Hydrogen Storage Engineering
CENTER OF EXCELLENCE

Key Technologies, Thermal Management, and Prototype Testing for Advanced Solid-State Hydrogen Storage Systems

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DOE Hydrogen Program

Jet Propulsion Laboratory
California Institute of Technology

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Project ID
ST045

Overview:
Project Details

Timeline

- Project start date: February, 2009
- Project end date: July, 2014
- % complete: 40% (Duration)

Budget

- Expected total project funding:
  - $3.195M (DOE)
  - $0.03M (Caltech)
- Funding received in FY10:
  - $672K (DOE)
- Funding received for FY11:
  - $465K (DOE)

Partners

- Caltech (subcontract)

Barriers/System Targets (2015)

- A. System Weight and Volume
  - 5.5 $\%wt_{sys}$, 55 gH_2/kg_{sys}, 40 gH_2/L_{sys}
- C. Efficiency
  - 90% on-board/60% off-board
- D. Durability/Operability
  - <1% degradation @ 1500 cycles, etc.
- E. Charging/Discharging Rates
  - 3.3 min fill, 0.02 g/kW-s minimum full flow
- G. Materials of Construction
- H. Balance-of-Plant Components
- I. Dispensing Technology
- J. Thermal Management

HSECoE

Overview:
JPL's Roles in HSECoE

Jet Propulsion Laboratory
California Institute of Technology

Hydrogen Storage Engineering Center of Excellence
D. Anton, SRNL
T. Motyka, SRNL

Materials Operating Requirements
E. Ronnebro, PNNL
- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- Reactivity & Compatibility – UTRC
- **Adsorption Properties – UQTR**
- **Metal Hydride Properties – SRNL**
- Chemical Hydride Properties - LANL

Transport Phenomena
B. Hardy, SRNL
- Bulk Materials Handling – PNNL
- Mass Transport – SRNL
- **Thermal Transport – SRNL**
- Media Structure - GM

Enabling Technologies
J. Reiter, JPL
- **Thermal Insulation – JPL**
- Hydrogen Purity – UTRC
- Sensors – LANL
- **Thermal Devices - OSU**
- **Pressure Vessels – PNNL**
- BoP Catalogue – PNNL

Performance Analysis
M. Thornton, NREL
- Vehicle Requirements– NREL
- Tank-to-Wheels Analysis – NREL
- Forecourt Requirements - UTRC
- Manufacturing & Cost Analysis - PNNL

Integrated Power Plant / Storage System Modeling
B. van Hassel, UTRC
- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

System Architects
- Metal Hydrides– SRNL
- **Cryoadsorbents– JPL**
- Chemical Hydrides– LANL

Subscale Prototype Construction, Testing & Evaluation
T. Semelsberger, LANL
- **Risk Assessment & Mitigation – UTRC**
- **System Design Concepts and Integration - LANL**
- **Design Optimization & Subscale Systems – LANL, SRNL, UQTR**
- **Fabricate Subscale Systems Components – SRNL, LANL**
- **Assemble & Evaluate subscale Systems – LANL, JPL, UQTR**

•Technology Area Lead
•Technology Team Lead
•Technology Task Support

Relevance:
Objectives

JPL's objectives align with the Center Goals:

- identify state-of-art concepts and designs
- discover and identify technical barriers to system development
- develop means and/or identify trajectories to overcome barriers
- describe and develop enabling technologies toward achieving targets
- design, build, and test subscale prototype demonstrator for the MH system

- The purpose and focus of the JPL effort is *technology management*
  - Assessment of current state-of-art / fitness evaluations of existing technologies
  - Identification of technology gaps re: system requirements and operational demands
  - Assessment of impact of technology gaps on system developability
  - Up-selection of candidate approaches to device design and implementation for gap mitigation
  - Technology development, hardware design and analysis for up-selected technologies
  - Continuing assessment and feedback of emerging technologies

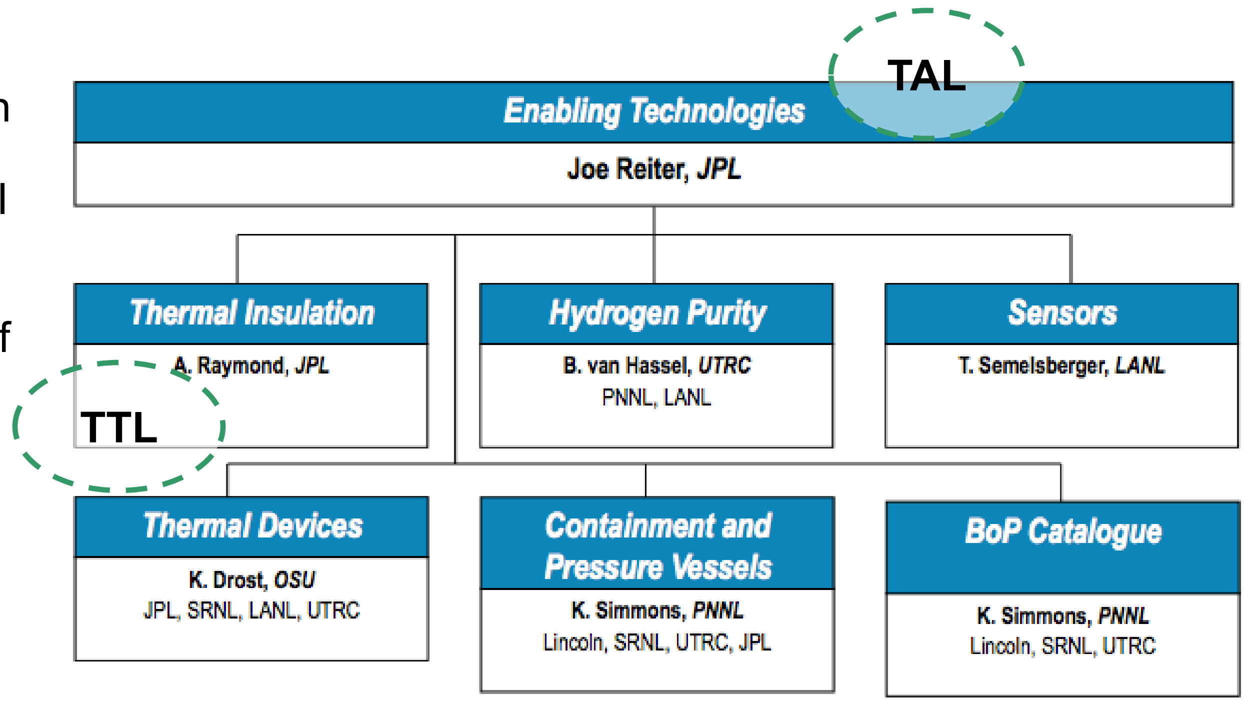
Relevance:
Milestones and Task Breakdown

- Management Tasks in support of Center
  - Enabling Technologies TAL (*Phases 1, 2 & 3*)
    - barriers: *all*
  - Cryo-adsorbent System Architect (*Phases 1, 2 & 3*)
    - barriers: *all*
- Technical Tasks
  - Task 1: Thermal insulation/vessel thermal management R&D (*Phases 1& 2)*
    - barriers: *thermal management, system weight and volume, on-board efficiency*
  - Task 2: Material/component thermal testing and design validation (*Phase 2*)
    - barriers: *balance-of-plant components, materials of construction, thermal mgmt.*
  - Task 3: Metal hydride prototype system testing and evaluation (*Phase 3*)
    - barriers: *all*
- Milestones (FY2010-2011)
  - 7/2010: Recommendation of MLVSI approach for cryogenic system insulation (Complete)
  - 10/2010: Advanced insulation concepts for cryo-absorbent system presented (Complete)
  - 1/2010: Fuel recuperator HX/flowthrough desorption design and modeling (Complete)
  - 2/2011: Go/No-Go recommendations presented to DOE for cryo-adsorbent system design (System Architect role) (Complete)
  - 3/2011: Initial CF tank material vacuum outgassing measurements (underway)
  - 4/2011: Construction of Low Temperature Insulation Test Facility (underway)

