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 and
Fuel Cells Program

Jet Propulsion Laboratory
California Institute of Technology

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Project ID
ST045

Overview

Timeline

- Project start date: February, 2009
- Project end date: July, 2014*
- % complete: 55% as of 4/1/12

Budget

- Expected total project funding:
  - $2.3M (DOE)*
  - $0.03M (Caltech)
- Funding received in FY11:
  - $465K (DOE)
- Funding received for FY12:
  - $350K (DOE)

* overall funding reduced via scope reduction in FY12; project may end earlier than 7/14

Barriers/System Targets (2017)

- A. System Weight and Volume
  - 5.5 $\%wt_{sys}$, 55 gH_2/kg_{sys}, 40 gH_2/L_{sys}
- C. Efficiency
  - 90% on-board
- D. Durability/Operability
- E. Charging/Discharging Rates
- G. Materials of Construction
- H. Balance-of-Plant Components
- J. Thermal Management

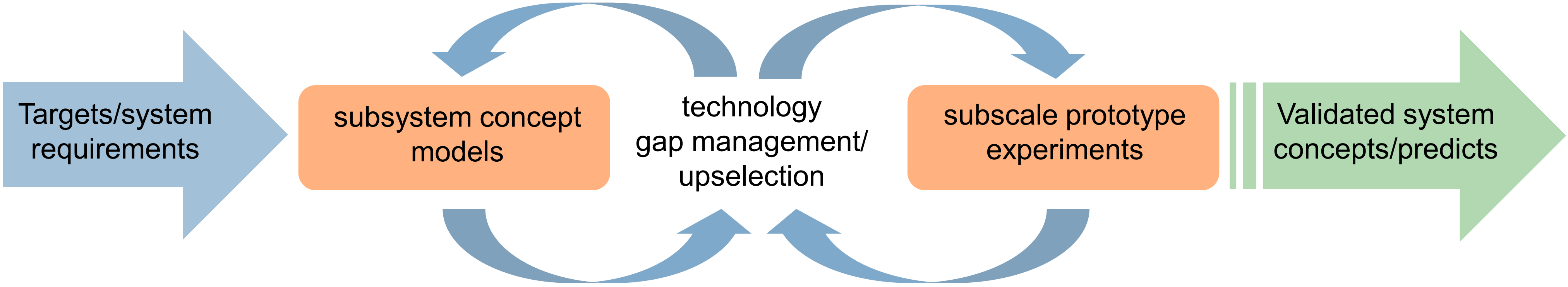
Partners

- Collaborations: HSECoE Partners
- Project Lead: SRNL
- Subcontract : Caltech

Project Objectives – *Relevance*

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 hardware components for model validation



Targets/system requirements

subsystem concept models

technology gap management/ upselection

subscale prototype experiments

Validated system concepts/predicts

JPL's mission is *technology management…*

- Assess current state-of-art and identify technology gaps
- Up-select and implement candidate approaches to mitigate gaps
- Development, design, and evaluate hardware implementations
- Continuously assess emerging technologies

…focused on *novel thermal/fluid system technologies*

- cryogenic system modeling, design, evaluation & testing
- multiphase heat transfer
- low-temperature material property measurements

Task/Target Alignment – *Relevance*

- JPL’s task areas address multiple DOE targets and technical barriers
  - cross-cutting technologies are implemented at the component/subsystem level, yielding performance at the system level that approaches all the targets *simultaneously*

JPL Task Area (2011-2012)	Targets Addressed[1,2]	Relevant Technical Barriers[1,2]
Design of high-isolation cryogenic vessel insulation	Loss of useable H_2 System Gravimetric Capacity System Volumetric Capacity WPP efficiency	J. Thermal Management A. System Weight and Volume C. Efficiency H. Balance-of-Plant Components
Measurement of COPV vacuum outgassing	Loss of useable H_2 Permeation and leakage Operational cycle life	D. Durability/Operability G. Materials of Construction
Design of downstream HX for fuel conditioning	Min/max delivery temperature Onboard efficiency Transient response System Gravimetric Capacity System Volumetric Capacity	J. Thermal Management H. Balance-of-Plant Components E. Charging/Discharging Rates C. Efficiency
Vessel cryogenic burst testing	Safety Operational cycle life	D. Durability/Operability G. Materials of Construction

