Thermal Endurance and Cryogenic Capable Pressure Vessel Designs for a (L)H_2 Fueled Toyota Prius

Master's Presentation

Ryan Shelby
University of California at Berkeley

May 21, 2008

Berkeley Expert Systems Technology

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Agenda

- Main Tasks
- Motivation: Boulders or Pebbles
- Background
- Thermodynamic Model
- Thermodynamic Results
- FEA of Pressure Designs
- Results of FEA
- Summary of Completed Work
- Future Plans
- Q/A?

Main Tasks

- Develop a thermodynamic model to gauge heat leak into a cryogenic capable pressure vessel

- Determine which mode of heat transfer is responsible for heat leak

- Create pressure vessel designs with minimal surface to volume ratios

- Perform finite element stress analyses on pressure vessel designs

Motivation: US 2005 Carbon Dioxide Emissions

- 84% of total US greenhouse gas emissions came from carbon dioxide emissions

- 33% of U.S. energy-related carbon dioxide emissions in'05 came from Transportation sector

	Carbon dioxide	Carbon
• US 2005 Emissions: (Million Metric Tons)	6,008.6	1,638.7
• Transportation Sector: (Million Metric Tons)	1,958.6	534.2

Source: http://www.eia.doe.gov/oiaf/1605/archive/gg06rpt/summary/carbon.html

Motivation: Boulders or Pebbles in the River?

- Climate change is a runaway train
- It is all our fault
- There is not much we can do about

- Carbon dioxide forms approximately 0.04% of the Earth atmosphere
- Our impact on the environment is negligible
- We don't need to worry about climate change

Motivation: Boulders or Pebbles in the River?

- Climate change is naturally occurring process

- However, human activities do contribute to climate change

- Climate change is manageable

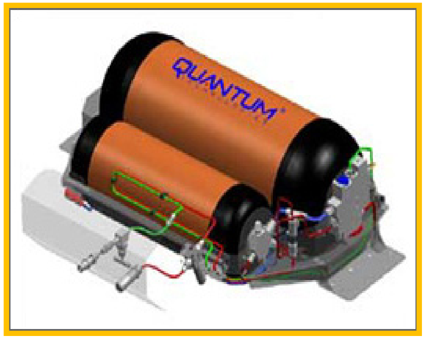
- Must provide tools and technologies to address this issue

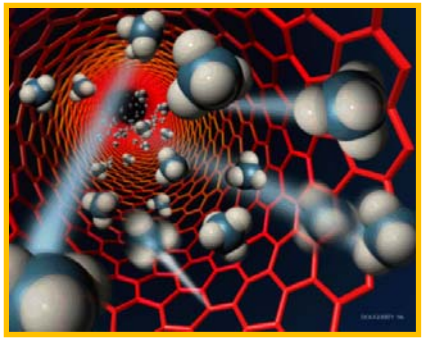
- Hydrogen powered vehicles are one option

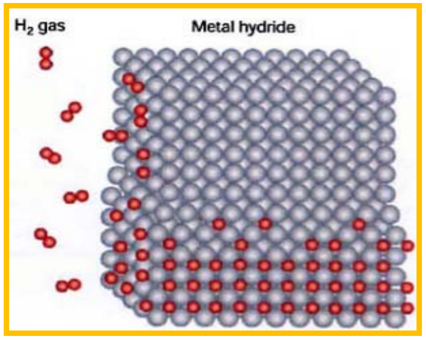
Background: H_2 Storage Options

- There are four automotive H_2 storage technologies:
- compressed gas,
- metal hydride materials,
- carbon-based materials, and
- cryogenic liquid.

- Each technology has its limitation: weight, volume, evaporation losses, or adsorption thermodynamics

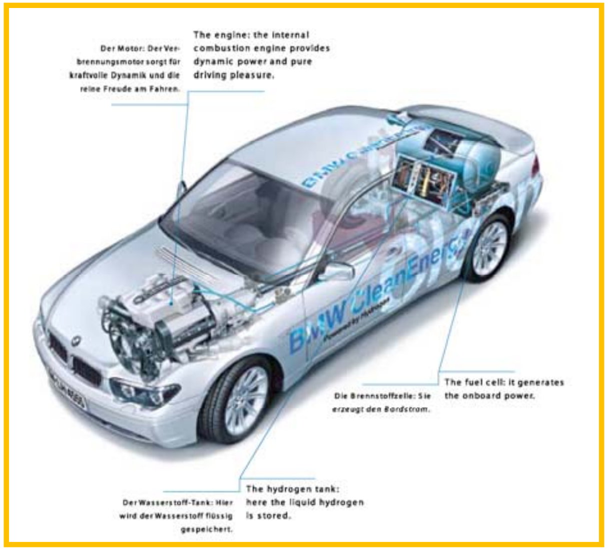






Background: BMW Prior H_2 Storage Research

- 7 generations of prototyped LH_2 cars.
- Current design:
  - Stores 8 kg of LH_2
  - Maximum operating pressure of 87 psi
  - ~17 hours of thermal dormancy

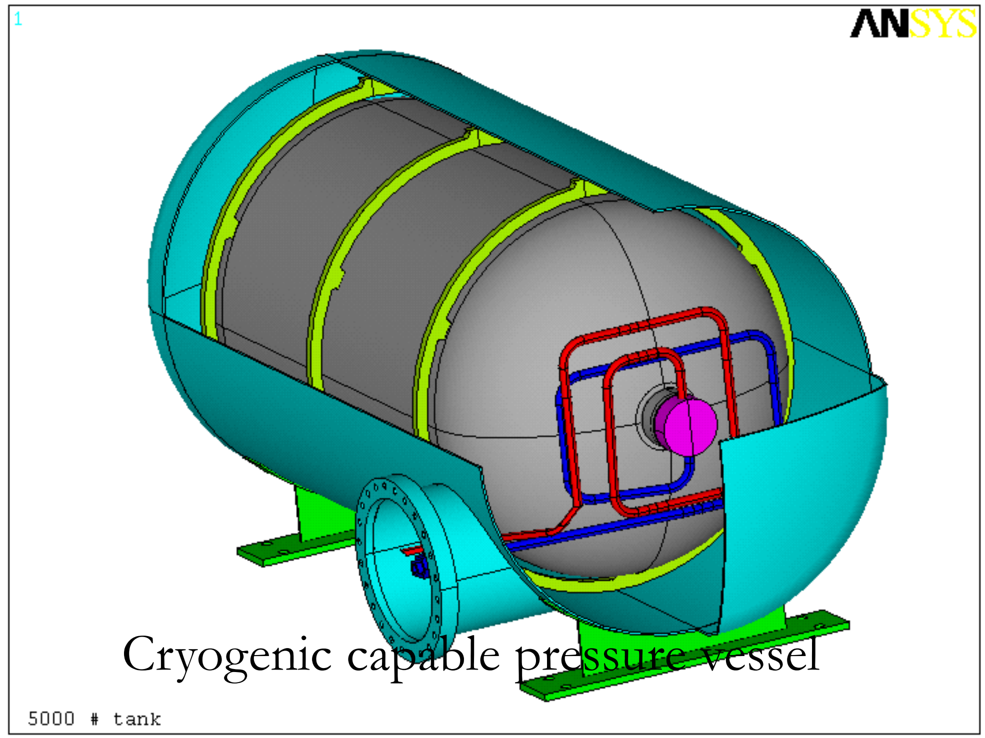


Source: http://www.wired.com/cars/energy/news/2006/11/72100?currentPage=1

Background: LLNL's Recent H_2 Storage Research

- LLNL's 151 liter cryogenic capable pressure vessel (CCPV) can store
  - LH_2,
  - compressed gaseous H_2,
  - compressed gaseous H_2 at 80K.

- CCPV Advantages: long range, compact, elimination of LH_2 evaporation, and flexible refueling options.