Approach:
JPL Management Tasks in Support of HSECoE

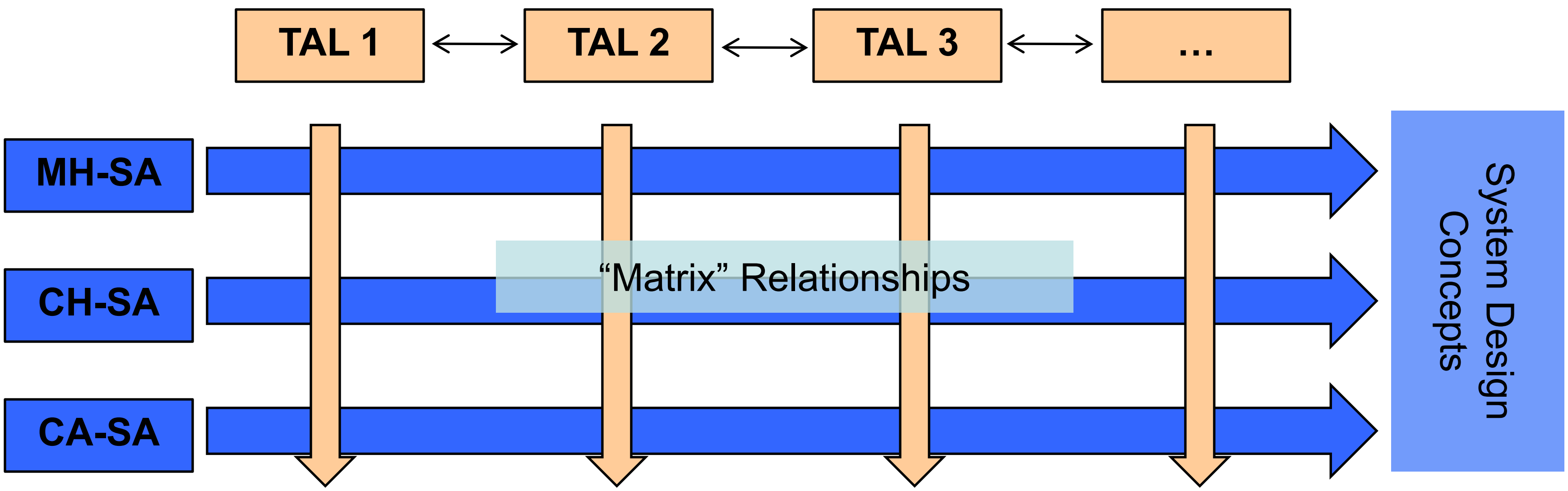
- JPL is the Technology Area Lead (*TAL*) for HSECoE's "Enabling Technologies" strategic technology area *(TA)*
  - This effort is dedicated to facilitating the evaluation of key technologies that serve as particular challenges to prototype development
  - As for other Technology Areas within HSECoE, the work will be managed via the Technology Team Leads (*TTLs*) that will directly interface at the task-level in each case
  - Within each Team, any number of individual tasks may be required to reach objectives

- JPL is also performing research within the TAL, developing approaches for passive thermal management of the storage vessel, thermal devices, and balance-of-plant components of the prototype system



Approach:
JPL Management Tasks in Support of HSECoE

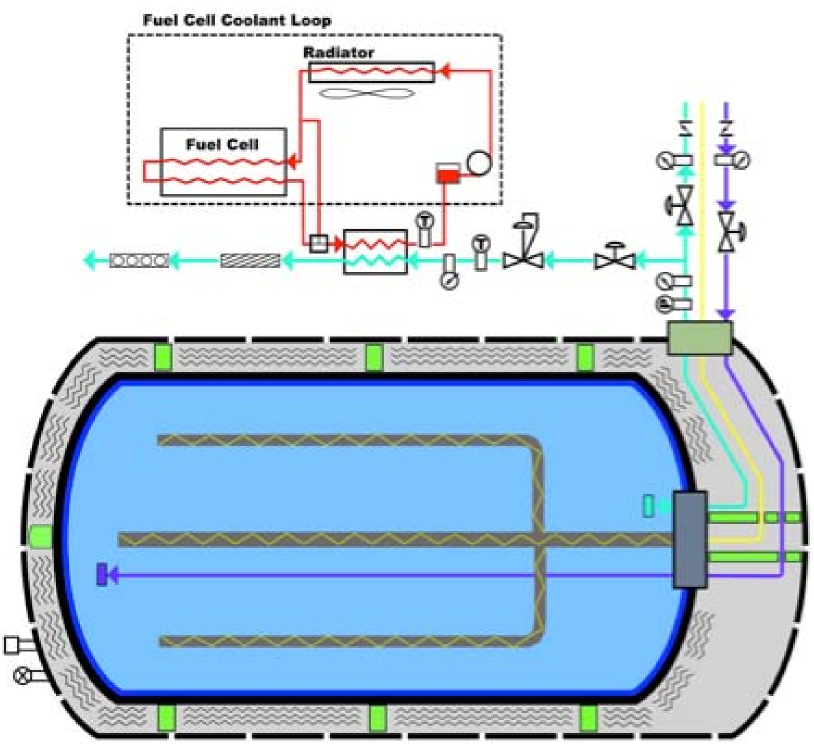
- JPL fills the role of System Architect (SA) for the cryo-adsorbent storage system design process
  - coordination of engineering efforts from Center partners
  - as SA, JPL interacts directly with HSECoE TALs, providing oversight and guidance toward the design of the CA system
  - maintains cognizance of the progress towards DOE targets/goals for the system design process



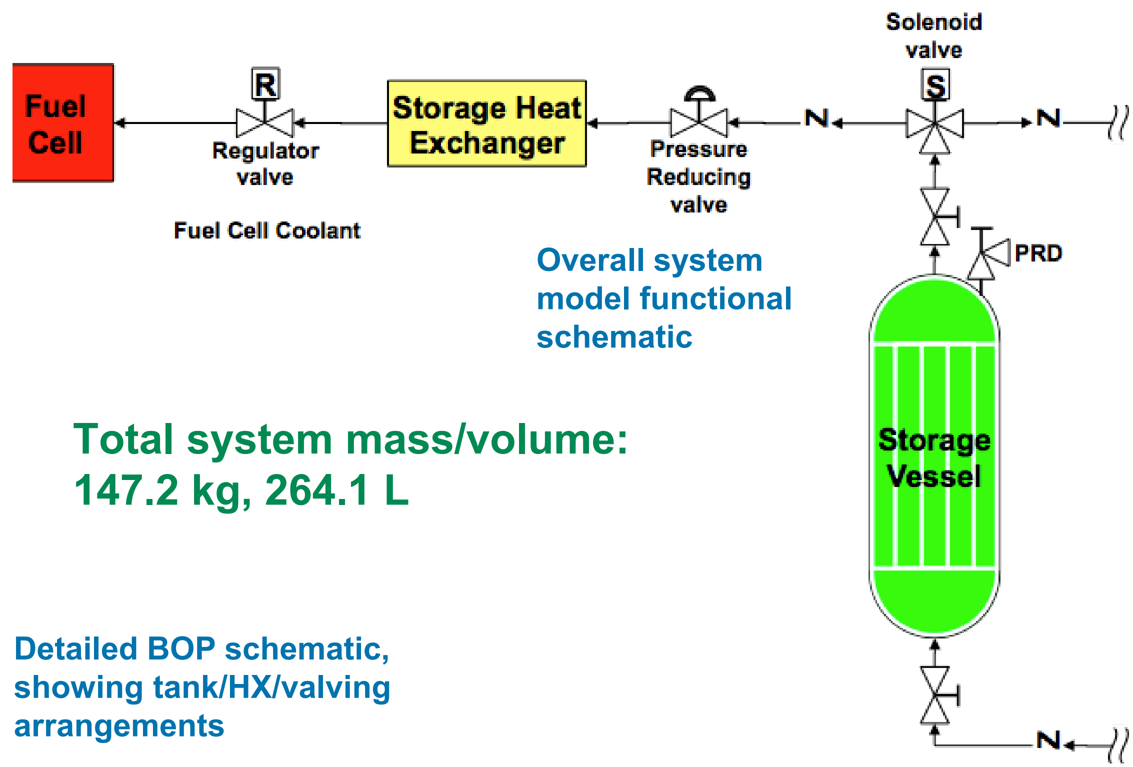
- SAs play a crucial role in maintaining the flow of data through the Center from TALs (data acquisition) to design teams and component/system builders (engineering); production of unified system design(s) was a focus in FY2010