[1] DOE MYPP, Storage Interim Update (2011)

[2] Targets and barriers listed in order of impact by each task

Programmatic Phases – *Approach*

- *Phase 1: System Requirements and Novel Concepts*
  - establish the Enabling Technologies development pathway (system engineering)
  - addressed passive thermal management for metal hydride and cryo-adsorbent systems (model development)
  - defined system architecture needs for the cryo-adsorbent system toward the Phase 1-2 Go/No-Go decision point (target metrics, benchmarking)

Go/No-Go (2011)

- *Phase 2: Concept Modeling, Design, and Evaluation*
  - formalize detailed model architectures for cryo-adsorbent system thermal management
  - implement facilities for model validation and hardware development
  - establish proof-of-concept subcomponent demonstrations, feed-forward to Phase 3

* JPL has shifted focus to novel cryogenic technology development and implementation as the Center has evolved

Go/No-Go (2013)

- *Phase 3: Subsystem Prototype Design, Fab, and Test*
  - fabricate and deliver validated components for cryo-adsorbent system demonstrator
  - JPL prototype test role descoped with metal hydride system (Go/No-Go 2011)

2011 Milestones – *Approach*

- 2011/12 Milestones align with “Future Work” projected at the time of the 2011 AMR
  - Some milestones added as new directions emerged

Date	Milestone	Status	Comments
7/2011	Experimentally validate model results for high-isolation cryo vessel design at 77 K, provide parametric results to Center.	Complete; validated model predicts < 2 W leak @ 77 K	Will extrapolate to 40 K; “subscale” 77 K dormancy validation experiments planned 5/2012
11/2011	Measure and characterize outgassing from carbon-fiber tankwall materials from 300 K > T 77 K	Partial; initial results show strong T-dependence	Inadequate instrumental resolution and sensitivity; new benchtop facility to be ready Q2 FY2012
1/2012	Refine coupled downstream HX model and predict performance for relevant drive cycles, conditions; fuel at 77 K and 40 K, 1.6 g/s (max)	Complete; targets currently met at all but coldest (-40° C) environment, device 1.1 kg, 1.0 L	Benchtop cryogenic validation experiments in design stage; expected operation late FY12
2/2012	Implement cryo-burst facility and determine burst limit for sample COPV at 77 K	Incomplete; temporary resource allocation shift to other tasks in 2011	Facility design complete; COPV tank articles are in manufacture at Lincoln Composites; initial burst at 77 K expected mid-FY2012

- Progress is on target to validate component designs in FY2012
  - Downstream HX
  - Advanced vacuum cryo-insulation
  - cryogenic COPV vessels (w/Lincoln Composites, PNNL)

JPL’s 2011 Task Breakdown – *Approach*

- Task Area: Advanced Thermal Isolation Design
  - demonstrate advanced techniques (exceeding current state-of-art) for insulating a cryogenic hydrogen storage vessel and increasing dormancy
- Task Area: Vacuum Outgassing Measurements
  - characterize impact of outgassing on storage vessel vacuum integrity
- Task Area: Downstream HX
  - validate fully-coupled model for external heat-exchanger and provide performance data to Center framework team
  - demonstrate potential mass and volume reductions over other candidate approaches to fuel conditioning/HX for JPL design
- Task Area: Vessel Cryo-Burst Testing
  - develop in-house facility and procedure for cryogenic (≤ 77 K) burst-testing of compact COPVs
  - perform cryo-burst operations for Center test articles; provide rapid turnaround for need-based testing