Cryogenic capable pressure vessel

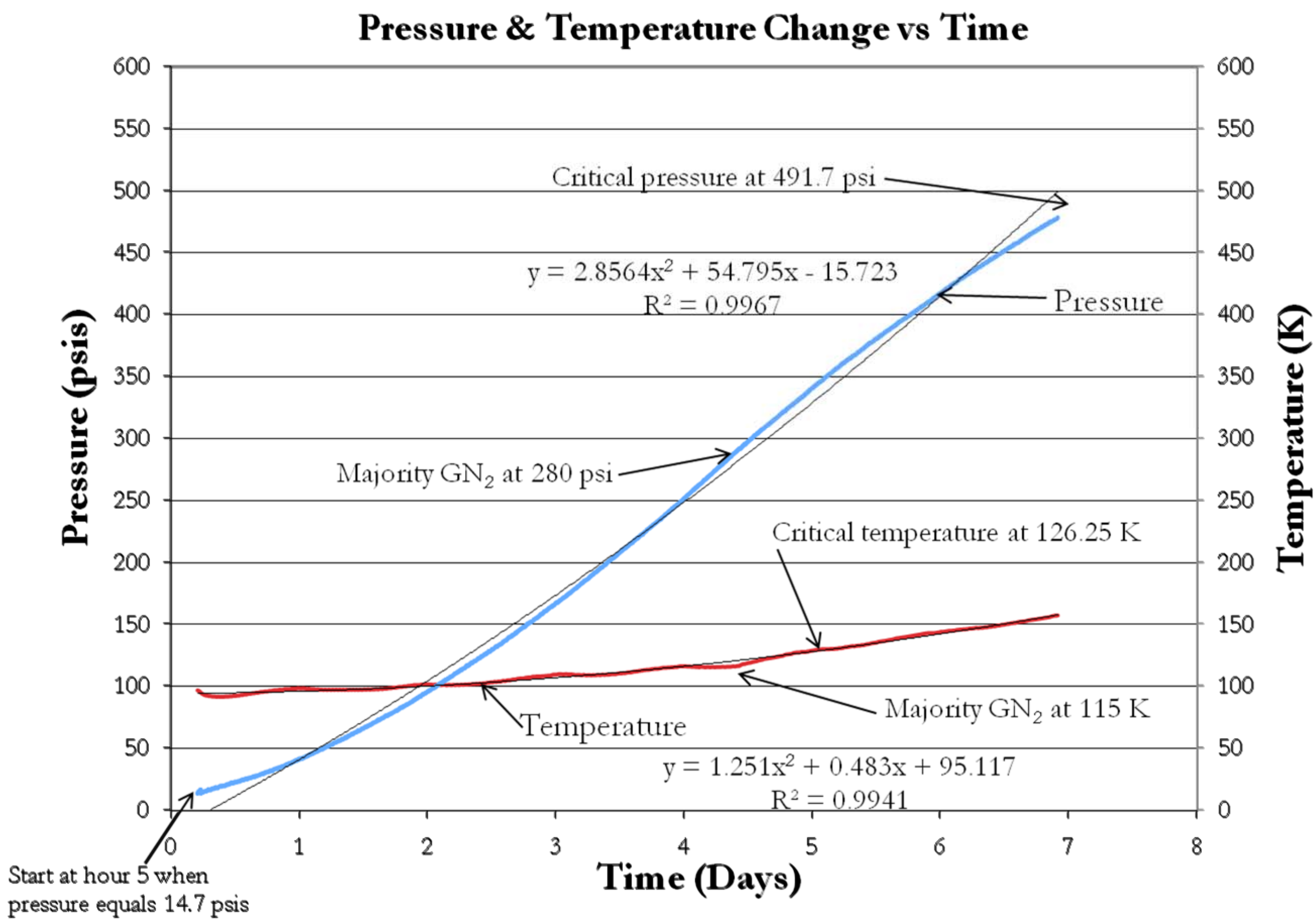
5000 psi maximum operating pressure

Methodology: Cryogenic Dormancy Test

- LN_2 as a surrogate for LH_2 during cryogenic dormancy test
- Created thermodynamic model of the CCPV using experiment data equations, REFPROP, and the Debye model
- Model estimates the both radiation and conduction heat transfer

Cryogenic dormancy test setup

Cryogenic Dormancy Experiment Results & Eqs.



Thermodynamic Model: Heat leak equations

- The change in temperature of the CCPV was derived in terms of radiation (Q_r), conduction (Q_c), and thermal mass.
- Heat added equations:

$$Radiation(Q_r) = \frac{\left[\varepsilon\sigma A\left(T^4{}_{outside} - T^4{}_{CCPV}(t)\right)\right]}{[1 + insulationlayers]}$$

$$Conduction(Q_c) = \frac{\left[kA\left(T_{outside} - T_{CCPV}(t)\right)\right]}{\Delta x}$$

- Thermal mass equation:

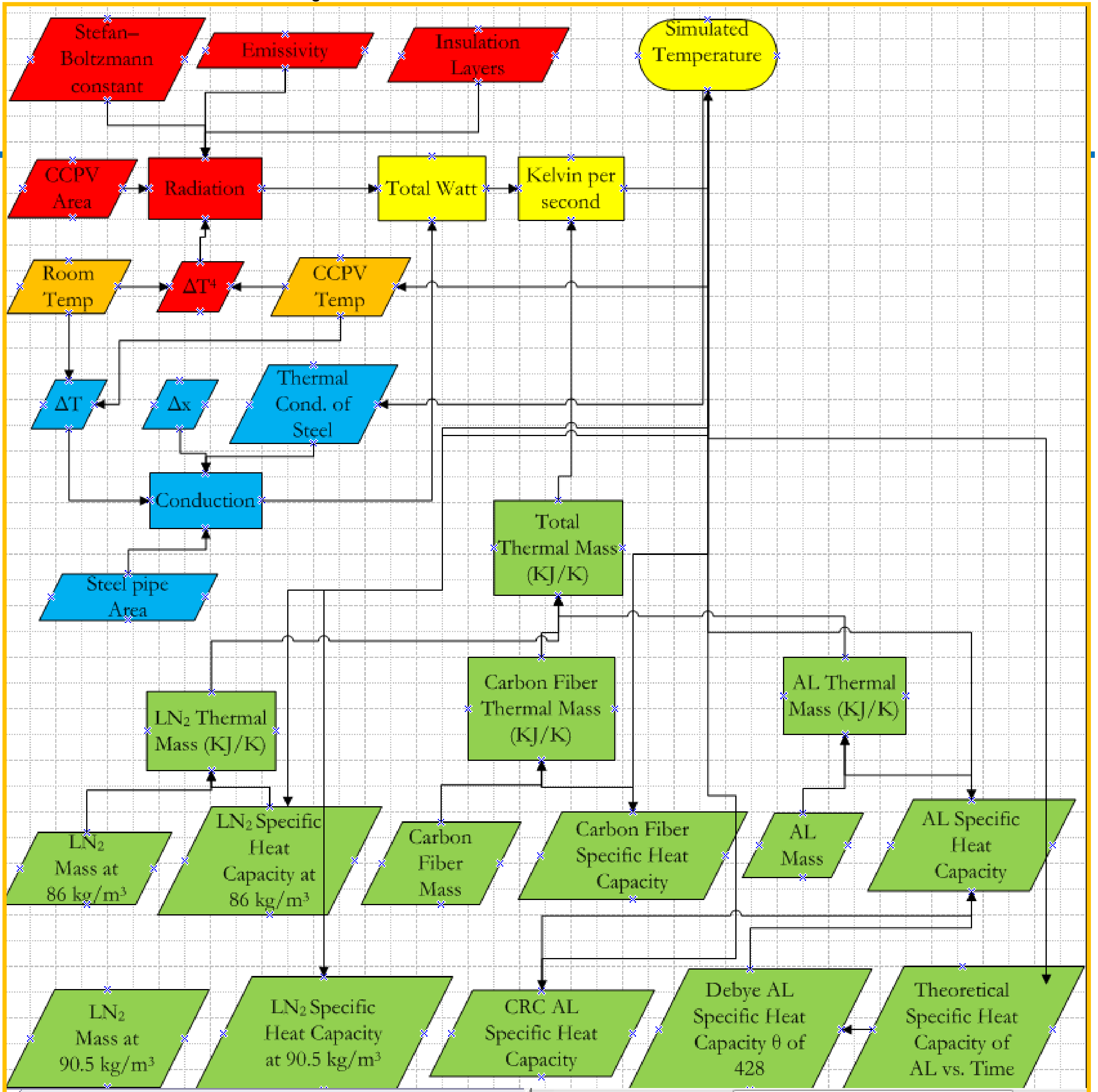
$$Thermalmass = \left[m_{Al}Cv_{Al}(t) + m_{Carbon}Cv_{Carbon}(t) + m_{LN_2}Cv_{LN_2}(t)\right]$$

- Change in temperature:

Heat conducts through both the liquid and gas fill pipe

$$Temperature(\Delta T) = \frac{(Q_r + 2Q_c)}{\left[m_{Al}Cv_{Al}(t) + m_{Carbon}Cv_{Carbon}(t) + m_{LN_2}Cv_{LN_2}(t)\right]}$$