Technical Accomplishments:
JPL Management Tasks in Support of HSECoE

- 200 bar AX-21 (MaxSorb^{TM}), no thermal enhancement, 80 K initial fill
- Porous-bed "flow-through" cooling/fueling design for adsorption
- Desorption heat via tank-integral electrical resistance elements/HX
- Fuel recuperation via fluid-coupled HX loop using PEMFC coolant
- Type 3 CF/Al lined pressure vessel, 2:1 aspect ratio
- Double-wall 60-layer MLVI jacket design, ~5W heat leak @ 80 K



Detailed BOP schematic, showing tank/HX/valving arrangements



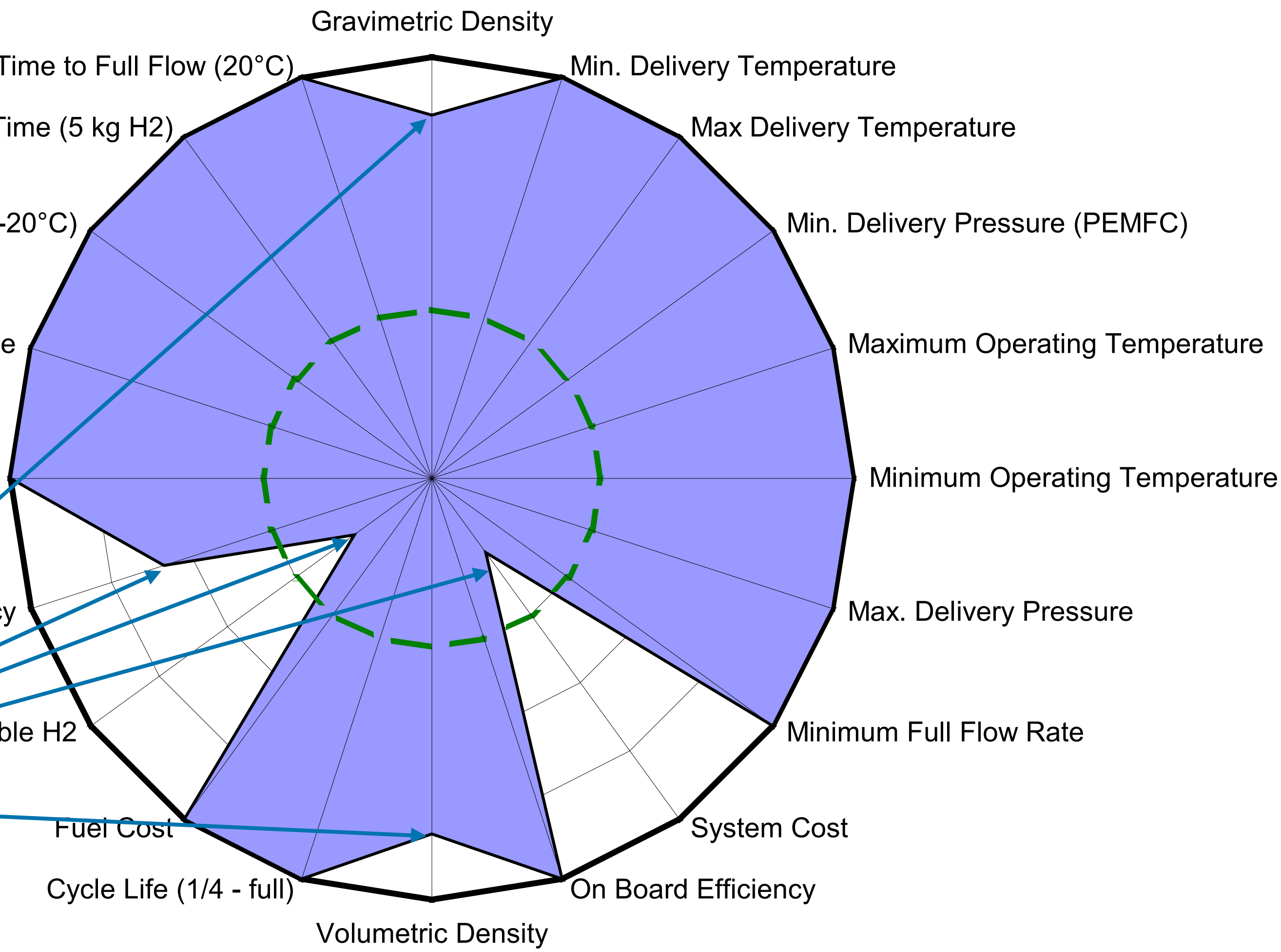
Overall system model functional schematic

Total system mass/volume: 147.2 kg, 264.1 L

Technical Accomplishments:
JPL Management Tasks in Support of HSECoE

"Spider Chart" - Measuring System Metrics vs. Targets (2010): *200 bar AX-21*

This chart highlights the challenges/barriers to the 2010 Targets, representing work across the **entire Center**



1. Gravimetric Density
2. System Cost
3. Volumetric Density
4. Loss of Useable Hydrogen
5. WPP Efficiency

- 15 Targets Fully Met
- 3 Targets above 40%
- 2 targets Below 40%

Technical Accomplishments:

JPL Management Tasks in Support of HSECoE

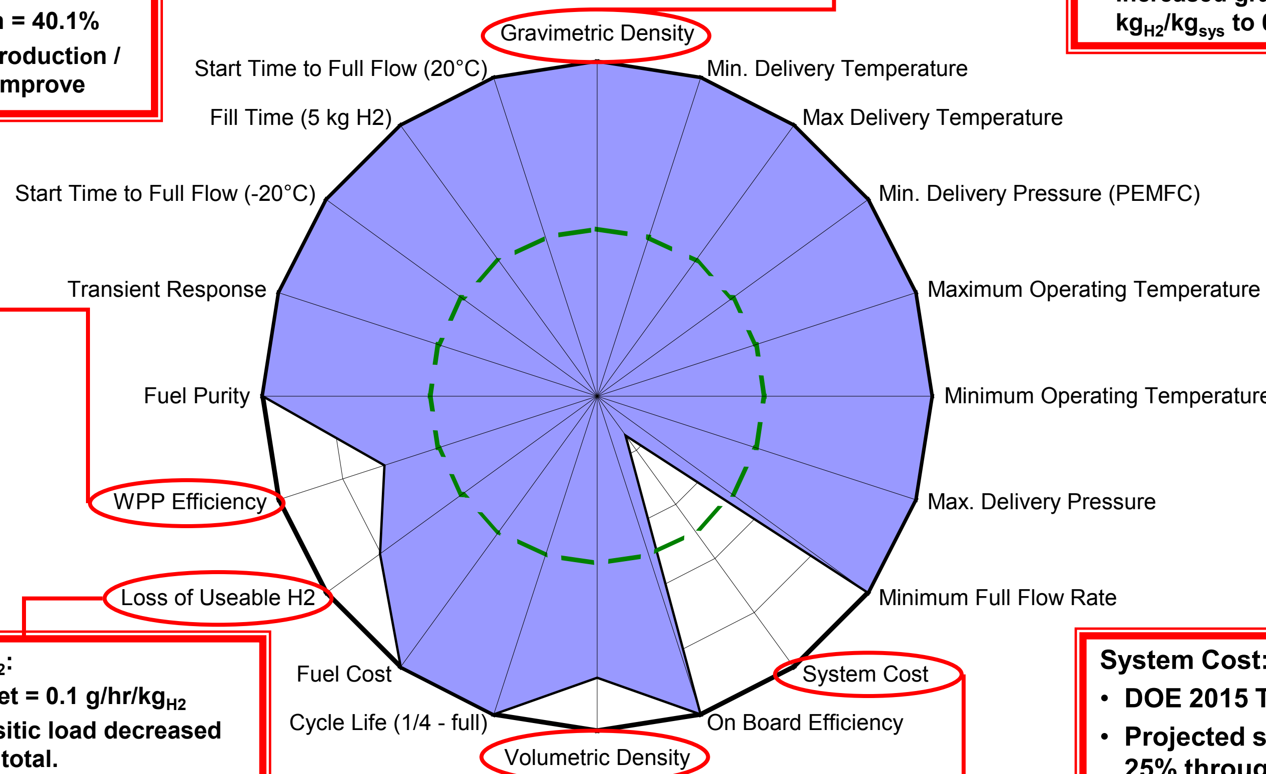
Metrics vs.Targets (2015) *200 bar MOF-5*

