DOE Hydrogen Program

# Cryogenic Capable Pressure Vessels for Vehicular Hydrogen Storage

**Salvador Aceves, Gene Berry,**
**Francisco Espinosa, Tim Ross,**
**Andrew Weisberg**
**Lawrence Livermore National Laboratory**

**May 18, 2007**

Project ID #
TV8

# Overview

## Timeline

- Start date: **October 2004**
- End date: **September 2008**
- Percent complete: **70%**

## Budget

- Total project funding
  - DOE: **$765 k**
  - SCAQMD: **$350 k**
- Funding received in FY06:
  - **$290 k**
- Funding for FY07:
  - **$250 k**

## Barriers

- **B. Weight and volume**
- **H. Sufficient fuel storage for acceptable vehicle range**
- **L. Hydrogen boil-off**

## Targets

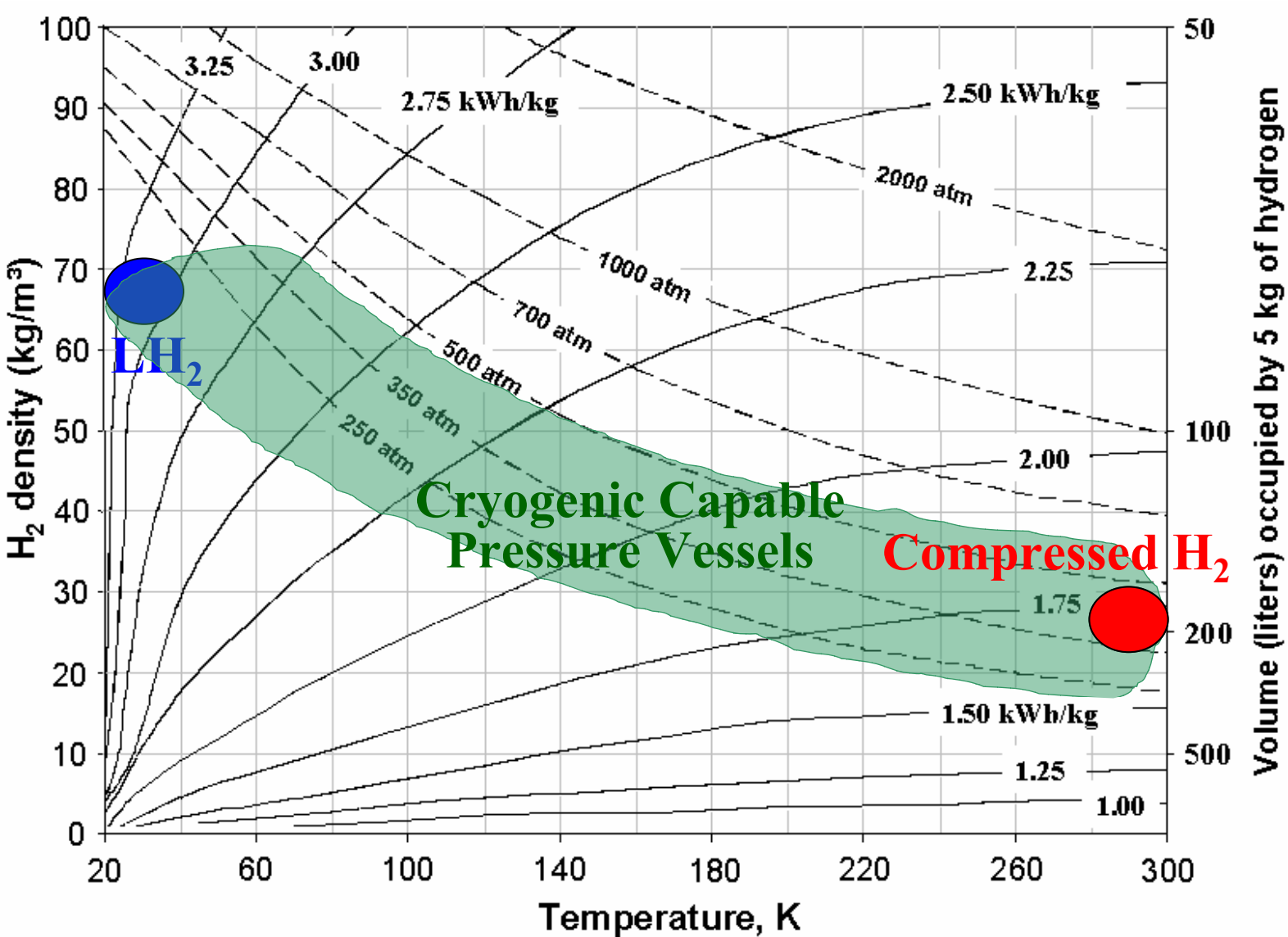
- **2007 DOE volume target**
- **2010 DOE weight target**