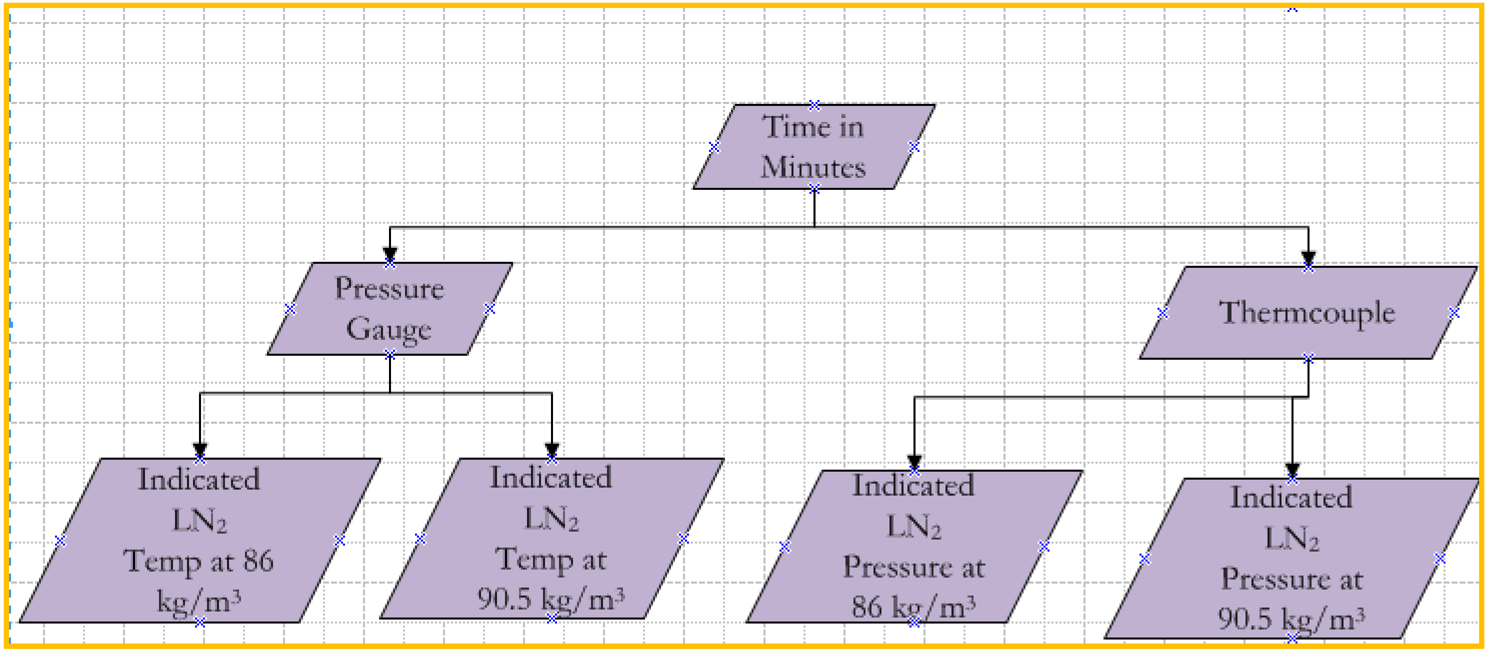
Thermodynamic Model: Flow Chart



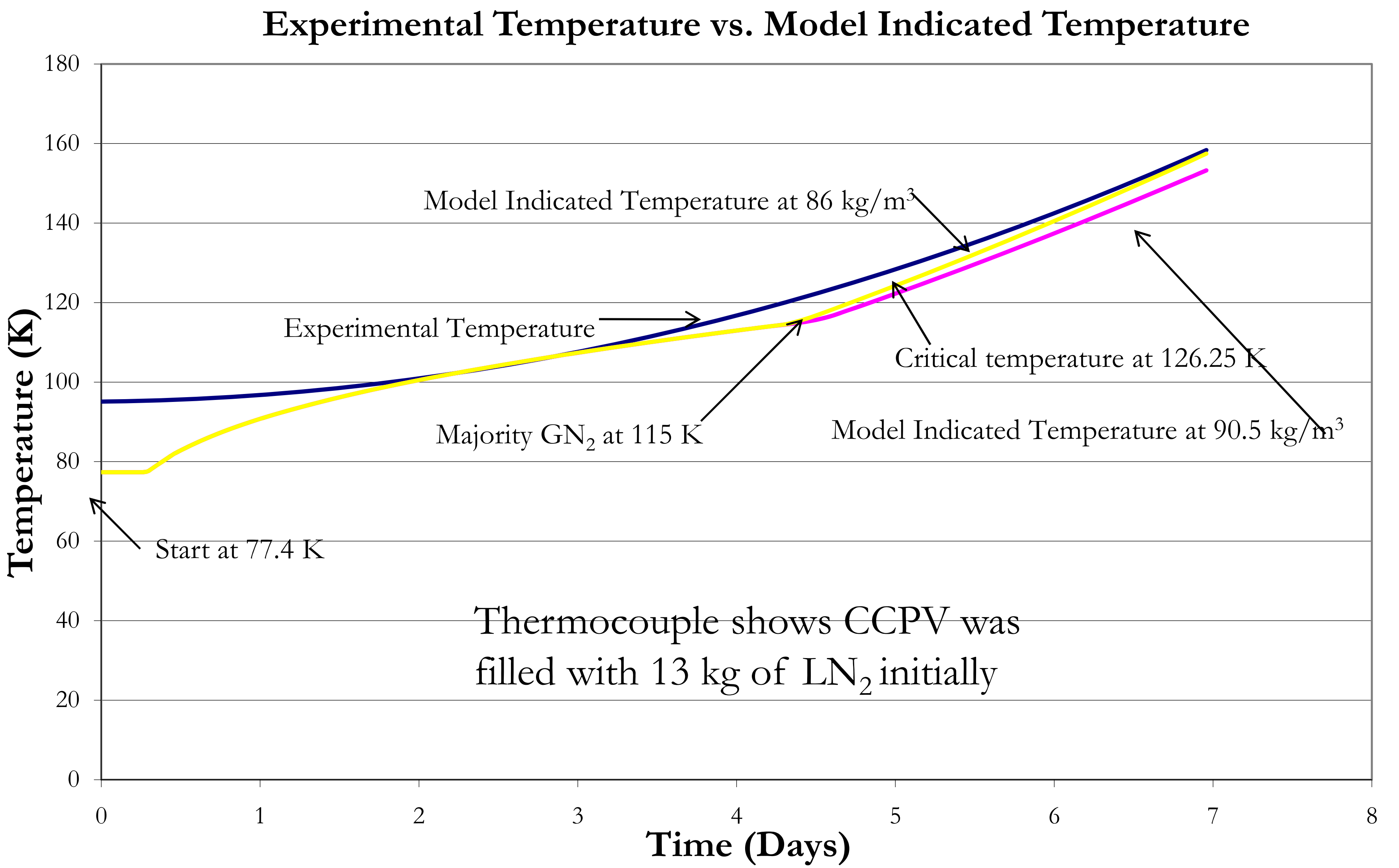
Thermodynamic Model: Flow Chart Continued

•It was unknown whether the 151 L CCPV was filled with 13 kg or 13.7 kg of LN_2

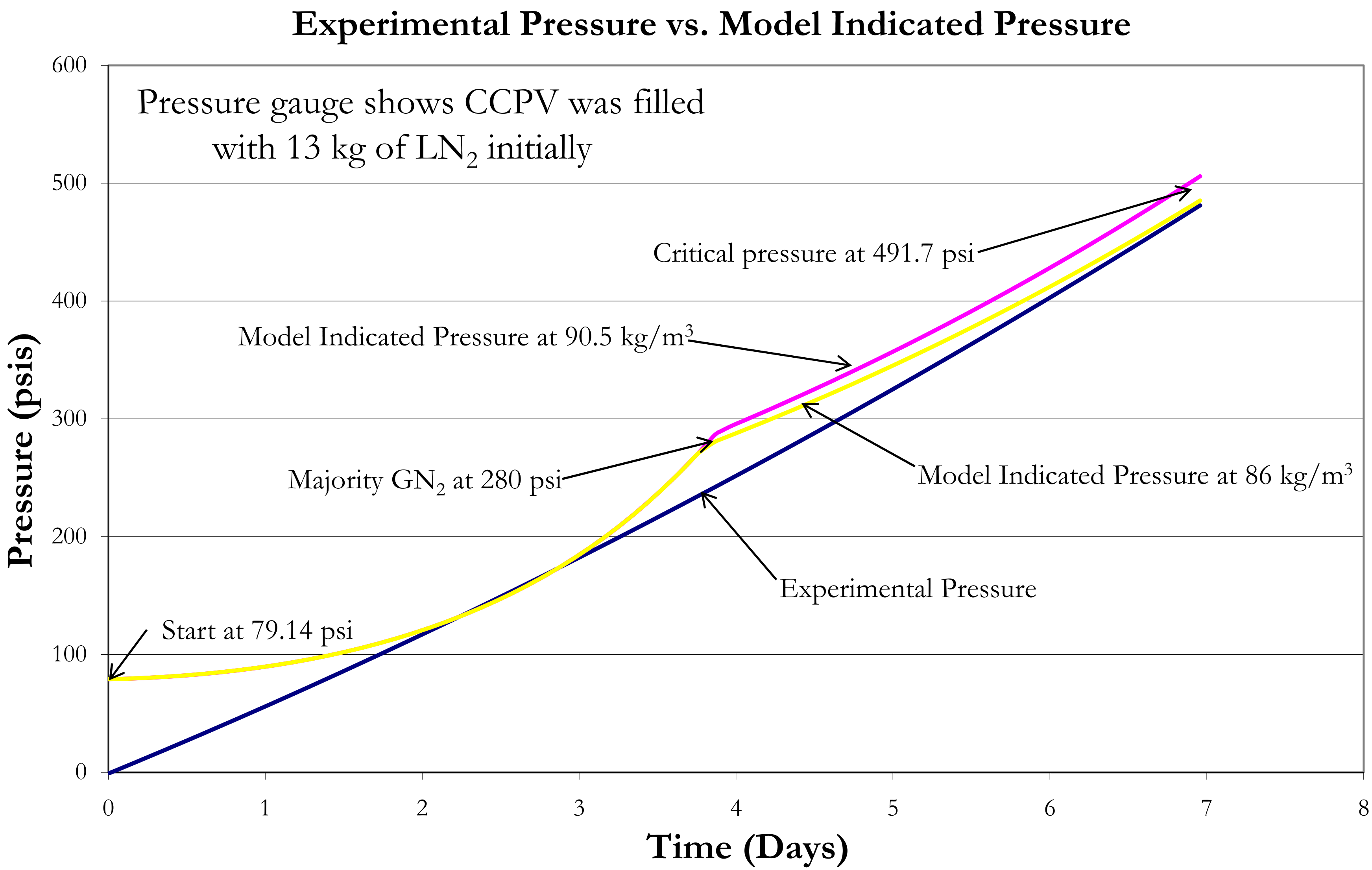
•A correlation between the thermocouple, pressure gauge, and PVT diagram was preformed to determine LN_2 amount