WPP Efficiency:

- **DOE 2015 Target = 60.0%**
- **Adsorbent system = 40.1%**
- **Coordinate with production / delivery peers to improve**

Gravimetric Density:

- **DOE 2015 Target = 0.055 kg_{H2}/kg_{sys}**
- **Projected system mass decrease by media change (22%), media compaction (14%), and tank improvements (11%)**
- **Increased gravimetric density from 0.038 kg_{H2}/kg_{sys} to 0.061 kg_{H2}/kg_{sys}**



This chart highlights the means to achieve the 2015 Targets, representing work across the **entire Center**

Loss of Usable H_2:

- **DOE 2015 Target = 0.1 $g/hr/kg_{H2}$**
- **Projected parasitic load decreased by 43% to 3 W, total.**
- **Dormancy can be improved by a similar factor, and enhanced by utilizing vented hydrogen in partial energy-recovery schemes**
- **Decreased loss of usable H_2 from 0.44 $g/hr/kg_{H2}$ to 0.062 $g/hr/kg_{H2}$**

Volumetric Density:

- **DOE 2015 Target = 0.040 kg_{H2}/Liter**
- **Projected system mass decrease by media change (4%), media compaction (29%), and tank improvements (7%)**
- **Increased volumetric density from 0.022 kg_{H2}/Liter to 0.034 kg_{H2}/Liter**

System Cost:

- **DOE 2015 Target = $2/kW-hr**
- **Projected system cost decrease by 25% through volume reduction (media compaction) and the system costing reported by Ahluwalia *et al* (2010)**
- **Decreased system cost from $18.4/kW-hr to $13.8/kW-hr**

Key assistance provided by D. Tamburello

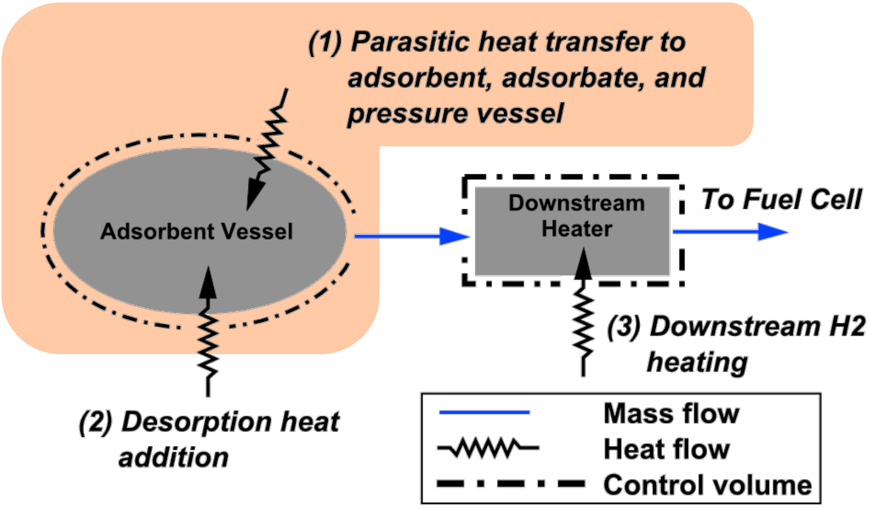
SRNL

Approach:

Task Area 1: Thermal Insulation R&D

Advanced Cryogenic Vessel Design

- Previous work
  - literature search/development; "Insulative Materials Database"
  - parametric verification of passive thermal management techniques
  - identification of MLVSI as "go ahead" approach for cryo system



- Insulation design criteria[1]
  - H_2 loss: 0.05 g·h-1·kg-1
  - Min/max operating temperature: -40 to 60°C

Why worry about thermal management?

While obvious that cryogenic systems must rely on passive thermal control due to the need to retain sensible heat (latency, dormancy, efficiency), it is somewhat less obvious that elevated-temperature systems (MH, CH) would also benefit from such passive control (onboard efficiency, etc.)

Vessel Configurations Used in Analysis

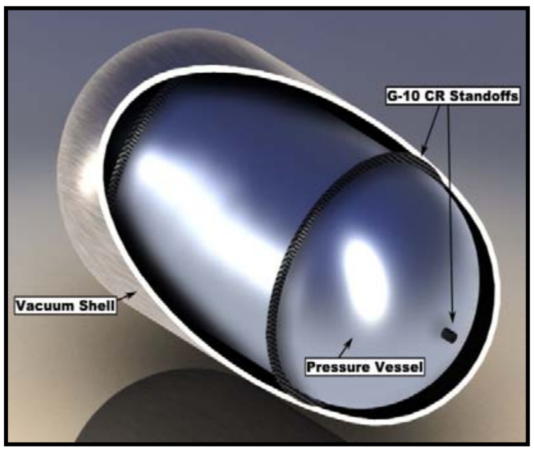
	AX-21[1]	MOF-5[2]
Fill Temperature	80 [K]	80 [K]
Fill Pressure	70 [bar]	70 [bar]
Adsorbent Mass[2]	48.3 [kg]	28.5 [kg]
Al Vessel Mass	61.8 [kg]	73.3 [kg]
Initial H_2 Mass	6.8 [kg]	6.5 [kg]

[1] DOE, Targets for Onboard Storage
[2] Sudik, *AIChE Annual Meeting Presentation* (2010), and Richard et al., *Adsorption* (2009, Pt. I)

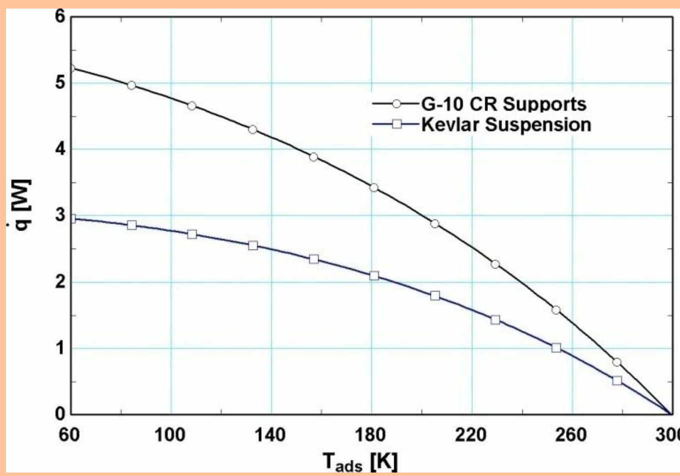
Technical Accomplishments:
Task Area 1: Thermal Insulation R&D

