW, GM, Honda, Linde etc.



Relevance to NASA

- NASA GRC is interested in long term airborne hydrogen storage, transmission or distribution systems applied to LEAP (low emission alternative power) and HALE ROA (High altitude long endurance remotely operated aircrafts) Programs. LH_2 is one of candidates where H_2 is consumed rather than regenerated in the aircraft applications.
- LH_2 tank systems are expected to provide airborne LH_2 storage for up to 30 days duration by more than 1,000 Lbs of LH_2 (~450 kg, 1,700 gal) at altitudes as high as 70,000 ft.
- Durable, light weight, high gravimetric energy density, high thermal control performance LH_2 storage/feed systems are required.

Budget, Schedule and Deliverables



Anticipated Technology End Use

- Long term airborne hydrogen storage, transmission or distribution systems applied to LEAP (low emission alternative power) and HALE ROA (High altitude long endurance remotely operated aircrafts) Programs.
- On-board hydrogen fuel storage for transportation
- Low loss cryo-propellant storage system (1-3%/month) in Low Earth Orbit (LEO) mission
- ZBO system for Long term exploration mission (2 year+) to eliminate the need for oversized tanks and extra propellant. Each pound of propellant tank mass saved is directly tradable for payload mass.
- Cryogenic Fluid Management (CFM) plays important role in exploration systems for Earth-to-Orbit Transportation, manned missions to the Moon and Mars, Planetary Exploration, and In-Situ Resource Utilization (ISRU).
- Infrared and x-ray astronomy, biological sciences, and fundamental investigations into the origins of our universe.

Densified liquid hydrogen system

- Densified LH2, which is ~6% denser than normal boiling point LH2
  - more hydrogen fuel can be stored in the same tank volume. As a result, airborne time can be increased.
- Densified hydrogen has lower sensible heat and higher latent heat
  - longer storage time is expected before evaporation.

For m=1000 lb of liquid hydrogen fuel,

T	ρ	Tank volume	[1]Heat loss	Sensible heat, $m*h_f$	Latent heat, $m*h_{fg}$	Storage time
(K)	(m^3/kg)	(gal)	(W)	(MJ)	(MJ)	(hr)
20	71.11	1685	~ 337	121.2	202.9	167
16	75.12	1595	~ 319	105.9	205.1	179
Δ	5.6% ↑	5.3% ↓	> 5.3% ↓	15.3 ↓	2.2 ↑	12 ↑

[1]Heat loss per volume is assumed to 0.2 W/gal (=8W/150L)

Hydrogen liquefaction and ZBO storage test facility at FSEC

ZBO (zero-boil-off) LH2 storage system

To minimize or to completely eliminate boil-off losses from LH2 storage tank and maximize airborne time with single storage filling, it's essential to employ both passive and active cooling techniques.