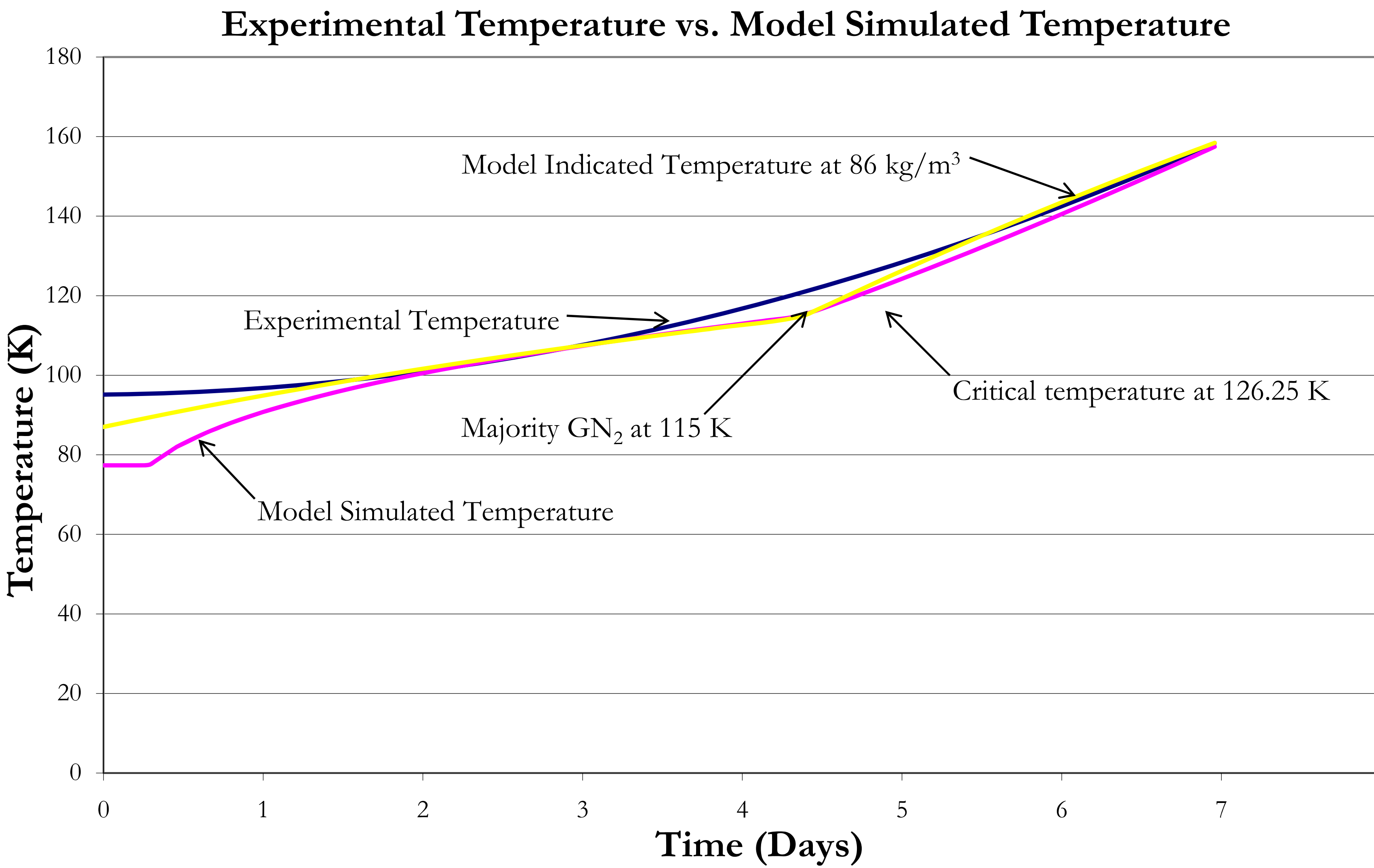
Correlation of thermocouple readings to determine amount of Nitrogen



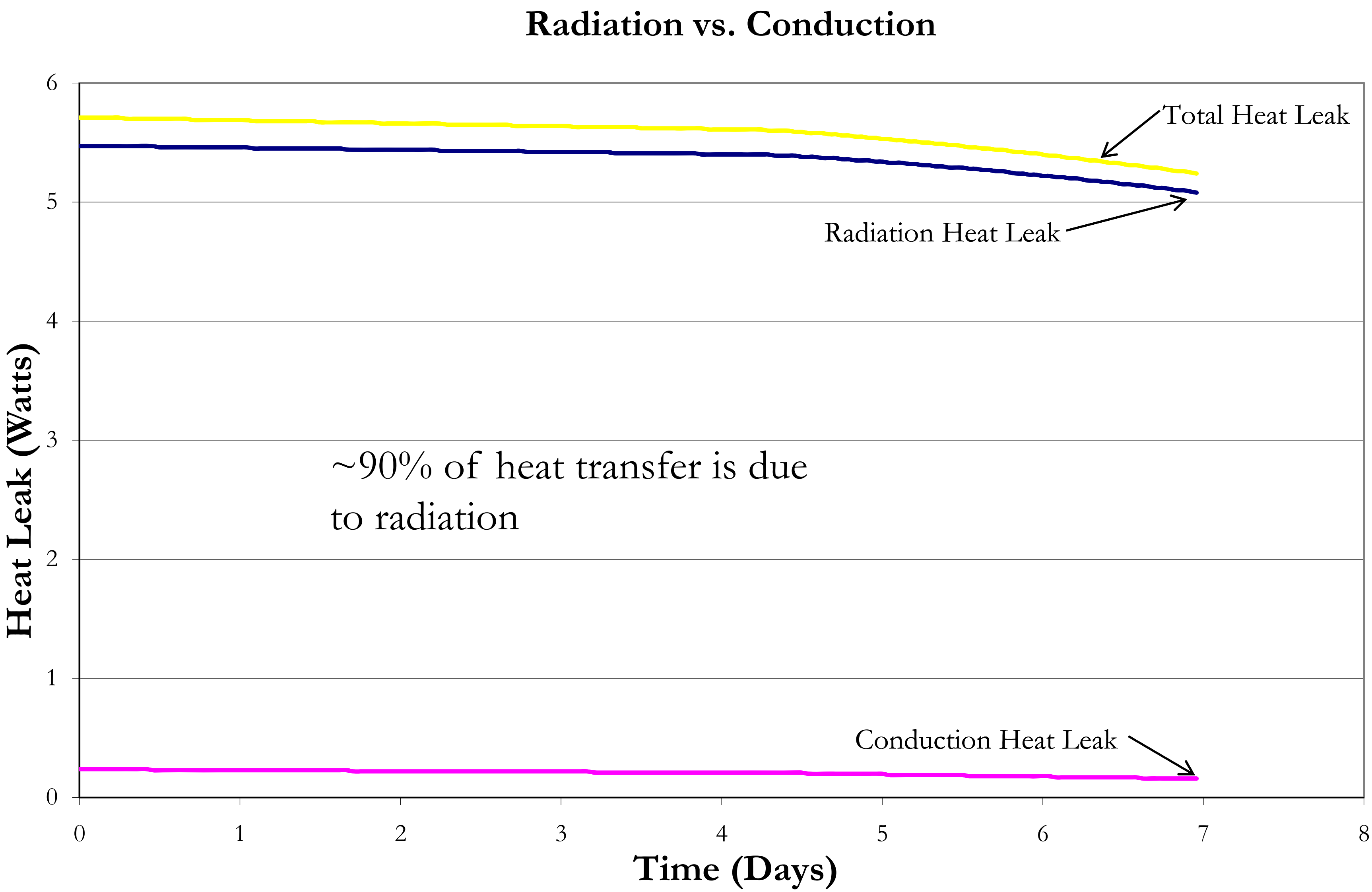
Correlation of pressure readings to determine amount of Nitrogen