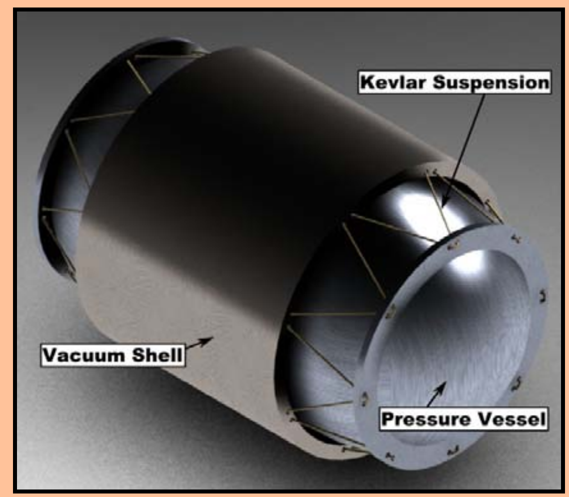
Advanced Cryogenic Vessel Design: thermal standoffs and vacuum insulation

- Current cryogenic vessel design has a total parasitic load of ~5 W: 25% radiation, 75% conduction (*via analytical model*)
  - utilizes 60-layer MLI, optimized for 80-160 K operating temps
  - advantageous to **engineer improvements to the physical supports** (i.e., reduce conductive load)



The baseline design utilizes an approach adopted by LLNL/ANL, etc.; cutaway shows the configuration of G-10 standoffs in the vacuum space.





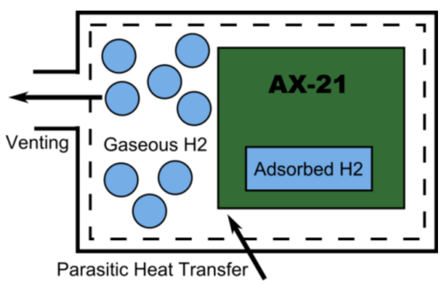
The proposed Kevlar® "web" suspension (cutaway shown) can reduce *total* parasitic losses by 43%, even when sized to support 8 g loads (as suggested for contingencies).

Technical Accomplishments:
Task Area 1: Thermal Insulation R&D

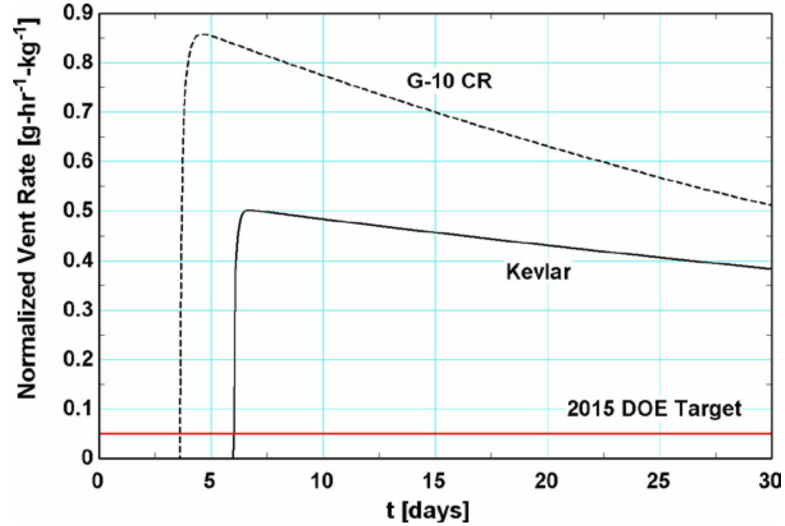
Advanced Cryogenic Vessel Design: dormancy and hold time

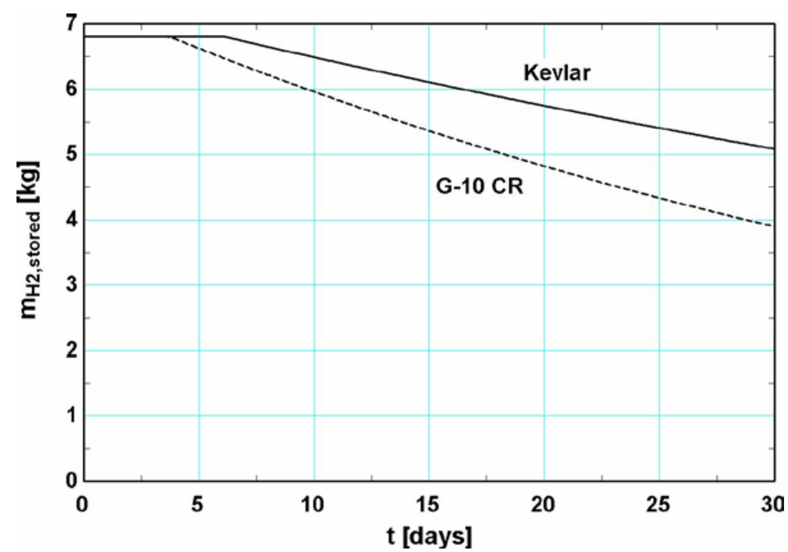
- Proposed Kevlar® "web" suspension shows 43% lower *total* heat transfer rate for AX-21 system
  - MOF-5 analysis underway

- Lumped-parameter sorption bed model used to predict venting
  - Relief setting: 100 bar
  - Properties based on solution thermodynamics[1]. Para-ortho conversion included[2]



Control volume for lumped-parameter dormancy model





[1]Richard et al. (2009, Pt. II) *Adsorption*
[2]Meagher (2008) *M.S. Thesis SUNY Buffalo*

With advanced design, system hold time (i.e., time to vent) is extended almost 2x *without any enthalpy reduction* via daily driving

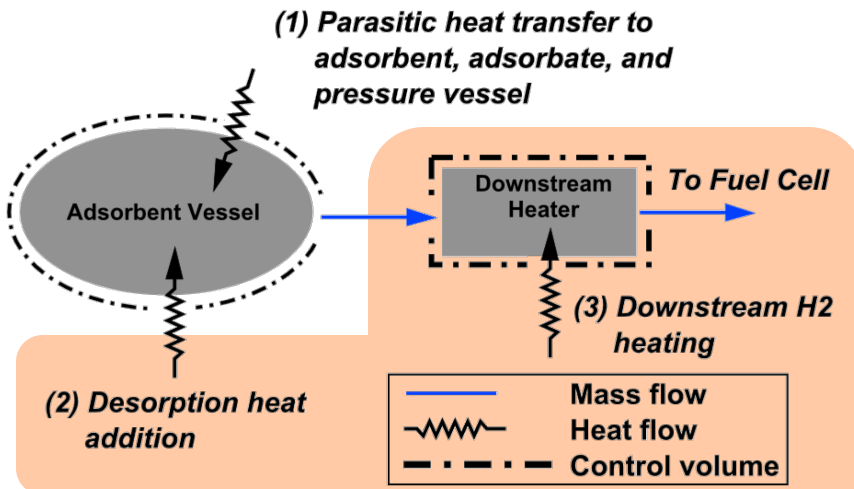
Proposed Future Work:
Task Area 1: Thermal Insulation R&D

- **Immediate Path Forward**: Will continue to refine the state-of-art analytical model and update for current/evolving design details (underway; next results mid FY2011)
  - run models for cases other than worst-case (already modeled)
  - analyze 200 bar dormancy: high pressure will give greater storage fraction, lower surface area & heat xfer
- **Benchtop Cryogenic Insulation Characterization**: Will characterize the performance of advanced vessel/insulation designs and their effects on system dormancy via custom-built cryogenic facility (underway; initial results late FY2011)
  - validate analytical model results in 80-160 K operating range
  - generate parametric results for T, #MLI layers, etc.
- **Subscale Dormancy Measurements**: Will determine the effects of advanced cryo-vessel design on dormancy/hold times for a subscale vessel assembly at cryogenic temperatures (planned; initial results mid FY2012)
  - will produce data to compare directly with published cryo-compressed system results