## Partners

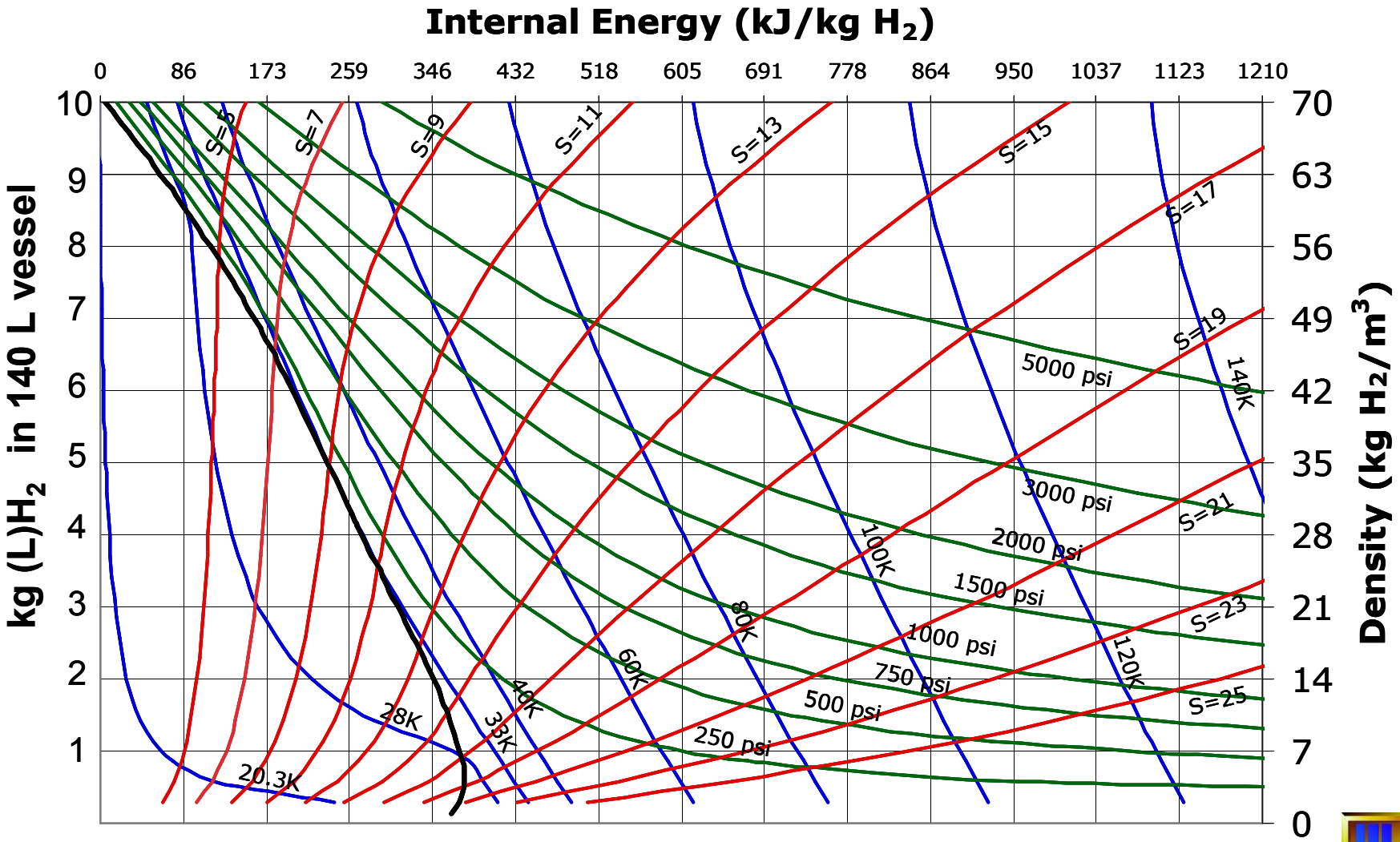
- Demonstrated cryotank technology with **SCI** and **SunLine,** funded by **SCAQMD**
- **Spencer composites,** CRADA **with Automotive Composites Consortium,** aerospace work funded by **DARPA**

# Rationale: Our Cryogenic *Capable* Vessels can Store either Gaseous $H_2$ or $LH_2$, Capturing the Advantages of Both

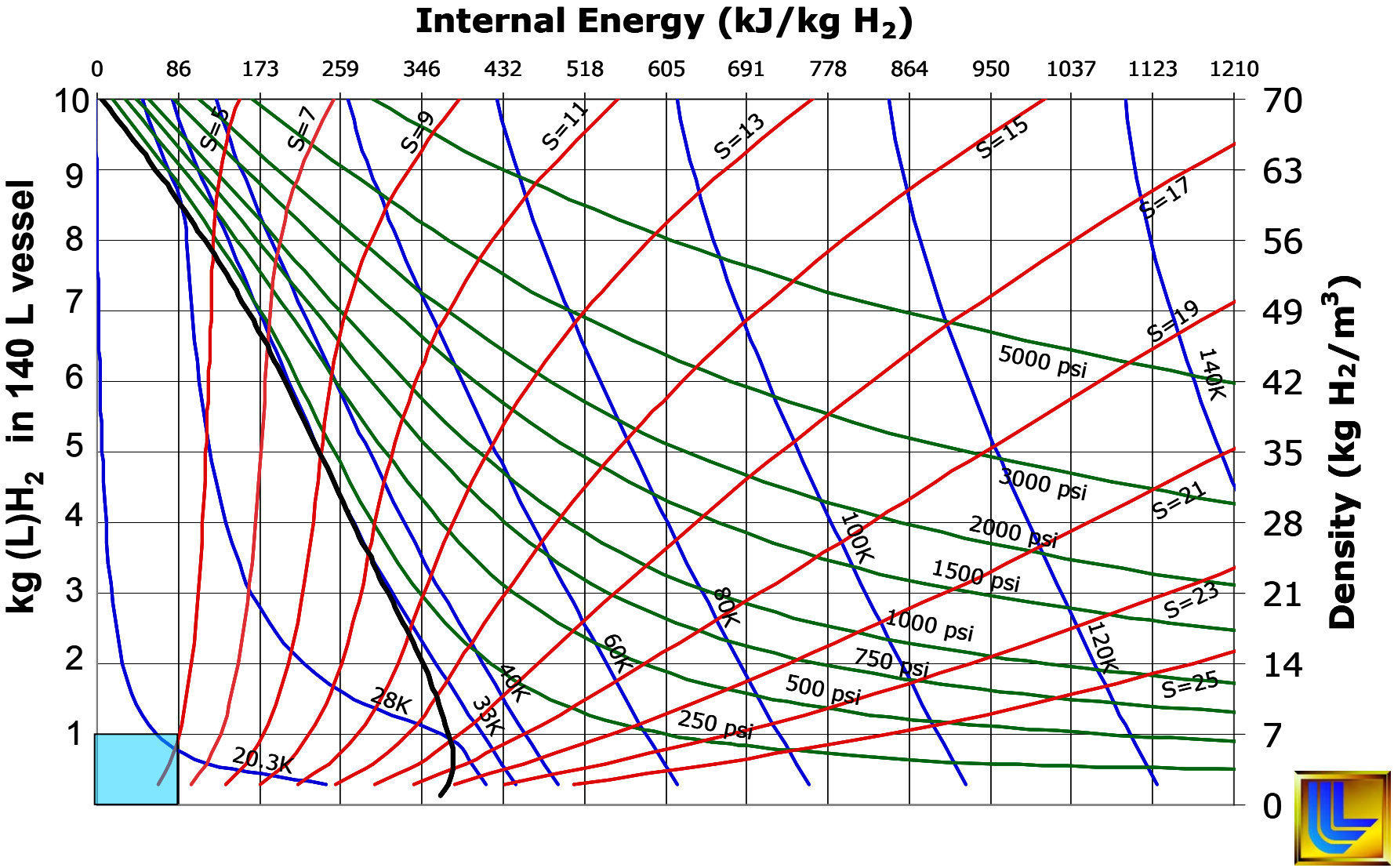
Cryogenic vessels operate across the entire $H_2$ phase diagram