Previous Work (ca. 2011 AMR)
Accomplishments

- **System Architect Role**: JPL managed inter-communication of groups contributing to design of cryo-adsorbent system as well as overcoming technical barriers discovered in Phase 1.
  - In the *System Architect* role, JPL 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 advanced 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^{TM} 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 H_2-loop desorption heating, citing additional onboard efficiency gains and identifying the H_2 recirculator pump as a *technology gap* for further investigation

Cryo Vessel Advanced Thermal Isolation Design *Accomplishments*

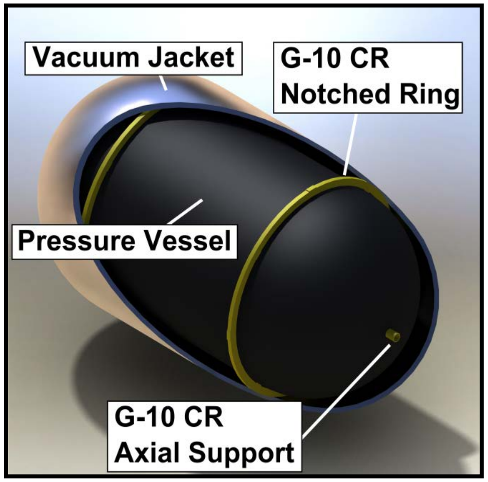
Detailed thermal and mechanical design performed for cryo vessel isolation system comparative model

- Advanced Kevlar™ "web" suspension (introduced at 2011 AMR) was compared to current state-of-art design using detailed model

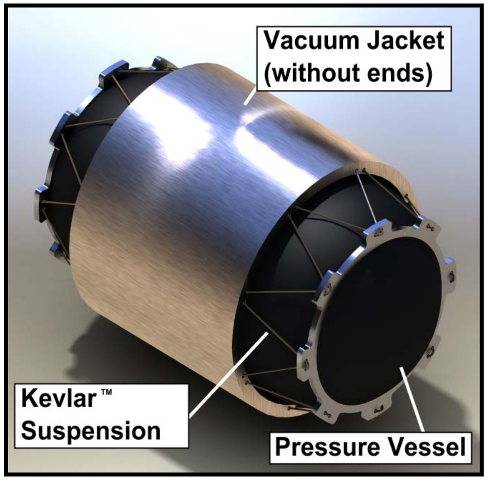
- G-10 CR standoffs and Kevlar™ 29 braid sized for ~8 g loads
  - G-10 fiber orientation, buckling sensitivity, and standoff location on par with current techniques
  - Kevlar designed for pretension, negative CTE and creep over 30 y

- Thermal design (conduction)
  - G-10 CR: 2-D conduction for rings, 1-D for tube
  - Kevlar™ 29: 1-D conduction
  - Vessel feedthroughs (H_2, etc.) designed as "torturous paths"

- Multi-layer insulation (radiation)
  - Using Lockheed equation[1] with gas effects for 60 layer blanket
  - Vacuum pressure assumed to be 10^{-4} torr, 38% more conservative than absolute minimum



The baseline "3 W" design utilizes a standard approach currently adopted[2,3].



JPL's advanced design uses a Kevlar web suspension to reduce conduction while retaining strength.

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[1] Keller et al (1974) NASA CR-134477

[2] Aceves (2010) DOE Merit Review

[3] Raymond and Reiter (2011) *Modeling and Testing of Cryo-adsorbent Hydrogen Storage Tanks with Improved Thermal Isolation*. Cryogenics Engineering Conference