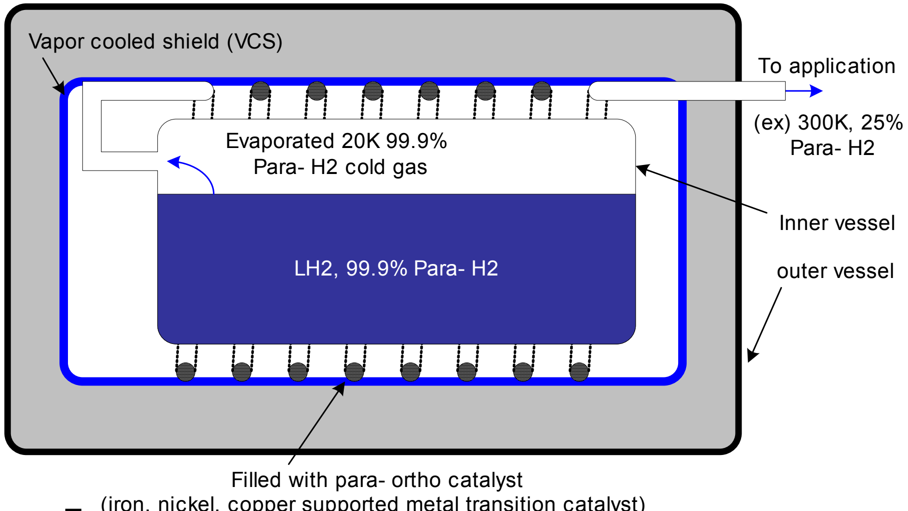
Passive cooling

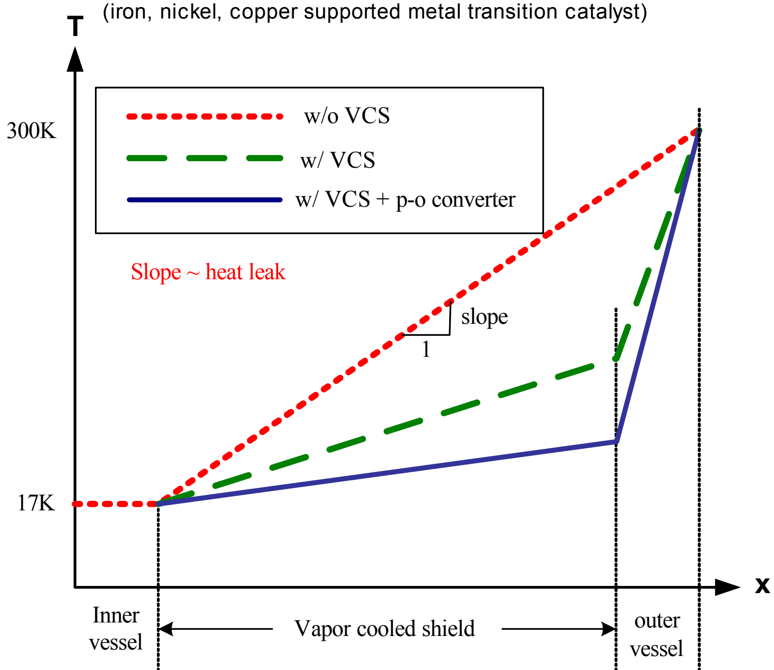
- combination of VCS (vapor-cooled radiation shields) and in-line para-to-ortho converter can minimize boil-off losses from LH2 storage tank.