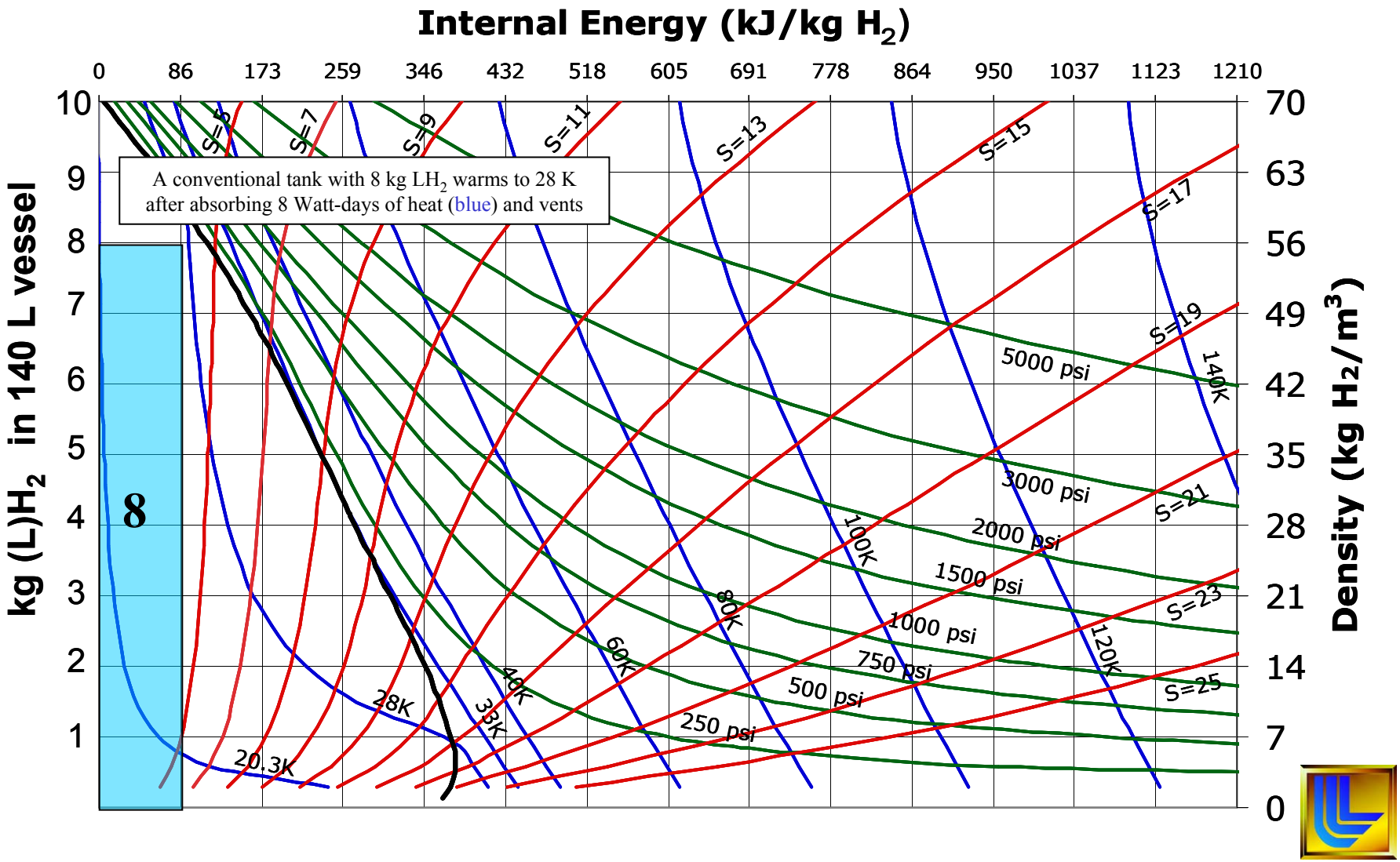
# Cryogenic hydrogen storage behaviors are best analyzed in terms of internal energy and fuel density



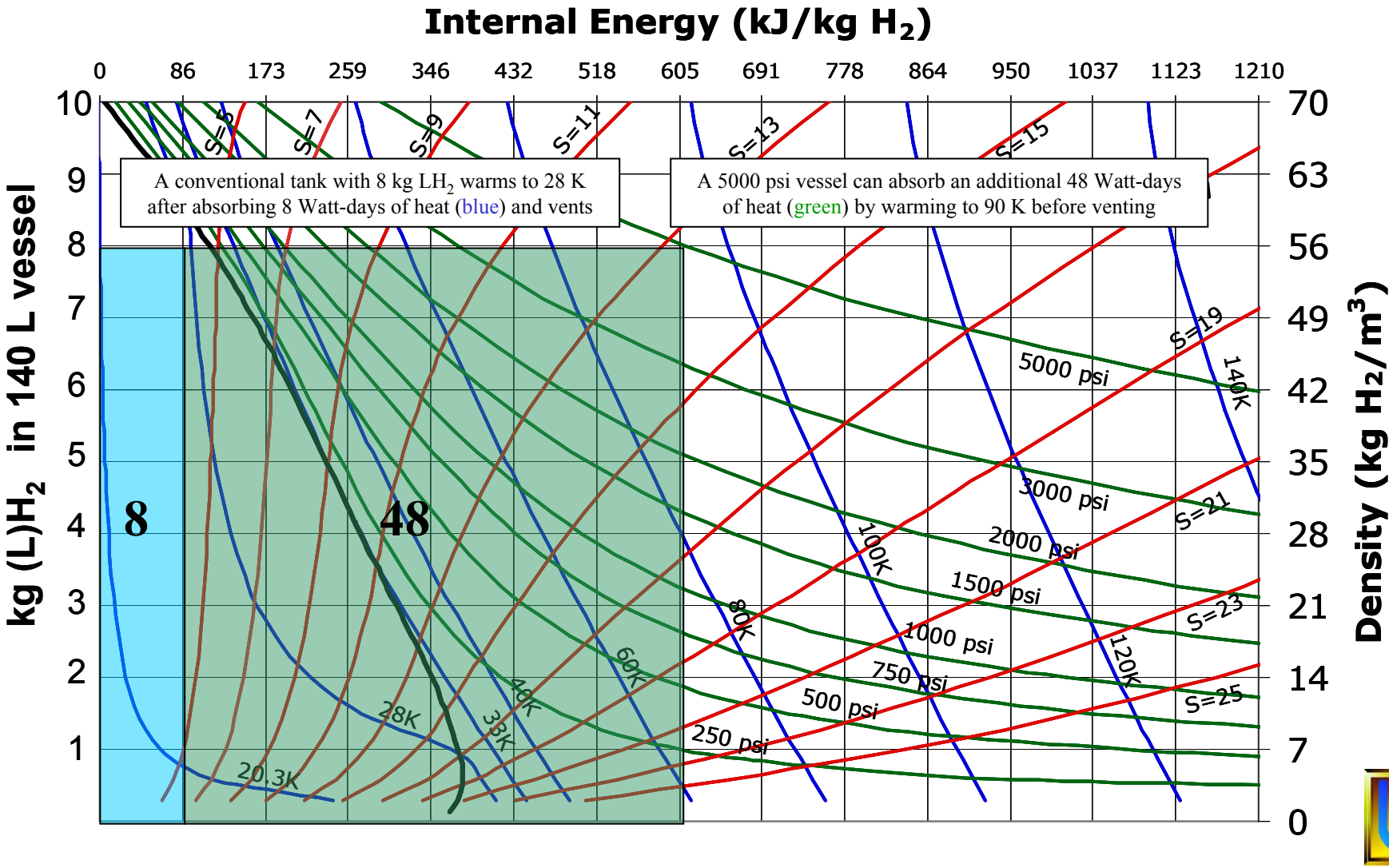
# Each square in this phase diagram represents 86 kJ (a watt-day) of thermal endurance