Approach:
Task Area 2: Thermal Testing & Validation

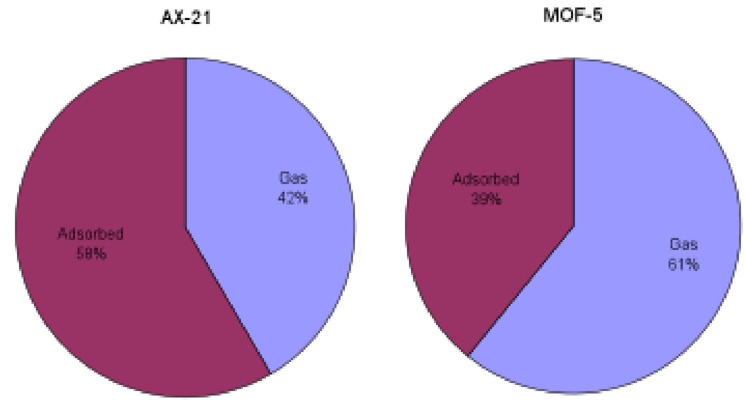
Cryogenic Fuel Energy Management

- Previous work
  - JPL-designed *Cryogenic Materials Test Facility* (late 2010, not built)
- Desorption heater design criteria
  - H_2 delivery rate: 1.6 g·s-1
  - Heat input: ~4 kW
- Downstream H_2 heater design criteria
  - Minimum H_2 temperature: -40°C
  - Various configurations considered



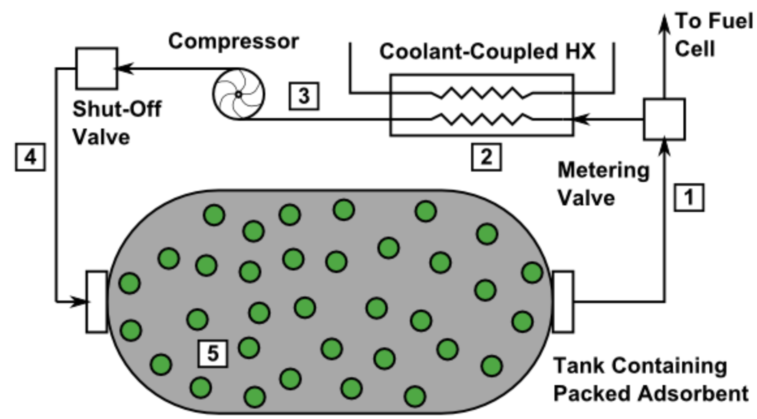
Cryogenic Fuel Energy Management: H_2 loop desorption heating

- Initially full tank delivering 1.6 g·s^{-1} is most demanding case
  - Assume desorption heating commences at 20 bar, use lumped model to obtain TTDH[1]
  - Resistance heating is one option, but SRNL modeling work suggests insufficient conduction may be a challenge; preferable to use available enthalpy where possible



H_2 storage phases at 200 bar, 80 K

- Recirculation loop leverages large surface area of packed bed
  - Adsorbent media have poor thermal conductivities; **convection is therefore a most effective method** for addition of desorption heat
  - Loop is driven by a compressor capable of operating at high pressure (~ 200 bar for current design) *but not necessarily* at high delta-P
  - Implementation can reduce tank volume by eliminating internal HX, and simplify tank/media assembly and packing

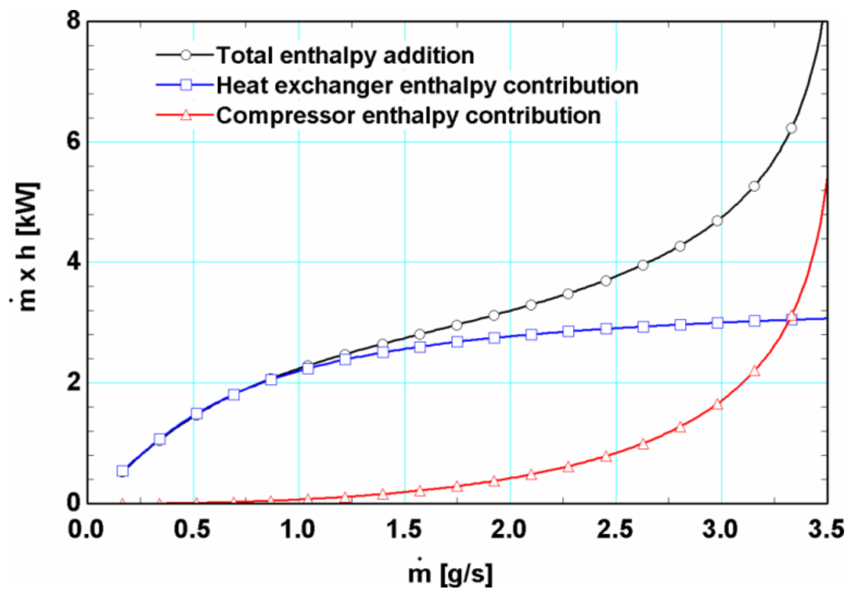


Recirculation loop desorption heater

[1]Time to Desorption Heating (TTDH): for tank delivering 1.6 g·s^{-1} from fill at 80 K, 200 bar

Cryogenic Fuel Energy Management: H_2 loop desorption heating

- 1st-order model developed using Fanno and Rayleigh flow relations
  - Evaluated at most demanding condition: low density H_2 near empty (5 bar)
- Continuing to evaluate combinations of tube geometry and operating temperature, pressure
  - Preliminary analysis shows pressure loss can be quite large with small-bore tubing
  - Additionally, high-pressure compressor and heat exchanger are **non-trivial**

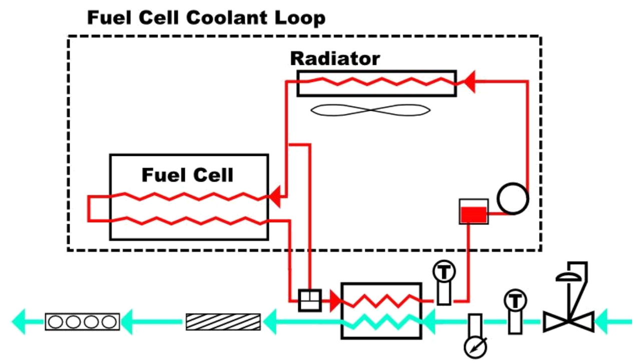


Contributions to enthalpy increase in circulated hydrogen stream versus mass flow rate for a representative system

Ongoing work with balance-of-plant (BoP) team leads to understand current capabilities for hermetic pumping of hydrogen at operating temperatures and pressures: identified technology gap (cf. "Future Work")

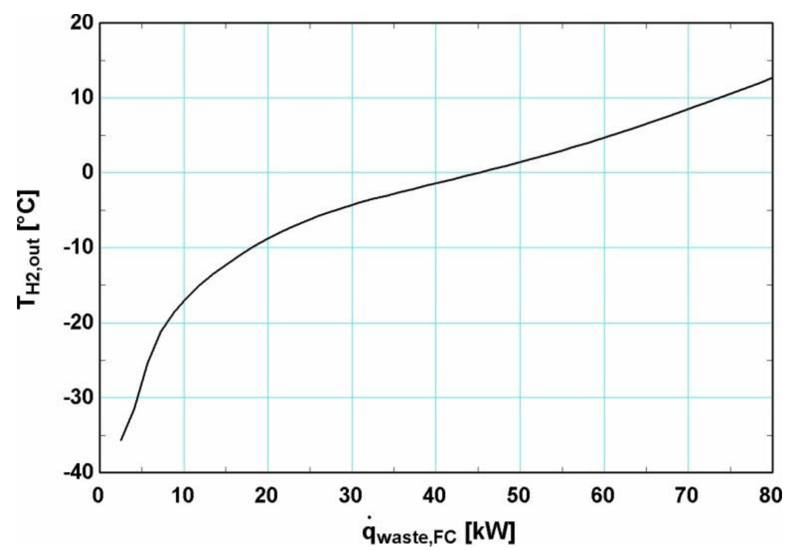
Cryogenic Fuel Energy Management: downstream H_2 HX design & modeling

- Modeled (3) configurations for a device to heat expanded H_2 from 60-233 K (~4 kW)
  - Air-coupled hydrogen HX with in-line heater: *unstable ice formation*
  - Independent hydronic loop: *size, unstable ice formation*
  - Fuel cell coolant loop: *utilizes available radiator and large coolant flow rate to avoid ice, frost stabilizing*



- Due to the cryogenic storage temperatures (all-time < 160 K), this requirement is best interpreted as a need to **raise the temperature of flowing fuel** to -40°C

T_{amb}	H_2 Flow Rate	$T_{H2,out}$
-30°C	0.8 g·s^{-1}	-40°C
-20°C	1.6 g·s^{-1}	-44°C



Delivered H_2 temperature versus fuel cell waste heat, -40°C ambient. Assumes H_2 flow rate is proportional to waste heat with 50% recovery

- This approach does require minimal additional pumping and fan power during idle, leveraging the coolant recirculation pump/fan within the FC subsystem. For off-nominal start-up at temperatures < -30°C, an additional in-line heater may be required.