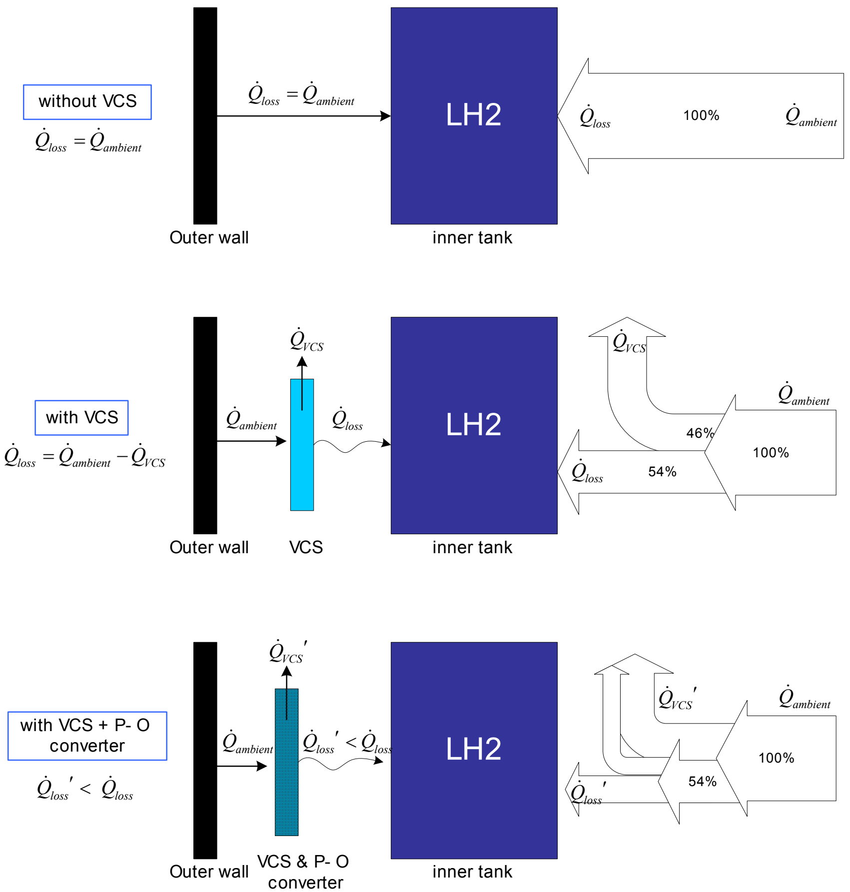
Active Cooling

- Integration of a Joule-Thompson expansion device in the hydrogen densifier to increase densification rate, and to expand boil-off gas to vapor cooled shield in the storage tank.

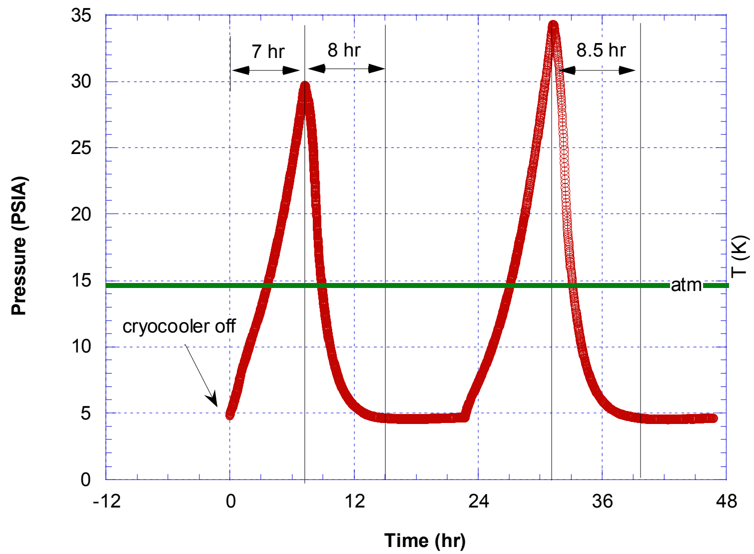
Vapor-cooled Radiation Shield (VCS) with para-ortho converter