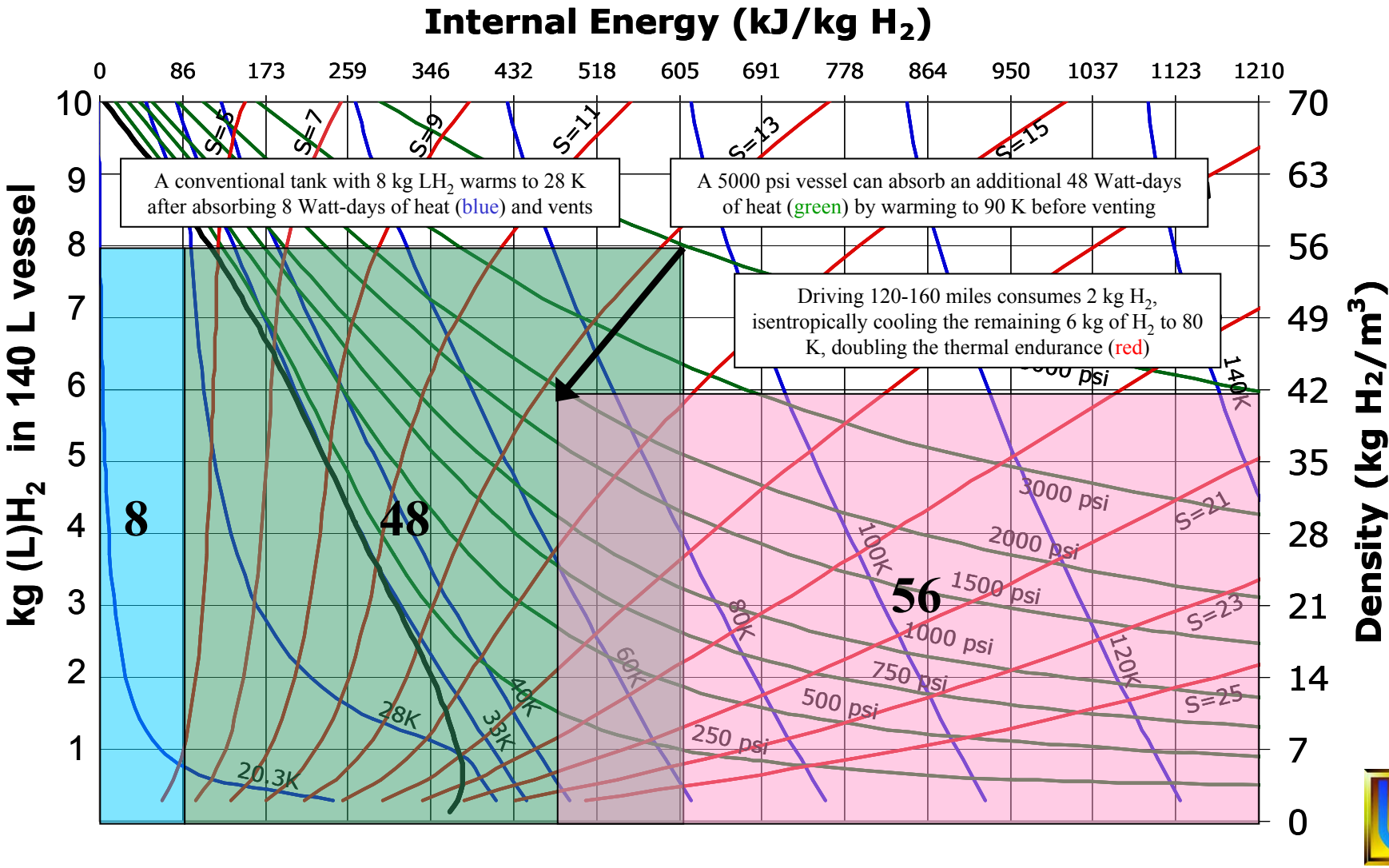
# A conventional tank with 8 kg $LH_2$ has 8 Watt-days of dormancy (warming from 20 K to 28 K and venting at 6 bar)