Experimental Validation of Parasitic Model
Accomplishments

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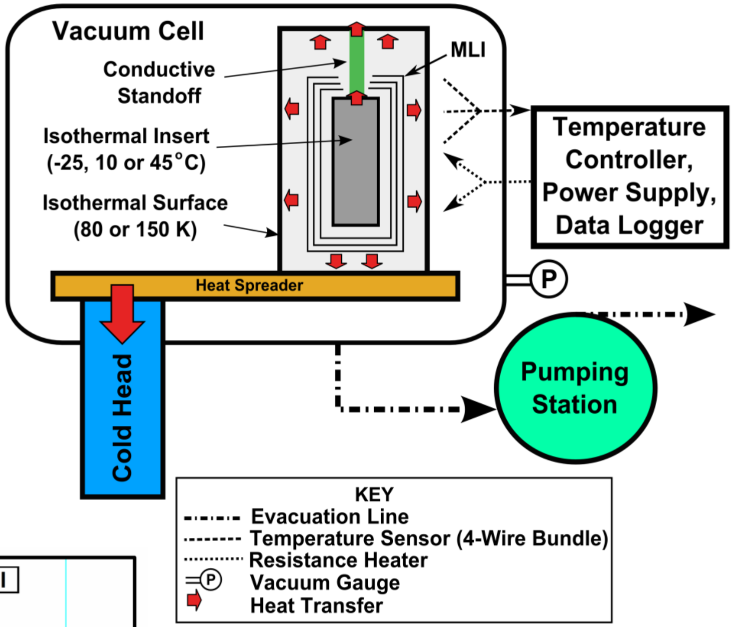
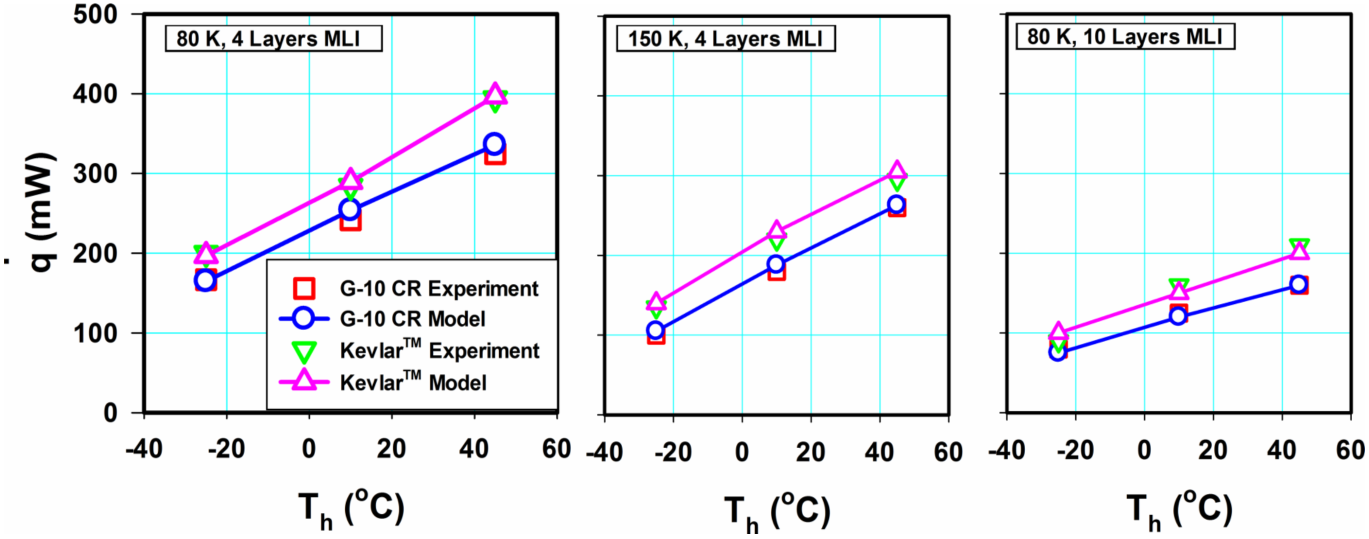
★ JPL's parasitic heat transfer model was validated to within ~10% by coupon-level experiments

- Heat load is simulated by a heated Al rod insert wrapped in MLI, suspended by G-10 CR or Kevlar 29; radiation controlled by MLI
- Cold/hot side temps: 80, 150 K / -25, 10, 45° C (~1 K uniformity)
- Measured pressure: ~10^{-7} torr, negligible gas conduction



Experimental setup (above) and test hardware (below)