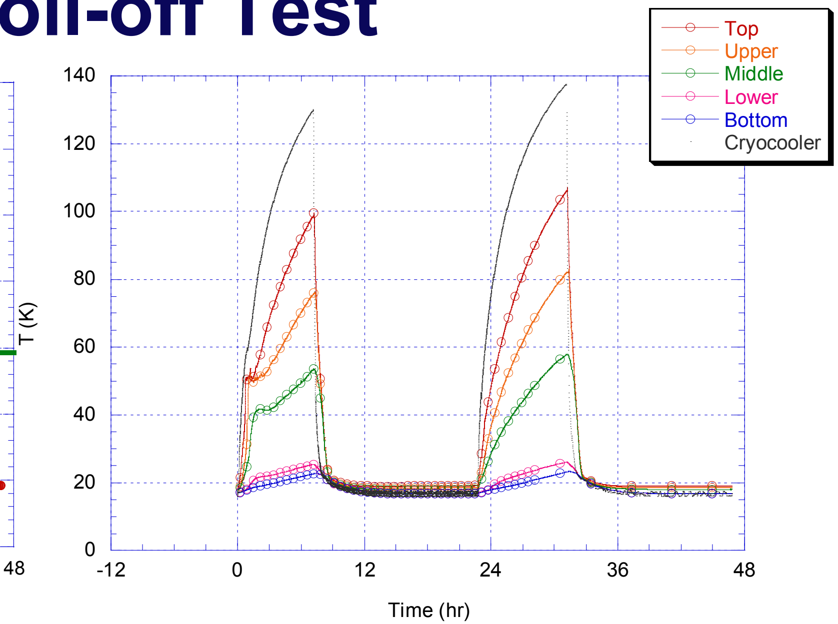






LH2 Boil-off Test



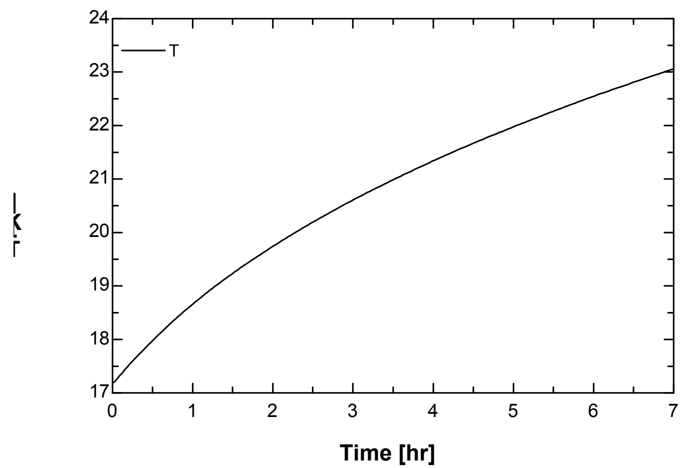


Energy conservation of Storage Tank

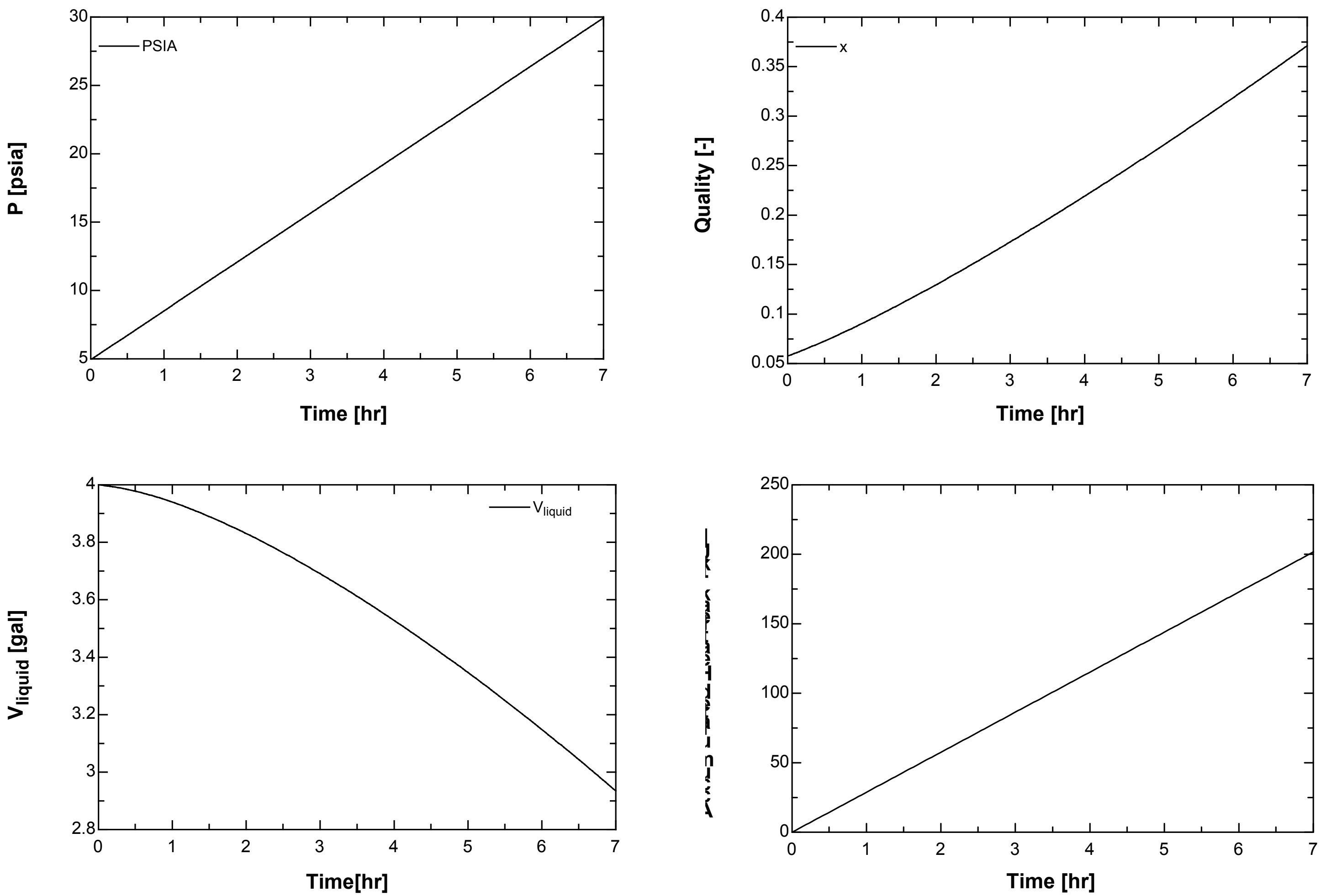
$$\frac{dU}{dt} = \dot{Q}_{leak}$$

$$or \text{ for consant } \frac{dP}{dt} \;\&\; \dot{Q}_{leak},$$

$$\frac{dh(T,P)}{dt} = \frac{1}{m}\left(V\frac{dP}{dt} + \dot{Q}_{leak}\right)$$