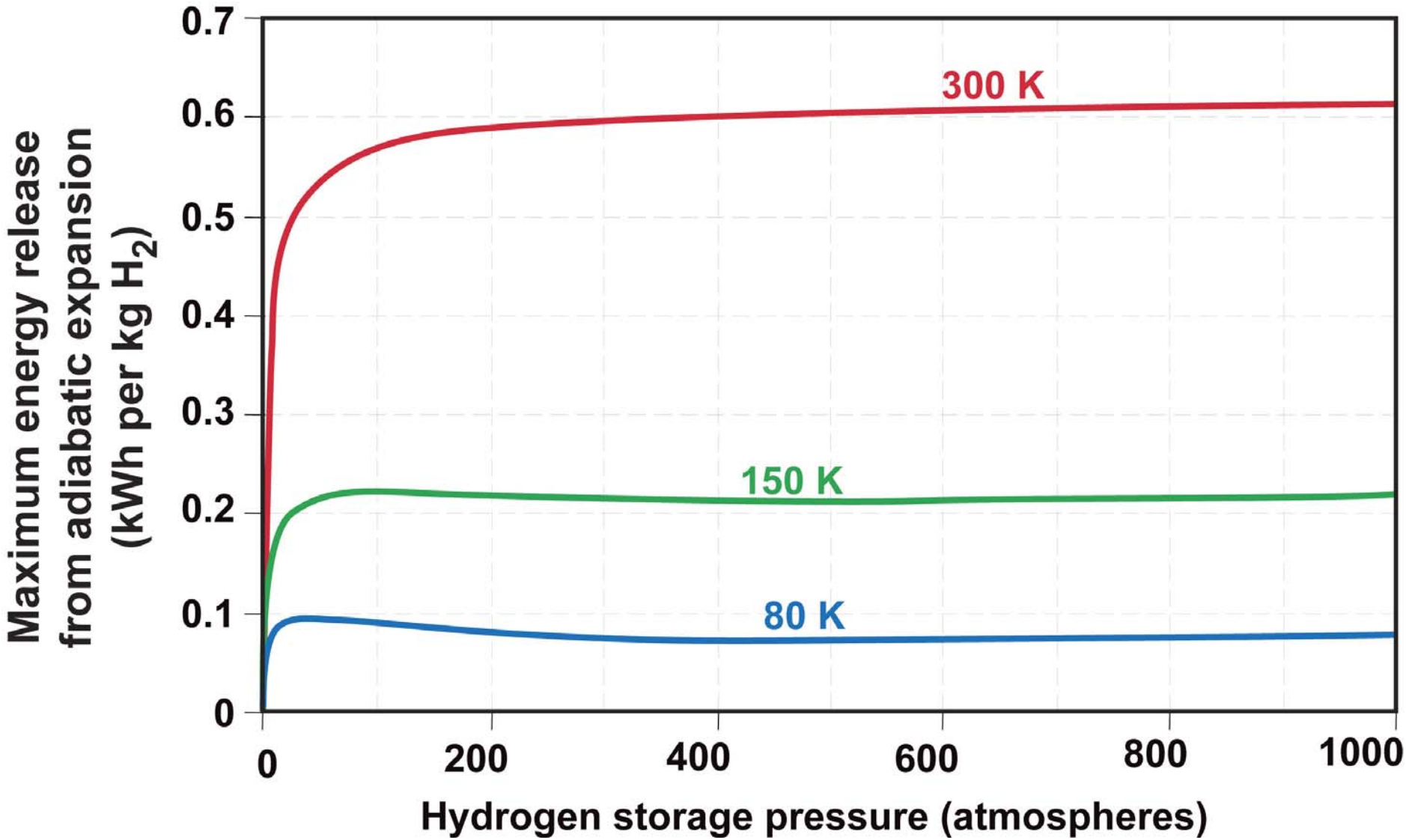
# A cryogenic capable 5000 psi vessel has 56 Watt-days of thermal endurance (when warmed from 20 K to 95 K)



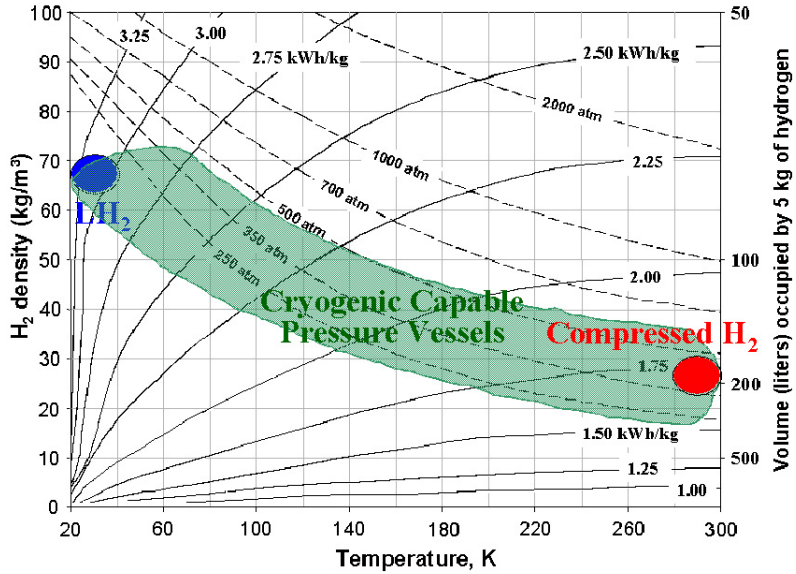
# Driving ~ 150 miles (using 2 kg of $H_2$) cools the remaining 6 kg $H_2$ to 65 K, 2000 psi, regaining 56 Watt-days of thermal endurance

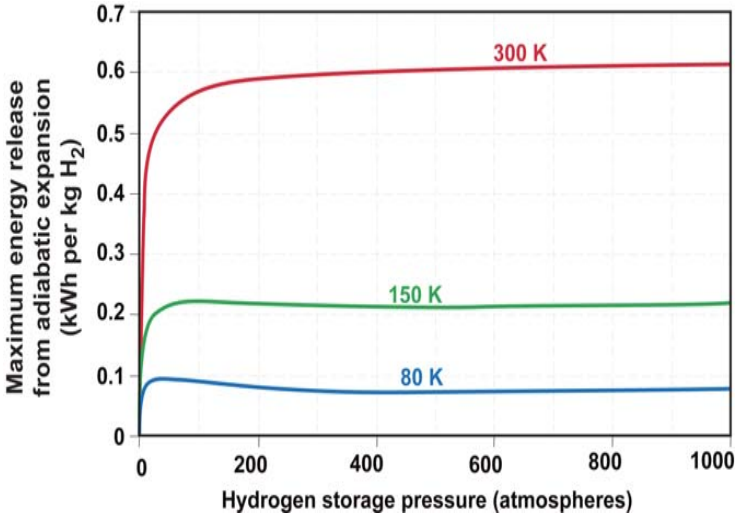


# Cooling high pressure $H_2$ can increase safety removing energy from the gas radically reduces theoretical burst energy at cryogenic temperatures