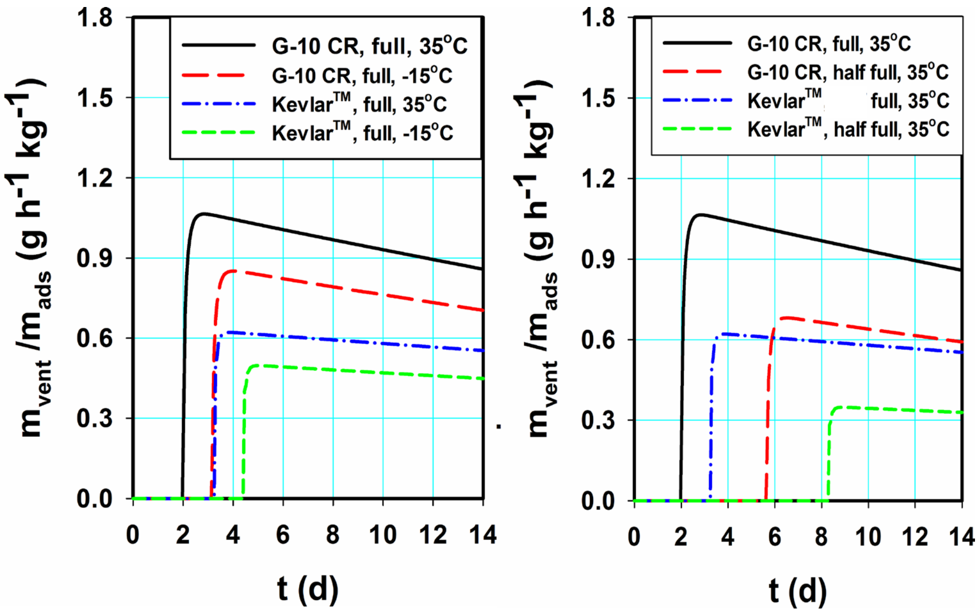


The correlation within each plot indicates good agreement between predictions and experimental results for both Kevlar™ and G-10 materials. The linear shape of the curves show the effect of T_{hot} on total heat transfer. The different plots illustrate expected variations in parasitic heat transfer for varying T_{cold} as well as the effect of variable MLI layer count.

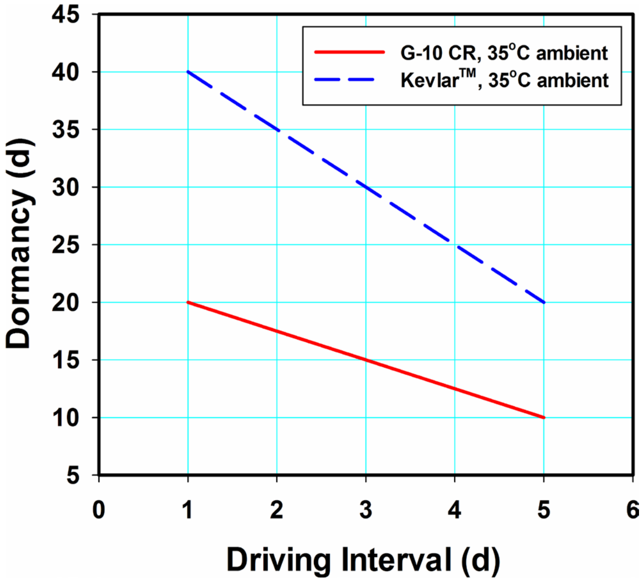
Validated Parasitic/Dormancy Model Predictions
Accomplishments

Validated model results show up to 38% performance improvement for advanced design over state of the art, from ~3 W to < 2 W total parasitic heat load

- G-10 CR: conduction ~60% of total, Kevlar^{TM}: conduction ~40% of total
- Dormancy cases were evaluated for representative vessel design using validated model
- Vent rates given for full tank at 80 K and half full (useable H_2 basis) at 110 K; initially full tank allowed to warm to 35° C will still store *some* H_2



Above plots compare the validated dormancy performance of the advanced design over the current state-of-art, showing an improvement in dormancy times for a full 5.6 kg H_2 tank from 2 to 3 d. The effects of a “half-full” tank are also shown.