Results: Simulated vessel temperature comparison



Model heat leak results

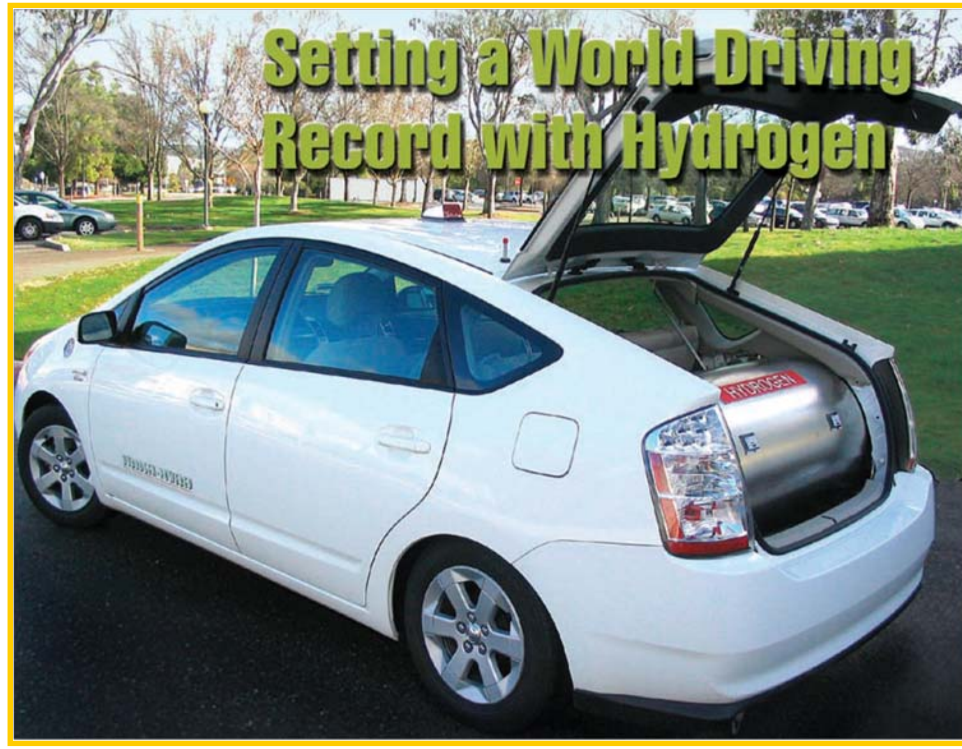


Thermodynamic Analysis Results Summary

- The temperature generated from the simulation are comparable to the experimental data.
- Radiation is responsible for ~90% of the heat transfer in to the CCPV.
- The average amount of heat transferred into the CCPV during the dormancy test was 5.5 Watts.
- Safely able to store 10.7 of LH_2 for 11 days before venting given current heat transfer rate

Implications of Model: Hydrogen Driving Record

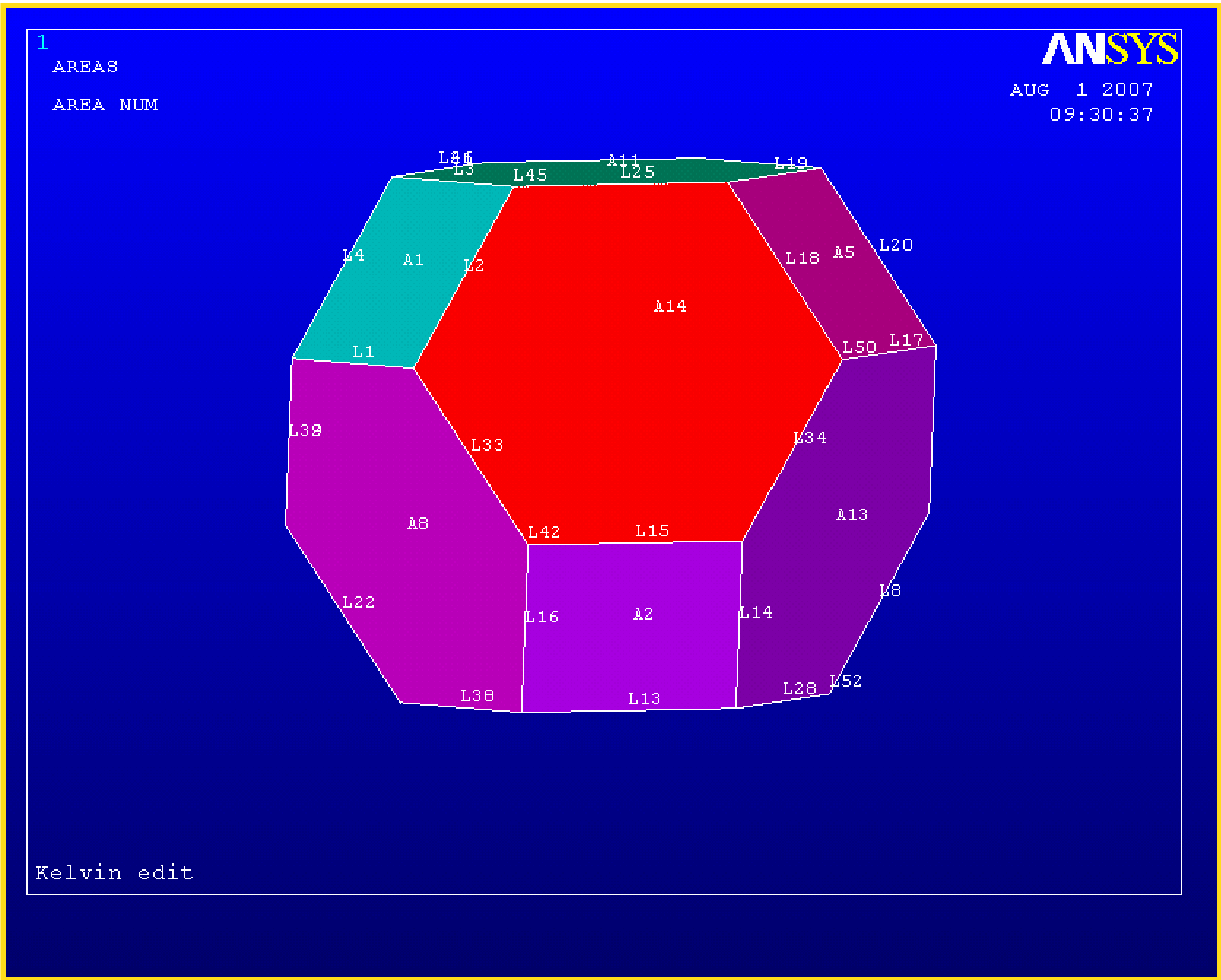
- A 653 mile range was obtained using the LH_2 fueled Toyota Prius in January 2007.
- Currently, conformable cryogenic capable pressure vessel designs are being modeled and tested.
- Can CCPV be redesigned to have smaller S/V ratio and store 6 kg of LH_2 ?



Feasibility of Pressure Vessel Designs

- A sphere has the smallest surface to volume ratio of any shape
- Isoperimetric quotient = $36 \pi V^2 / S^3$ (based on a sphere)
- Volumetric quotient = $S^3 / 36 \pi V^2$ (based on a sphere)
- A Kelvin Cell has a .0757 isoperimetric quotient and a 0.683 volumetric quotient
- A double bubble uses the least area to enclose two equal volumes
- Radiation is a function of emissivity (ε), Stefan-Boltz constant (σ), area (A), and temperature difference (ΔT).