# Rationale: Why Insulate Pressure Vessels?




- **Flexible refueling continuously matches storage method to drivers' current needs (cost, range, safety)**
- **Cold (L)$H_2$ has less stored PV energy**
- **Liquid hydrogen capability lowers cost (50-75% less fiber than compressed $H_2$)**
- **$LH_2$ boiloff can be eliminated. Vehicle cannot be stranded**
- **Thermal endurance *increases* as fuel is used**
- **Vessel temperature partially self-regulated (cools when driven – more so when fuller and/or warmer)**
- **Greatly extended dormancy (~5-10x vs. $LH_2$ )**

# Objective: Demonstrate long range (500+ miles) hydrogen hybrid vehicle with cryogenic capable pressure vessel

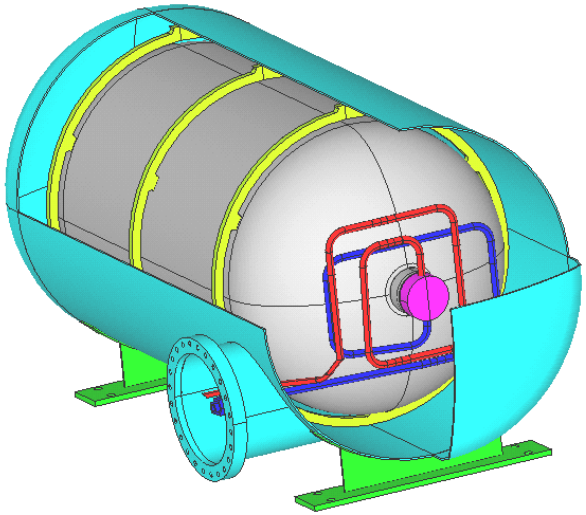

## The vehicle

- Toyota Prius converted to $H_2$ fuel by Quantum.
- Originally equipped with 5000 psi 68 L pressure vessels (1.6 kg $H_2$)
- Est. fuel economy 50 miles/ kg $H_2$

## LLNL Cryotank

- 151 L capacity
- stores 3.5 kg $H_2$ at 300 K, 5000 psi
- stores 6 kg $H_2$ at 150 K, 5000 psi
- stores 10.7 kg $LH_2$ at 20 K, 1 atm
- Meets DOE 2007 weight goal and is within 20% of DOE 2007 volume goal using $LH_2$ and including all system components

# Approach: we are designing, building, testing and demonstrating a compact insulated pressure vessel for long range hydrogen vehicles



design

construction

testing

demonstration

# Accomplishments: We have designed and built a new cryogenic pressure vessel

1. Attach instrumentation and heater to inner pressure vessel

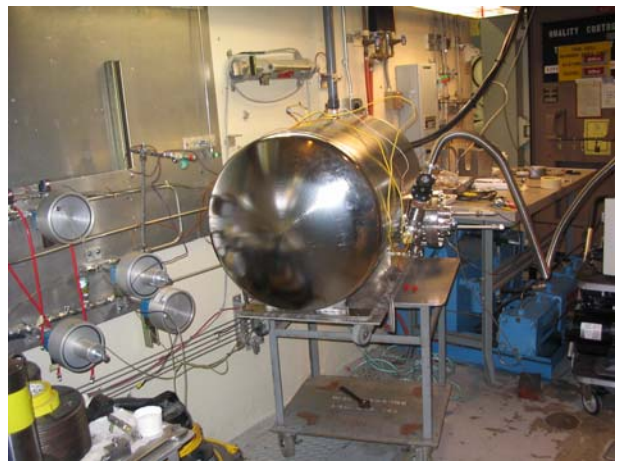
2. Install mechanical support rings and multilayer insulation