Proposed Future Work:
Task Area 2: Thermal Testing & Validation

- **Immediate Path Forward:** Will continue to refine analytical models for HX and desorption heating systems (underway; next results mid FY2011)
  - modify circulation loop tube geometry wrt. pressure loss for Desorption Loop Heater and evaluate operation over range of conditions; continue development of resistance heater (with SRNL) while examining capabilities of required BoP equipment (H_2 compressor/fan, valves, etc.)
  - Develop coolant metering scheme for Fuel Recuperator HX and feed-forward to model framework (via SRNL/UTRC) for incorporation into master FC module; consider inline resistance heater for startup conditions.
- **Carbon Fiber Outgassing**: Will measure outgassing rates for typical CF vessel wraps at variable T, P. (underway; initial results mid-late FY2011)
  - Identify outgassing rates and chemical species, ideally for typical and advanced CF/resin systems
  - Measure efficacy of selected mitigation technologies; acceptable vacuum level is < 10e-5 Torr.
- **Subscale Fuel Recuperator HX Testing:** Will construct a bench-top facility to verify that low-temperature hydrogen can be heated to the target delivery conditions in a downstream HX. An understanding of sealing within heat exchanger joints will be gained as a result of this testing. (planned; initial results early FY2012)
  - nominal test conditions derived from DOE Targets: -40°C, 5 bar minimum at 1.6 g/s flow rate.
  - testing will assist understanding the technical challenges of maintaining hermiticity of a fluid-coupled H_2 HX.
- **Mechanical Testing of Vessel Thermal Supports:** Will characterize the onboard survivability of a vacuum-insulated cryogenic vessel as a means to demonstrate the robustness of this technology. (planned; initial results mid FY2012)
  - perform impact and vibration testing of a subscale test device..
  - The target for thermal standoff inertial loading is 8 g; the target for allowable resonant frequency is not yet defined.

HSECoE

Approach:
Task Area 3: Prototype Testing and Evaluation

Jet Propulsion Laboratory
California Institute of Technology

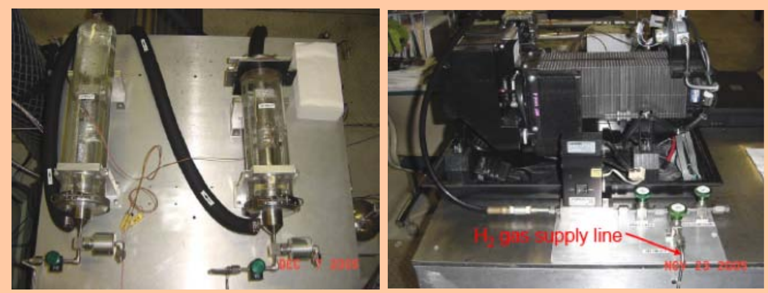
- This activity is JPL's primary role in **Phase 3** and supports the entire Center
  - **Presupposes the selection** of a metal-hydride based prototype demonstrator, although contributions may be made in the event a MH system is not selected
- Utilizes a currently active fabrication/testing/characterization laboratory at JPL with available space for ~2 test-stands
  - *Hydrogen Storage Engineering Laboratory* (HSEL) features fully-instrumented ($LabVIEW^{TM}$) test stands with H_2/pressure/vacuum manifolds, outfitted with dry-pumping capability and gas analysis

Subscale Prototype Construction, Testing & Evaluation

T. Semelsberger, LANL

- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

- Tasks aligned under this objective are currently scoped to run from Q1FY2013 through Q2FY2014; i.e., 1.5y +
- Selected subtasks:
  - Develop test procedures and test safety plan
  - Build test stand, develop test software
  - Assemble system/fill/closeout hydride storage vessels
  - Integrate system with test facility
  - Analyze and disseminate data
  - Disposition storage prototype at conclusion of testing



Testing an integrated MH-bed/PEM-FC hybrid power system on a facility within JPL's Hydrogen Storage Engineering Lab (HSEL)

Although ongoing improvements at JPL's HSEL facility will ultimately contribute to this effort, all the details described above are ***Future Work***; JPL intends to utilize development of experimental systems and approaches in Phase 2 to lead to easy transition to Phase 3 prototype testing work

Collaborations:
Selected; Non-exhaustive

- General
  - SSAWG, HSECoE-at-large
  - Center collaborations are constantly leveraged within the matrix structure & function

- System Architecture
  - D. Tamburello (SRNL): CA system models, performance metrics, flowsheets
  - C. Ahn (Caltech): CA materials performance and testing approaches
  - D. Kumar (GM): CA vessel design approach, testing/performance
  - A. Sudik (Ford): MOF-5 material characteristics, novel developments

- Technology Area discussions/regular technical interchanges
  - K. Simmons (PNNL): Pressure Vessels TTL/tank design and costing, BoP studies
  - N. Newhouse (Lincoln): tank design criteria and novel approaches
  - S. Garrison, D. Tamburello (SRNL): cryo-system thermal management

Summary

- **Relevance & Approach:** JPL is uniquely suited to performing in the roles it fulfills for the HSECoE, and maintains close coordination with Center management to incorporate mission changes and technical demands
  - JPL maintains the *Hydrogen Storage Engineering Laboratory* (HSEL), outfitted for high-pressure hydrogen supply, sampling, and measurement; cryogenic testing capabilities, and hydrogen storage material handling facilities

- **Technology management (TAL/SA)**: Managing inter-communication of groups contributing to design of cryo-adsorbent system as well as overcoming technical barriers discovered in Phase 1.
  - Coordinating the *Enabling Technologies TA* is important to maintaining an "upward" flow of results and data to enhance system development (thermal device design & modeling, composite vessel manufacturing and testing, balance-of-plant component identification and testing, etc.)
  - The *System Architect* role enabled a path for the Center to produce collaborative results of the Phase 1 development and modeling work at the DOE Phase1/2 Transition; AX-21 was identified as a "baseline" design with a goal of engineering a MOF-5 based advaned technology system for 2015/Ultimate

- **Technical Accomplishments**: JPL expanded the model space for several thermal technologies in Phase 1
  - Advanced cryogenic vessel design: re-analysis of the MLVSI "baseline" design (~5 W parasitic) vs. Kevlar® suspension (~3 W parasitic)
  - Examined dormancy and hold time in greater detail – focus on the *importance of daily driving* in achieving the DOE H2 Loss target vs. a *true* 31-day case criterion
  - Incorporated a design for hydrogen fuel conditioning (Fuel Recuperator HX) into the Center model framework; this design capable across the operating envelope of the AX-21/MOF-5 system(s) utilizing FC waste heat in closed-loop
  - Developed a design criteria and initial analytical model for H2-loop desorption heating, citing additional onboard efficiency gains and identifying the H2 recirculator pump as a *technology gap* for further investigation