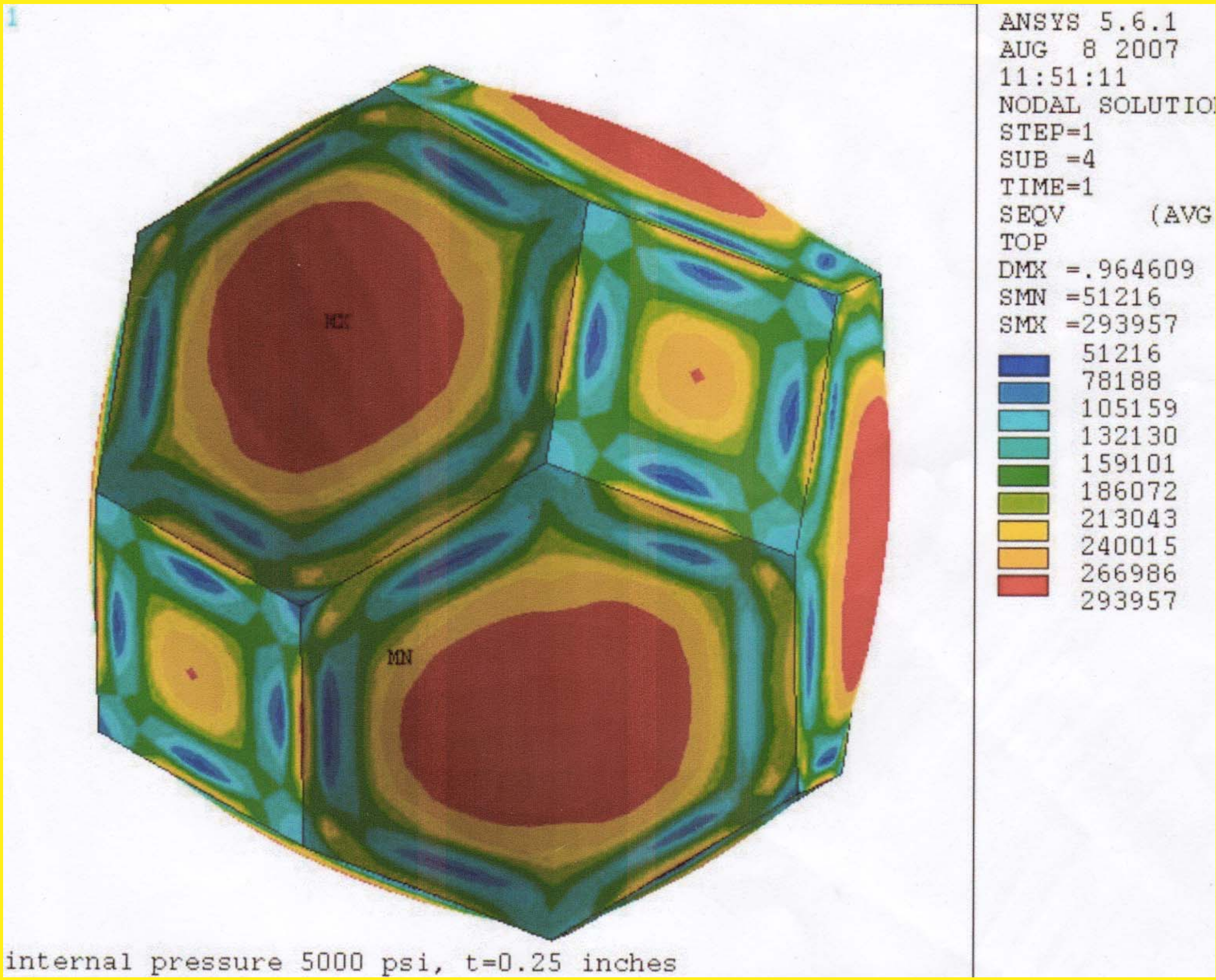
FEA Cryogenic Capable Pressure Vessel Designs



Double Bubble Sphere 1Kelvin Cell

- Aluminum 2024
- Thickness of .25 inches
- Volume: 2587.3 in^3 or 42.4 L
- S/V ratio: .65

Pressure Design Results with Carbon Fiber Layer



Kelvin Cell

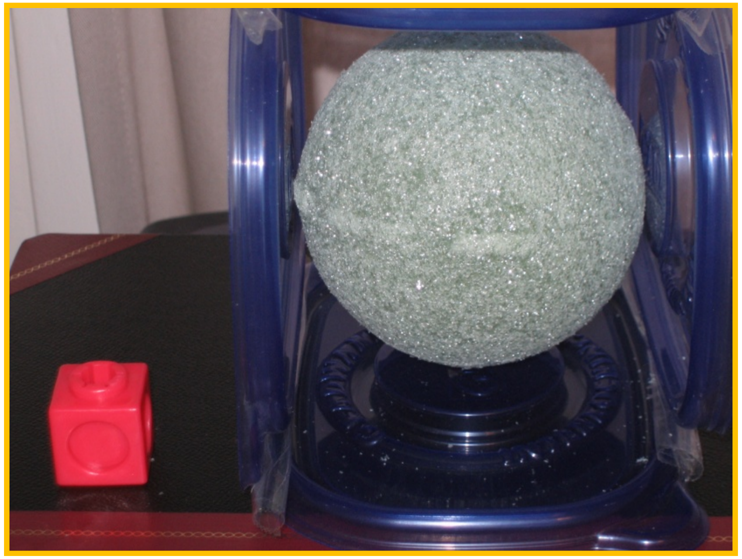
- Pressure: 5000 psi
- Aluminum 2024
- Thickness of .25 inches
- 5 layers of Toray T700 Carbon fiber
- T700 layup of 45, -45, 0, -45, 45 deg.
- ANSYS Solid 45 & 46 Element

FEA Pressure Vessel Results Summary

- The Kelvin Cell design has excellent packing characteristics, but it fails at high pressures
- The Kelvin Cell design experienced the most stress and displacement at 5000 psi
- Stainless steel 304 could increase the Kelvin Cell design resistance to failure

FEA Pressure Vessel Results Summary Continued

- The spherical design experienced the least stress of all the designs with or without carbon fiber
- At 5000 psi, the carbon fiber wrapped spherical vessel design's Von Mises stress was 28.394% less than the double bubble
- Feasible to create a modular cubic cryogenic capable pressure (MC^3PV)
- MC^3PV would have a spherical inner vessel and a cubic vacuum outer jacket.



Modular Cubic Cryogenic Capable Pressure Vessel

Summary of work completed

- Created thermodynamic model of CCPV
- Estimated ~90% of heat transfer due to radiation and 5.5 Watts transferred over 7 days
- Develop FEA models of pressure vessel designs
- Determined feasibility of creating a pressure vessel with cubic outer jacket and spherical inner vessel

Future Plans

- Further refine model to better account for
  - specific heat capacity of AL at cryogenic temperatures
  - phase change of LN_2 and LH_2
- Redesign CCPV to store 6 kg of LH_2 and be mounted underneath Toyota Prius
- Construct cubic outer jackets and test connection between pressure vessels
- Create a econometric model to determine users willingness to adopt a cubic cryogenic capable pressure vessel

Acknowledgements

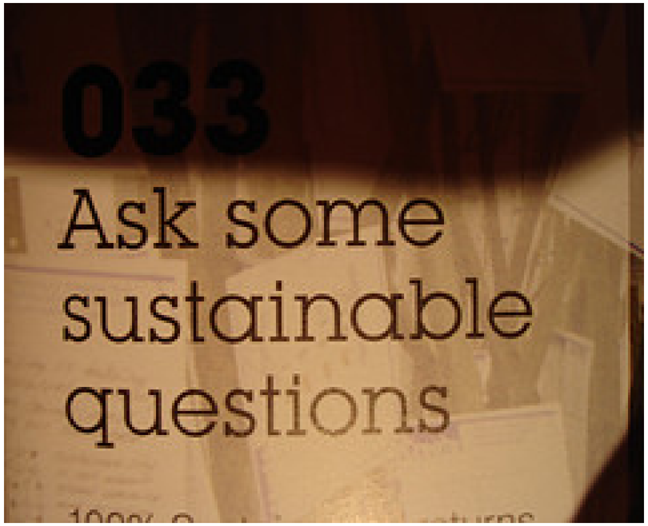
LLNL Energy Storage & Conversion Group:

- Salvador Aceves
- Gene Berry
- Francisco Espinosa-Loza
- Tim Ross
- Vern Spitzer

UC Berkeley

- Professor Agogino
- Professor Robert Dibble
- Professor Samuel Mao

Q/A?



Supplementary Slides

Introduction: Why Hydrogen?

- Hydrogen, like electricity, is an energy carrier; it is not an energy source.