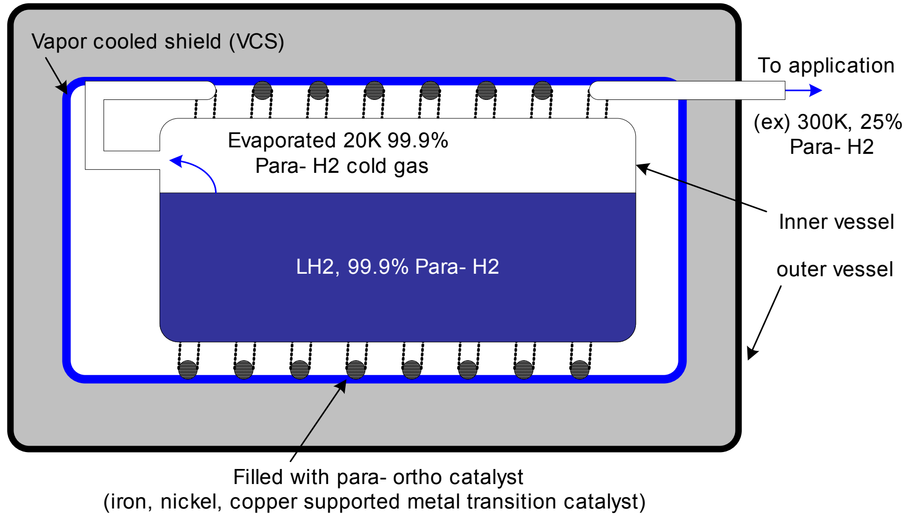


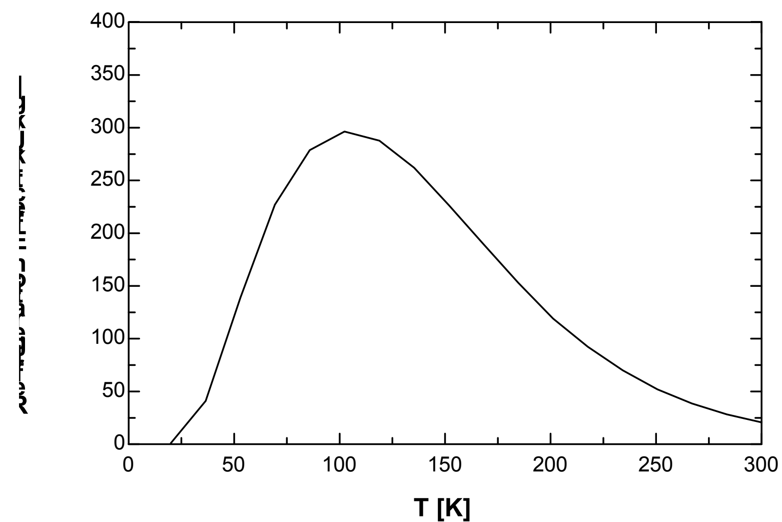
LH2 Boil-off Estimation



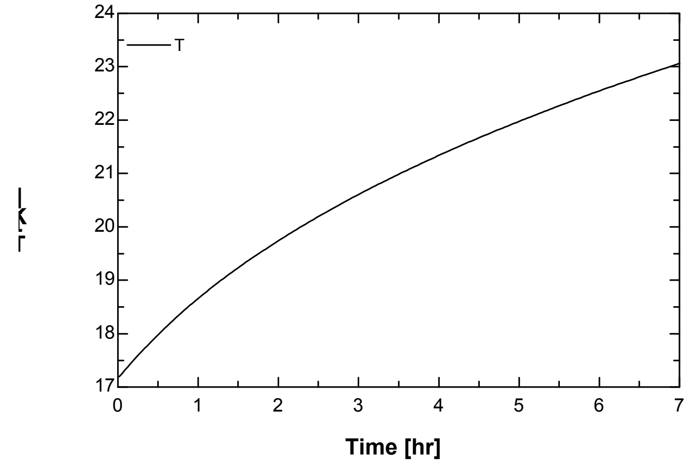
Refrigeration Effect of Para-ortho Conversion

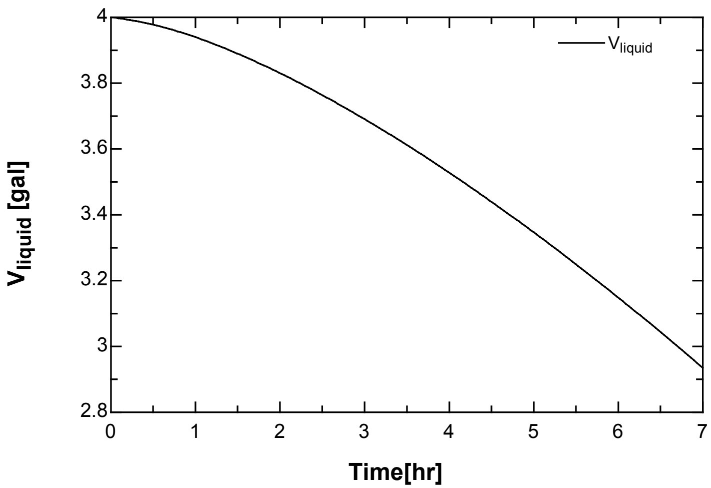
T [K]	para-H_2 concentration [%]	Heat of conversion [kJ/kg]	Refrigeration effect [kJ/kg]
20	99.82	527.1	0.9436
40	88.73	527.1	59.42
60	65.57	525.5	180.9
80	48.54	513.9	264.5
100	38.62	481.7	295.6
120	32.99	427.2	286.3
140	29.65	358.9	252.5
160	27.71	288	208.2
180	26.54	222.4	163.3
200	25.97	163.8	121.2
220	25.54	119.5	88.95
240	25.32	84.66	63.22
260	25.2	58.75	43.95
280	25.11	40.4	30.26
300	25.07	27.56	20.65