- **Future Work in Phase 2**: Experimental data will aim to validate existing model architectures, with a focus on testing designs at cryogenic temperatures
  - Experiment: validate advanced cryogenic vessel architecture (dormancy and H2 loss)
  - Experiment: demonstrate H2 fuel conditioning HX design, validate model
  - Experiment: composite material outgassing measurements
  - Experiment: mechanical robustness of vessel thermal standoffs

Technical Back-Up Slides

Technical Backup:

Insulative Materials Database

Material/Products	Company	Temperature Range C (oustide temp -30/50)		K Value (mW/m-K)	Density	Cost	units/size
Blankets							
CryogelZ	Aspen Aerogel	-270	90	15	8.0 lb/ft^3	$150.00	5mm 60"x59"
Pryogel XT	Aspen Aerogel	-40	650	21	11 lb/ft^3	$150.00	5mm 60"x59"
Pryogel XTF (fire protect)	Aspen Aerogel	-40	650	21	11 lb/ft^3	$250.00	10mm 60"x59"
Pryogel 2250	Aspen Aerogel	-270	250	15.5	10.7 lb/ft^3	$150.00	2mm 60"x59"
SpaceLoft Subsea	Aspen Aerogel	-200	200	13.9	8 lb/ft^3	$150.00	5mm 60"x59"
JPL Aerogel	JPL	cryo	1600	9 (1 atm @23 C)	N/A	N/A	N/A
composite silica aerogel, titania and silica powder	JPL	cryo	1600	4 (23 C)	N/A	N/A	N/A
Nanogel Thermal Wrap	Cabot	-200	125	21 (12.5 C)	4.68 lb/ft3	$150.00	8 mm X1m X1m
Nanogel Compression Pack	Cabot	-200	200	~18 (25 C)	~6.24 lb/ft3	custom	
The Nanogel Expansion Pack	Cabot	-200	200	~18 (25 C)	~6.24 lb/ft3	custom	
Thermablok Blanket	Thermablok	-200	200	13.6 (25 C)	9.4 lb/ft^3	$4.99	125'x57"x0.4" (593.75 sq ft)
Semi-Rigid/ Molded							
Trymer Polyisocyanurate (PIR)	Atlantech Distribution / made by Dow Chemical	-183	148	27.38 (24 C)	1.65 lbs./ft^3	$24.96	15" pinpe size x 1" thick in 3" sections 3 per ft
Semi-Rigid Cork Insulation	McMaster-Carr	-200	130	37.5 (20 C)	7-8 lbs/ft^3	$7.68	12"x36"x1" sheets
Semi-Rigid PVC Foam Insulation	McMaster-Carr	-198	71	24.5 (24 C)	3 lbs/ft^3	$68.66	32"x48"x1"
Rigid Fiberglass Insulation	McMaster-Carr	-17.78	232	31.7 (24 C)	3 lbs/ft^3	$12.43	24"x48"x1"
Ultra-Flexible Fiberglass Insulation	McMaster-Carr	-17.78	538	37.5 (24 C)	2.4 lbs/ft^3	$14.10	24"x96"x1"
Rigid Mineral Wool Insulation	McMaster-Carr	-17.78	649	33.1 (24 C)	6.8-8.6 lbs/ft^3	$8.50	1"x1"x3"
Semi-Rigid Mineral Wool Insulation	McMaster-Carr	-17.78	649	34.6 (24 C)	8 lbs/ft^3	$6.19	24"x48"x1"
ısulation Extra-High Temperature Sheets	McMaster-Carr	-17.78	1051.7	40.35 (800 C)	19 lbs/ft^3	$171.97	24"x40"x1"
Loose-Fill							
Glass Bubbles K1	3M	cryo	<600	47 (21 C)	7.8 lb/ft3	$5.00	.25 lbs
Glass Bubbles K15	3M	cryo	<600	55 (21 C)	9.36 lb/ft3	$5.00	.25 lbs
Cryogenic Perlite	Perolite Products, Inc	below -100	800	40-60 (24 C)	2-25 lb/ft3	$5.50	4 cubic feet bag
Evacuated Perlite	l Tech or Exfoliators PTY LTD or incon c	below -100	800	.7 (-107 C)	8-9.5 lbs./ft^3	$5.50	4 cubic feet bag
Non-Evacuated Perlite	Perl Tech or Exfoliators PTY LTD	below -100	800	37 (24 C)	2- 6.24 lbs./ft^3	$5.50	4 cubic feet bag
Provosil / Perlite Fill	Redco II	-240	1093	29 (-101 C)	2 to 20 lbs./ft^3	$13.00	4 cubic feet bag
Nanogel Translucent Aerogel	Cabot	-200	250	18 (25 C)	5.6 – 6.2 lb/ft3	$49.95	1 gallon (.5 lbs)
Nanogel IR Opacified Beads	Cabot	-200	250	10-15 (-88 C)	6.24 lb/ft3	$65-100	per kg
Nanogel Fine Particle Aerogel	Cabot	-200	250	18 (25 C)	2.5 – 6.2 lb/ft3	$65-100	per kg
MISC							
Void-Filling Foam Insulation	McMaster-Carr	-128.9	93.3	23.1(24 C)	1.75 lbs/ft^3	$34.15	12 sq. ft 1" thick

Raw data as well as parametric results are provided to Center partners via *Sharepoint* site

Technical Backup: *Adv. Vessel Design Model Details*

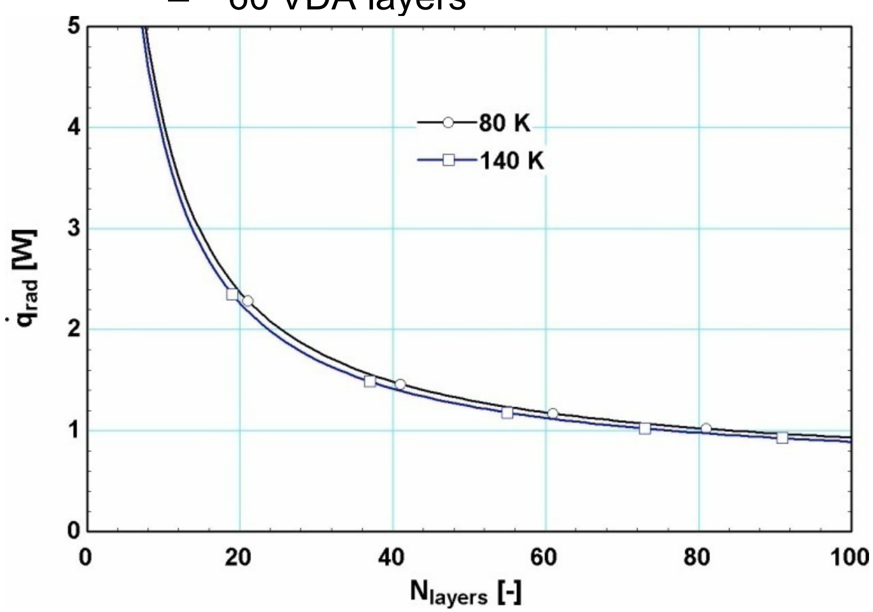
Advanced Cryogenic Vessel Design: parasitic load analysis and modeling

Parasitic Conduction

- Temperature-dependent conductivity
  - G-10 CR Fiberglass Epoxy supports: NIST Cryogenic Technologies Group
  - Stainless steel H_2 lines: *Marquardt et al. (2000) International Cryocooler Conference*
  - Kevlar® supports: *Ventura and Martelli (2009) Cryogenics*
- 1-Dimensional: end caps and H_2 lines
  - Averaged G-10 CR conductivity in normal and wrap directions
- 2-Dimensional: notched-ring supports
  - Assume negligible contact resistance between supports and tank/shell

Parasitic Radiation

- Evacuated gap between pressurized tank and shell
- Model for specular-diffuse reflections, two-band approximation
  - Seam affected zone included
  - 60 VDA layers



This "load vs. layers" plot for radiation through the MLI blanket, (T_{amb} = 300 K) shows little room for optimizing the radiative loss.

Technical Backup:
Relative Strength of Parasitic Loads in Adv. Design