3. Slide insulated vessel into outer vacuum vessel

4. Weld vacuum vessel and install flanges for high pressure lines

# We have conducted vessel testing to verify performance and safety

1. Vacuum test

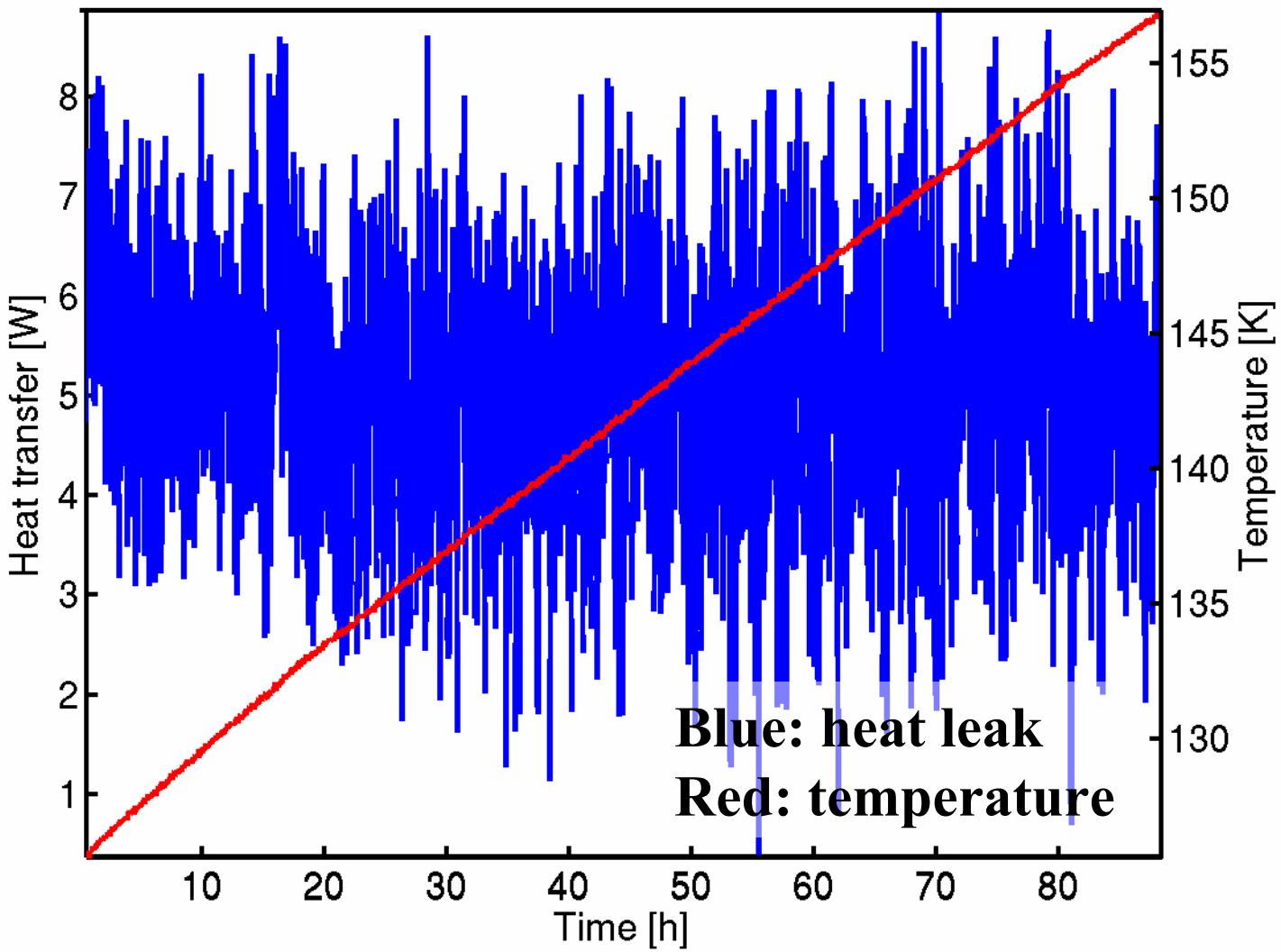


2. Pressure test

3. Instrumentation and data acquisition test


4. Cryogenic cycling and dormancy test

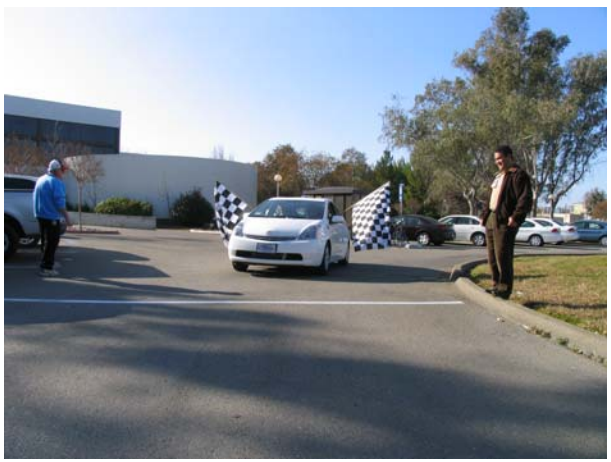
# Thermodynamic analysis confirms adequate thermal endurance in our $LN_2$ dormancy experiments (~5 W)



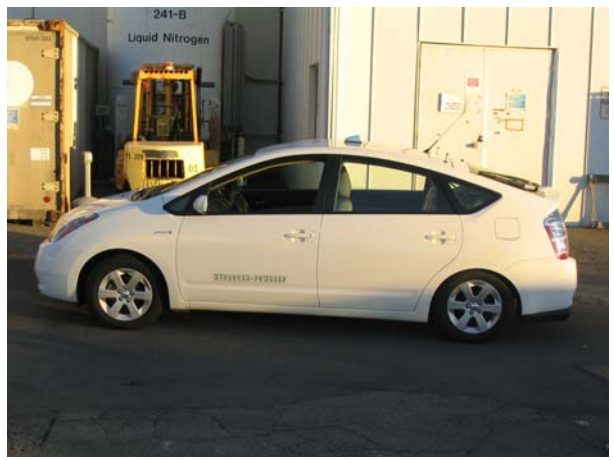
# We have installed our cryogenic capable vessel in a hydrogen fueled hybrid Prius