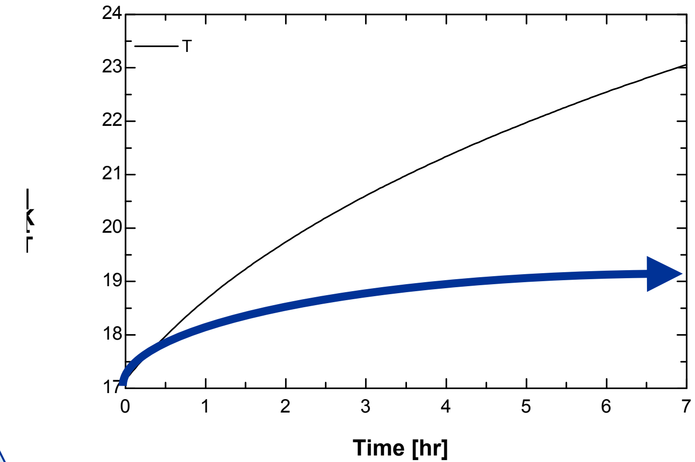


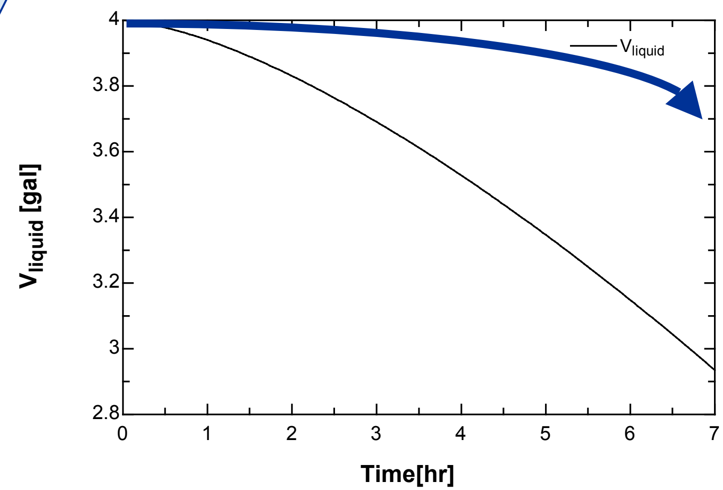
w/o VCS



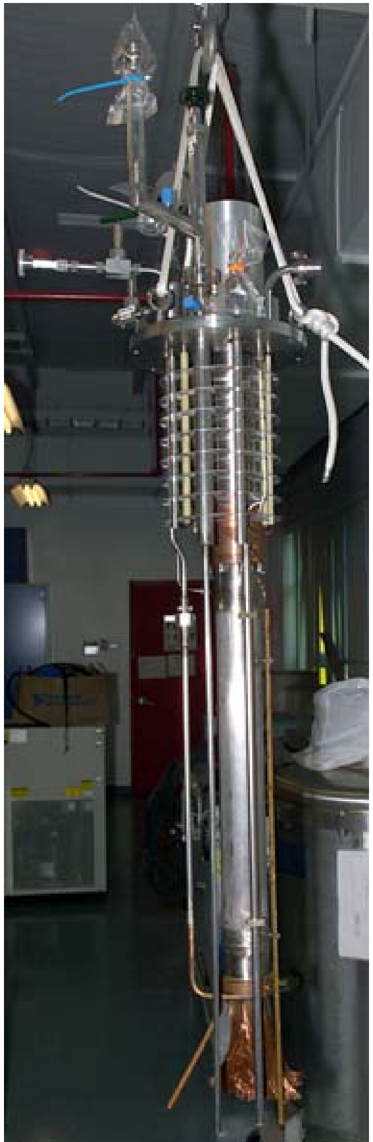


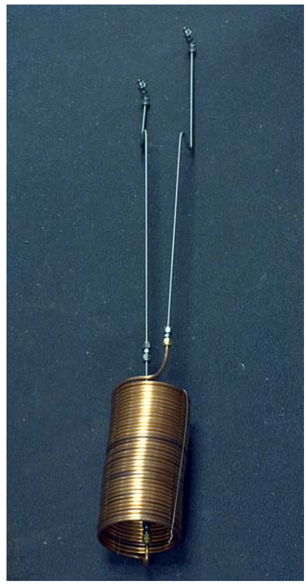
w/ VCS + p-o converter



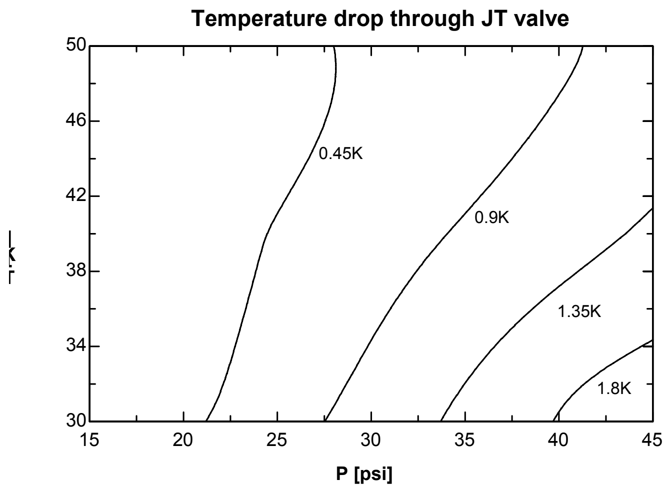


Ortho-Para H2 Converters

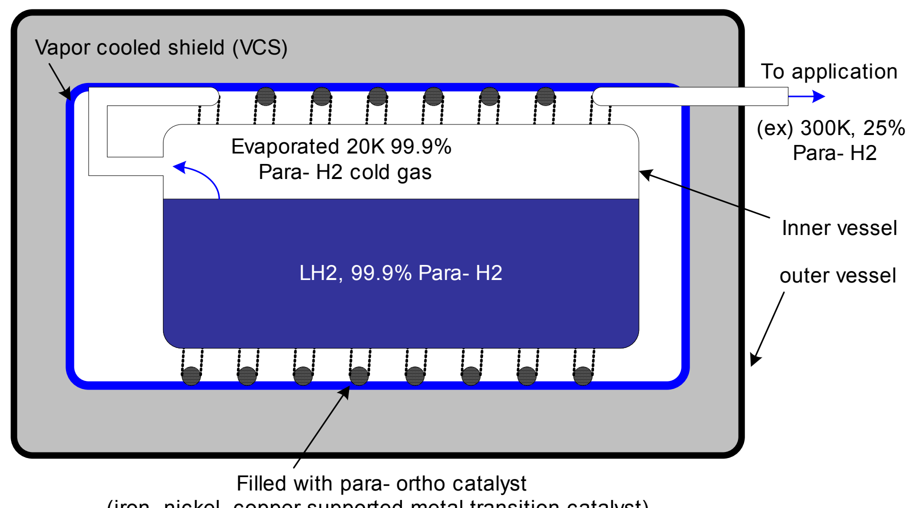




Active cooling with miniature JT expansion device




(Courtesy : The Lee Company)



Future Plans

- Densified liquid hydrogen system
  - To produce larger quantity of LH2 at the field facility
  - To perform in-line LN2 precooler and ortho-para hydrogen converter test
  - To integrate inline JT expansion device in the densifier
  - To integrate fuel cell powered backup power system.

- Development of vapor cooled shield (VCS) tank with para-to-ortho H2 converter
  - To design and fabricate 10 Gallon VCS LH2 storage tank with inline para-to-ortho H2 converter
  - To integrate inline JT expansion device in the VCS
  - To conduct catalysts performance test for para-to-ortho hydrogen conversion or interconversion between ortho-H2 and para-H2 (ex. Iron, nickel, copper supported metal transition catalysts to increase para-to-ortho conversion)
  - To perform pressurization test by transferring densified LH2 into VCS tank in sub-atmospheric environment, and conduct boil-off reduction test.