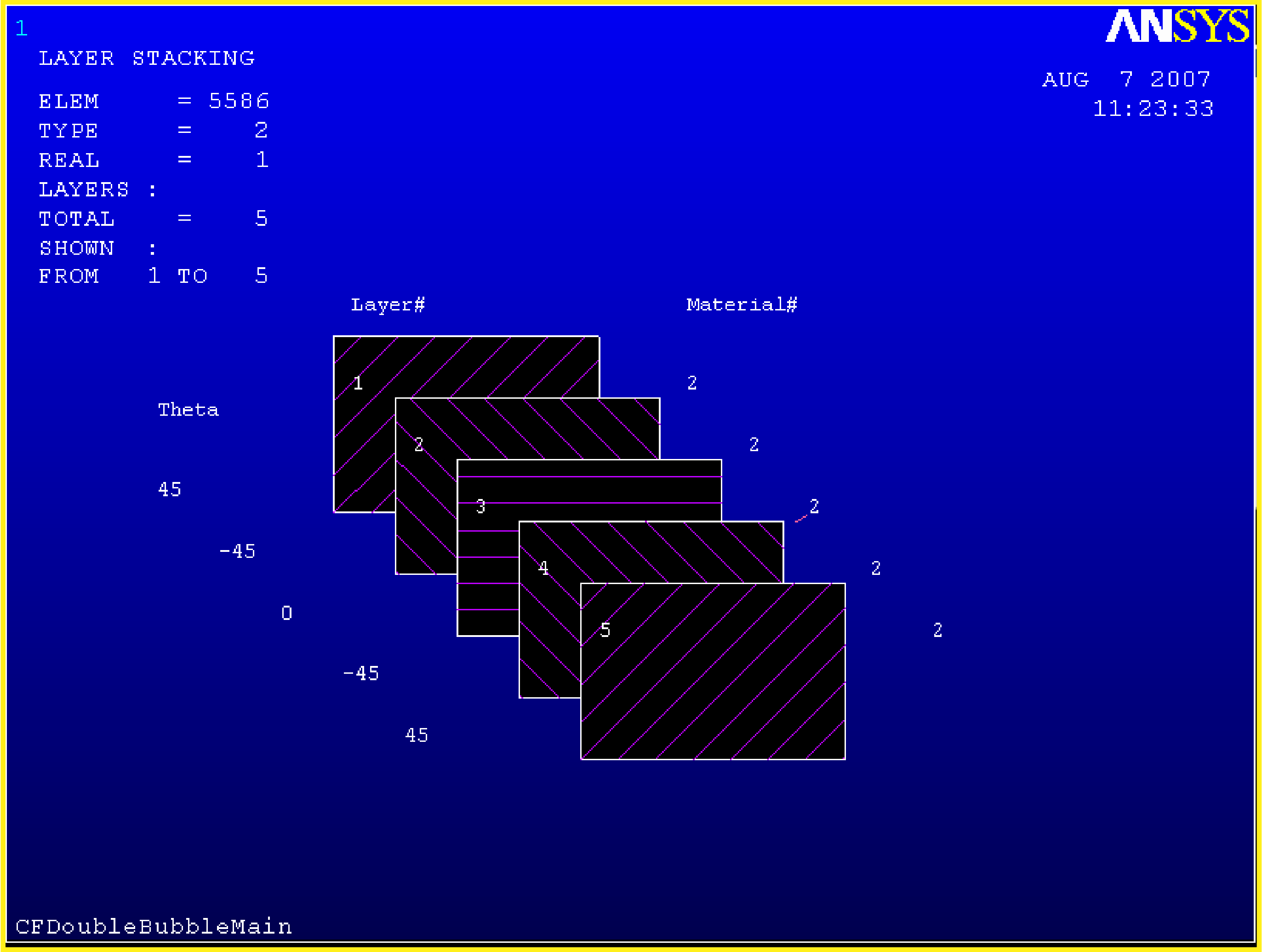
- 19.6 lbs -- amount of carbon dioxide emitted from burning 1 gallon of gasoline in a car

- 1 kg of hydrogen has the same energy content of 1 gallon of gasoline.

- Heat and water -- the emissions from burning 1 kg of hydrogen in a car

- Hydrogen issues: production, distribution, and storage

Carbon Fiber Layup



Rule of Mixtures Model

- $Ec11 = Ef11*Vf+Ee11*Ve$
- $NUc12 = NUf12*Vf+NUe12*Ve$
- $Ec22 = 1/((Vf/Ef22)+(Ve/Ee22))$
- $Gc12 = 1/((Vf/Ge12)+(Ve/Ge12))$

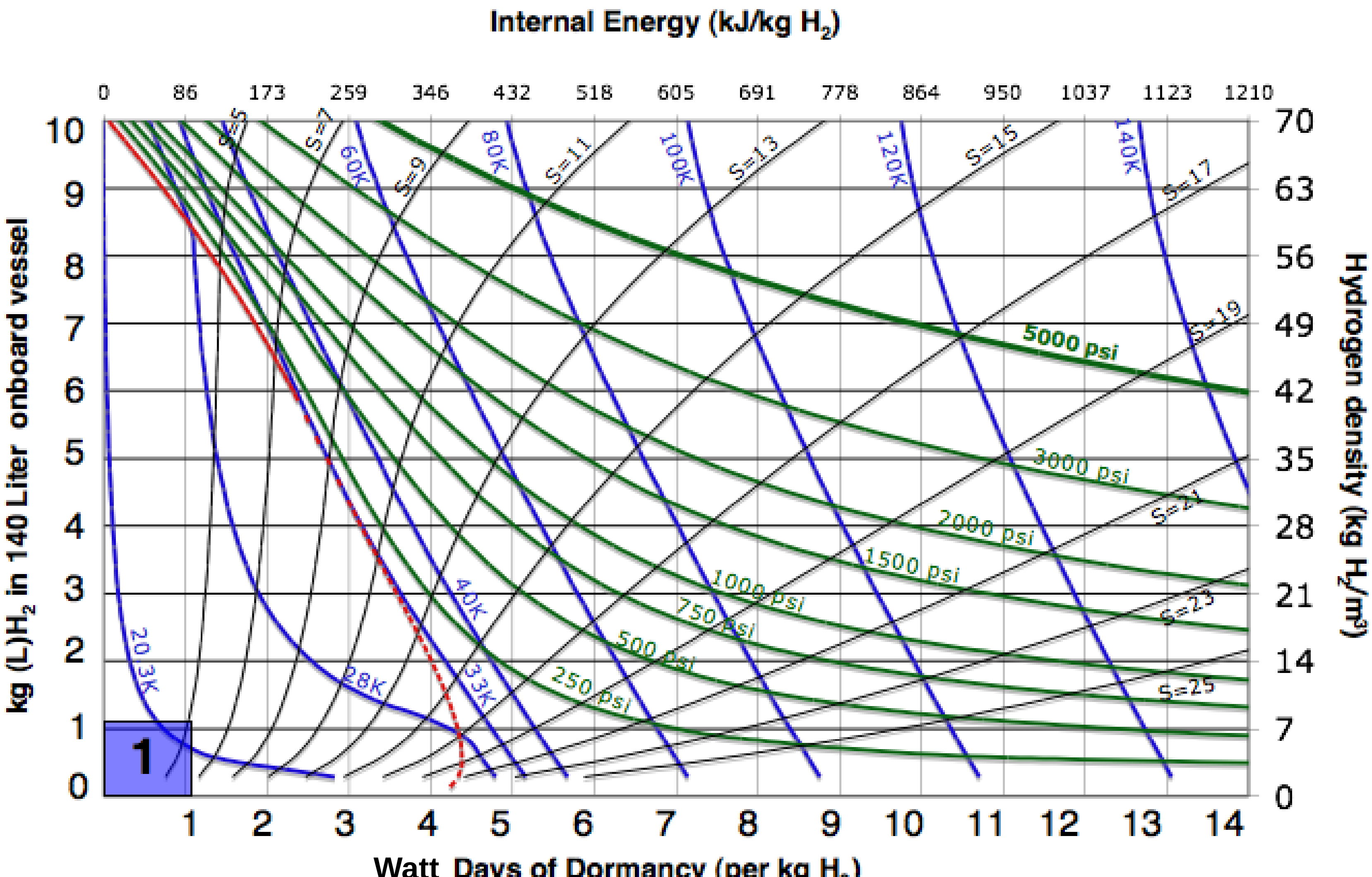
Halpin-Tsai Model

- Ec11 = Ef11*Vf+Ee11*Ve
- NUc12 = NUf12*Vf+NUe12*Ve
- Gc12 = Ge12*(1+EPS_G12*ETA_G12*Vf)/(1-ETA_G12*Vf)
- Ec22 = Ee22*(1+EPS_E22*ETA_E22*Vf)/(1-ETA_E22*Vf)
- Gc23 = Ge23*(1+EPS_G23*ETA_G23*Vf)/(1-ETA_G23*Vf)