1. Install cryogenic capable pressure vessel in vehicle

2. Fuel and test vehicle on compressed and liquid $H_2$

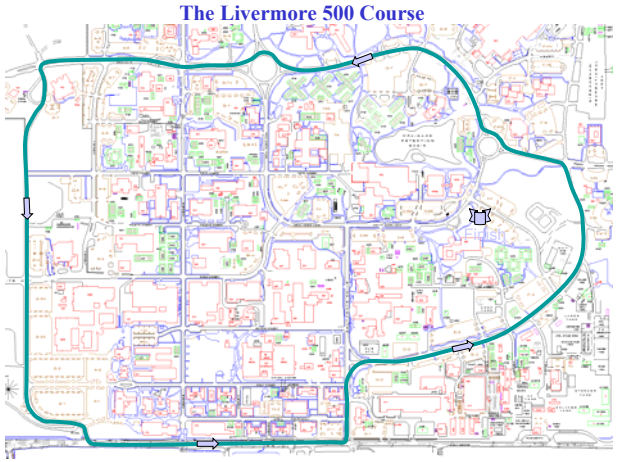


3. Drive test

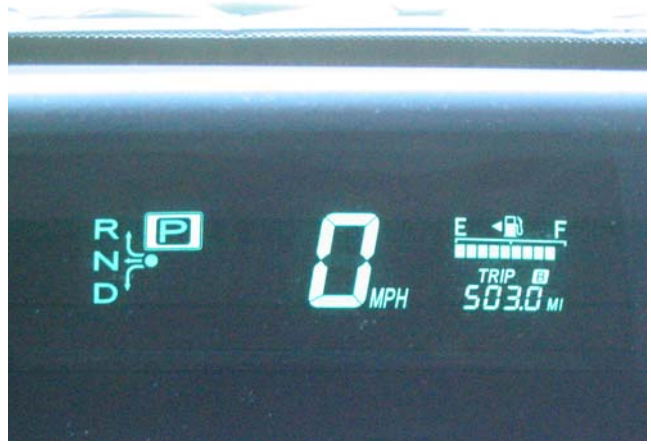



4. Dormancy test

# We drove 650 miles (under atypical conditions) without refueling our cryogenic capable vessel

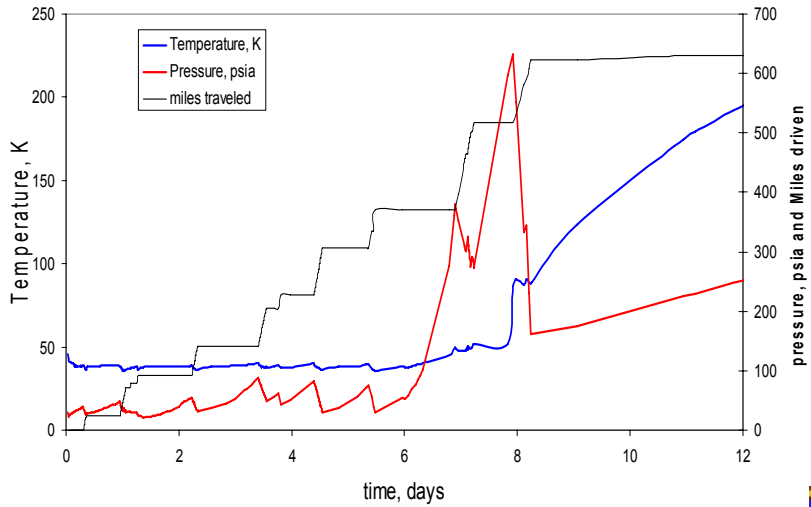



Livermore 500 racetrack



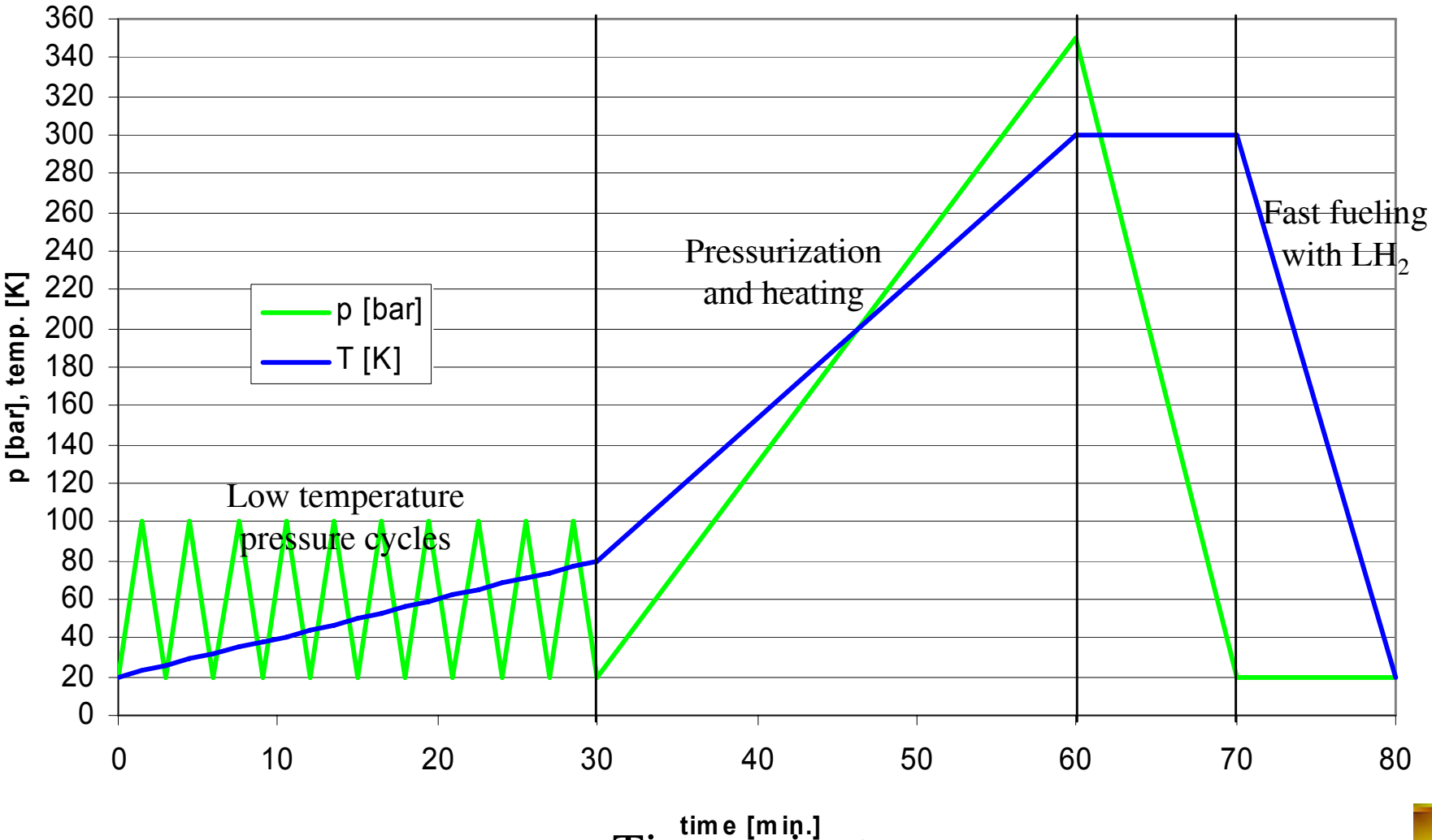

Met 500 mile target

Team picture at 1,000 km (622 miles)




Pressure and temperature during drive

# Future Work: The two outstanding issues are vacuum stability and cycle life
# Our planned experiment can characterize both




Repeat cycle 360 times

# We can efficiently perform all the cyclic tests at our liquid and compressed hydrogen fueling station

# Summary: Cryogenic *Capable* Vessels can Refuel with Gaseous $H_2$ or Liquid $H_2$, Capturing the Advantages of Both

Cryogenic pressure vessel installed in Prius hydrogen hybrid vehicle. The vehicle has been driven 650 miles on a single tank with 10 kg $LH_2$ (under atypical conditions)

- $LH_2$ capable vessels can use 2-3x less carbon fiber than conventional vessels
- $LH_2$ boiloff is eliminated. Vehicle cannot be stranded.
- $LH_2$ fuel allows maximum range
- Compressed $H_2$ for urban driving saves energy of cooling and liquefaction
- High pressure vessels make hydrogen insensitive to heat transfer, enabling thinner insulation or lower cost
- Performance figures: 6.0% $H_2$ weight fraction and 33 grams per liter