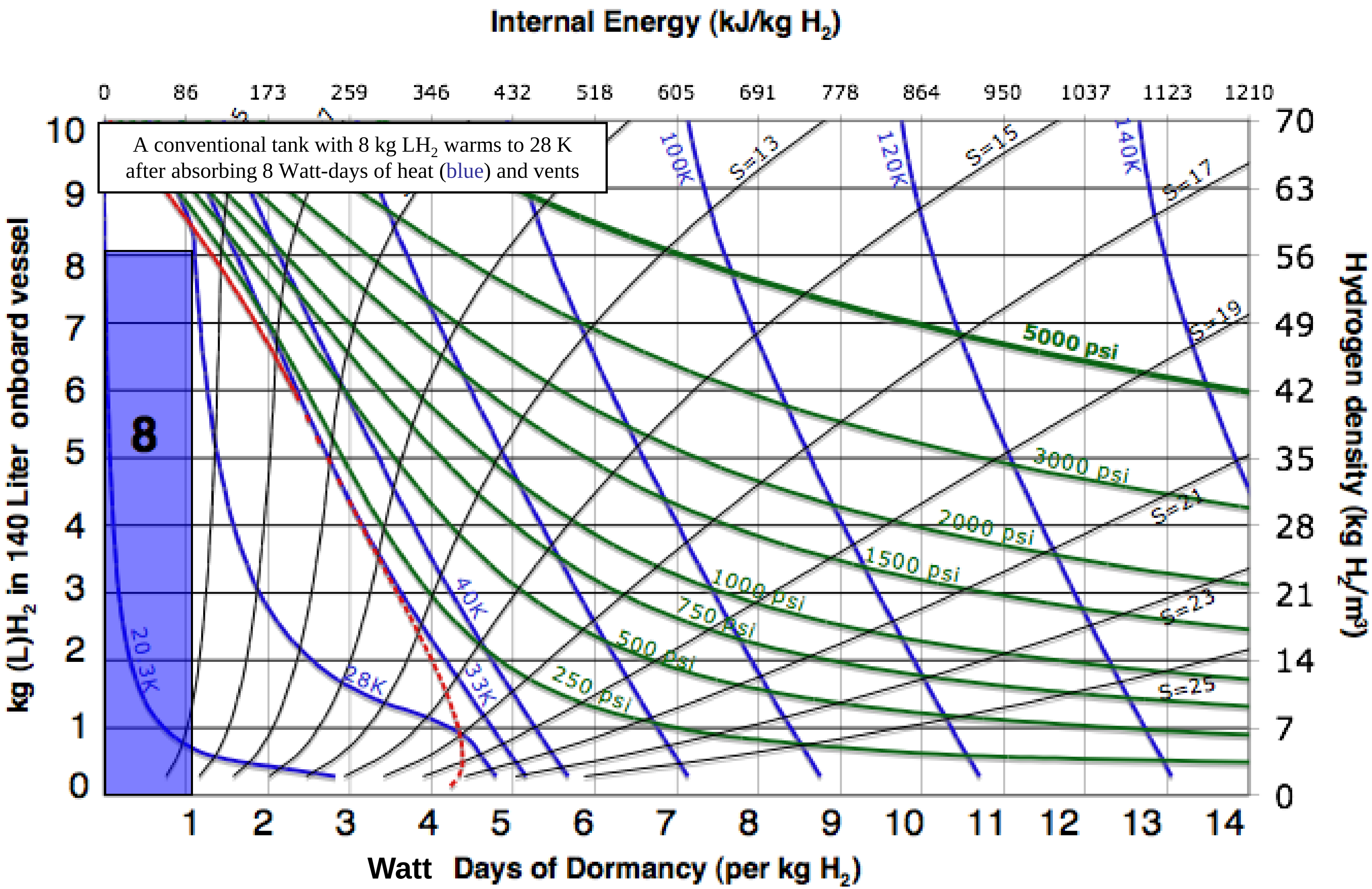
Concentric Cylinder Model

- Ec11 = Ef11*Vf+Ee11*Ve+TT1
- NUc12 = NUf12*Vf+NUe12*Ve+TT2
- Gc12 = Ge12*(Gf12*(1+Vf)+Ge12*(1-Vf))/((Ge12*(1-Vf))+Ge12*(1+Vf))
- Gc23 = Ge23*(1+(1+B1)*Vf/(P Vf*(1+3*(B1^2)*(Ve^2)/(A*(Vf^3)+1))))
- Ec22 = 4/(1/Gc23+1/Kc23+4*(NUc12^2)/Ec11)
- NUc23 = Ec22/(2*Gc23)-1

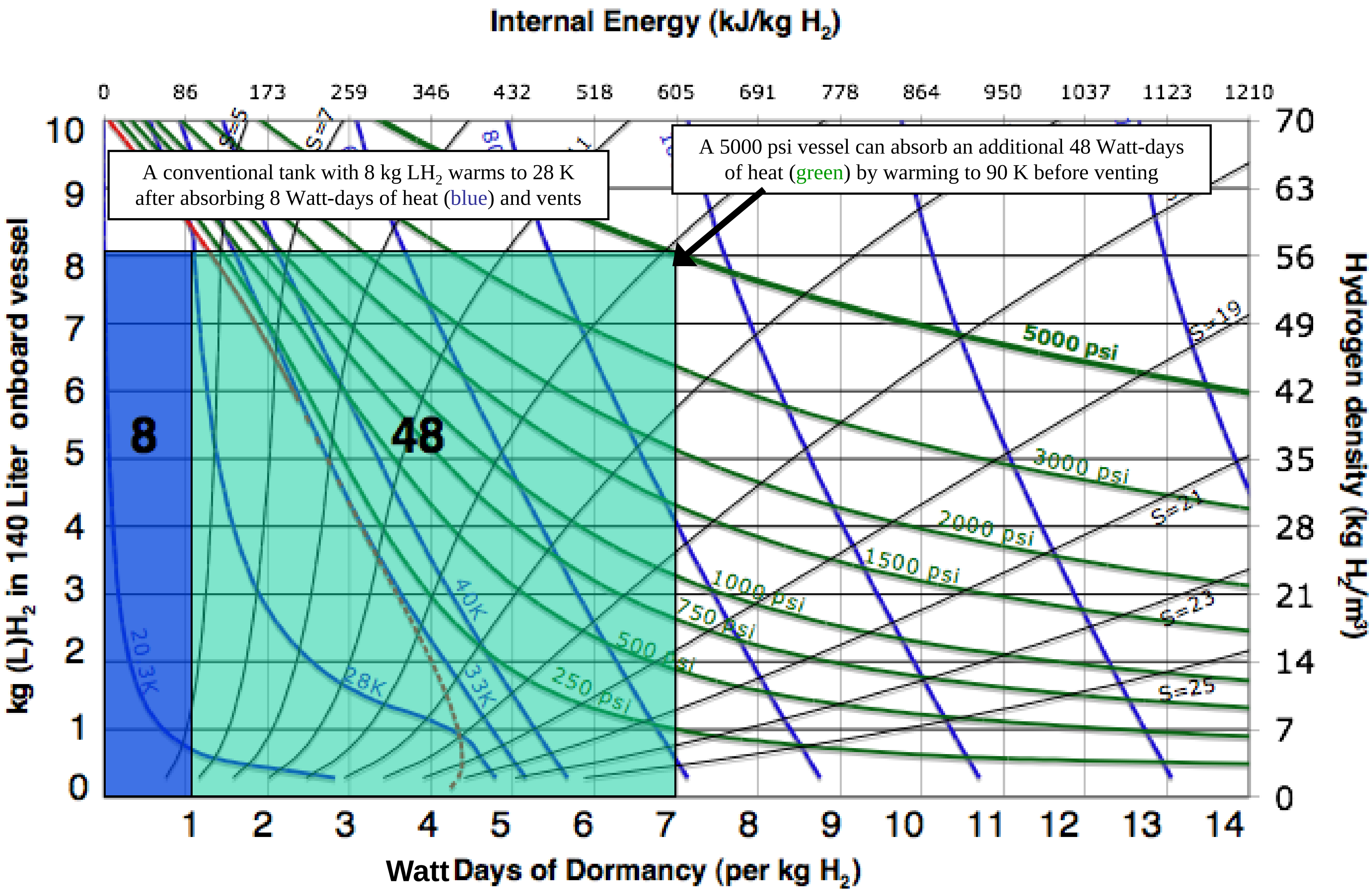
Cryogenic hydrogen vessel dormancy is best analyzed in terms of internal energy and fuel density with pressure, entropy, and temperature contours



A conventional tank with 8 kg LH_2 has 8 Watt-days of dormancy (warming from 20 K to 28 K and venting at 6 bar)



An insulated 5000 psi vessel has 56 Watt-days of thermal endurance (warming from 20 K to 95 K).



Consuming 2 kg H_2 (driving ~150 mi) cools the remaining 6 kg H_2 to 70 K, 2000 psi, regaining ~50 Watt-days of thermal endurance