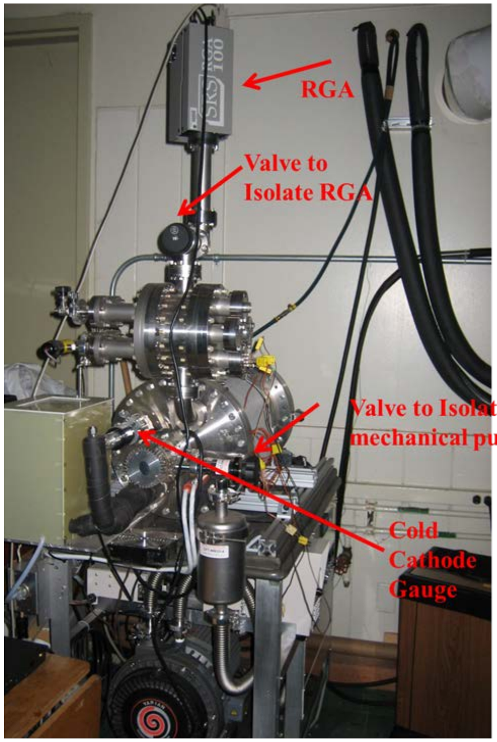
The plot at left shows the results of a dormancy simulation wherein an H_2 vehicle fitted with a cryosorbent storage system was “driven” for ~10 miles at arbitrary intervals (d = days). The increase in dormancy with decreasing interval (i.e., increased driving frequency) can clearly be seen, as can the marked difference between the state-of-art thermal design and the JPL advanced design, which need only be driven 20% as often to achieve the same level of performance.

Vacuum Outgassing Experiments
Accomplishments

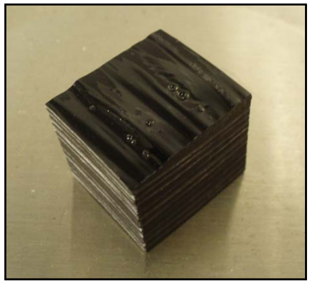
★ Initial "ad-hoc" outgassing test apparatus identified and quickly outfitted for measurements within ~60 d

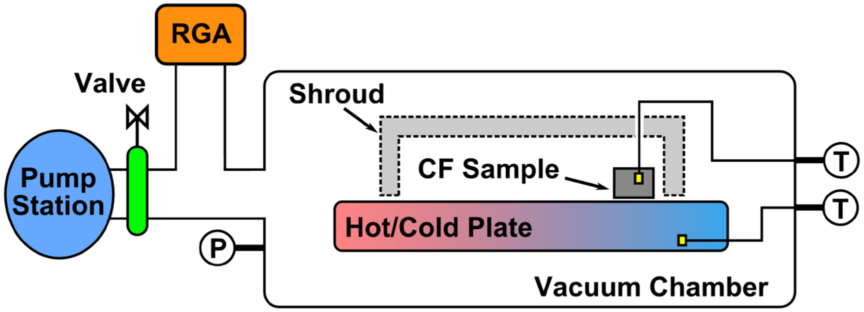
- *Effective thermal isolation of cryogenic storage vessels – and therefore long dormancy times – presumes the presence of a "good" vacuum (< 1e-3 Torr); assuming no leaks, what are the effects of materials in the vacuum gap?*

- Used vacuum chamber (SS 316 L) capable of variable temperature (P_{ult} < 5e-8 Torr, +90° C/-150° C), with mass spectrometer for species ID; pressure measurement via cold cathode gauge; valve closure/static rise
- Temperature control via semi-closed-loop LN_2/GN_2
- Samples fabricated by sectioning overwrap of 700 bar COPV (provided by Lincoln Composites); included "neat" as well as "UV-coated" material



Original experimental facility (above); ~1 in^3 COPV sample coupon (below)





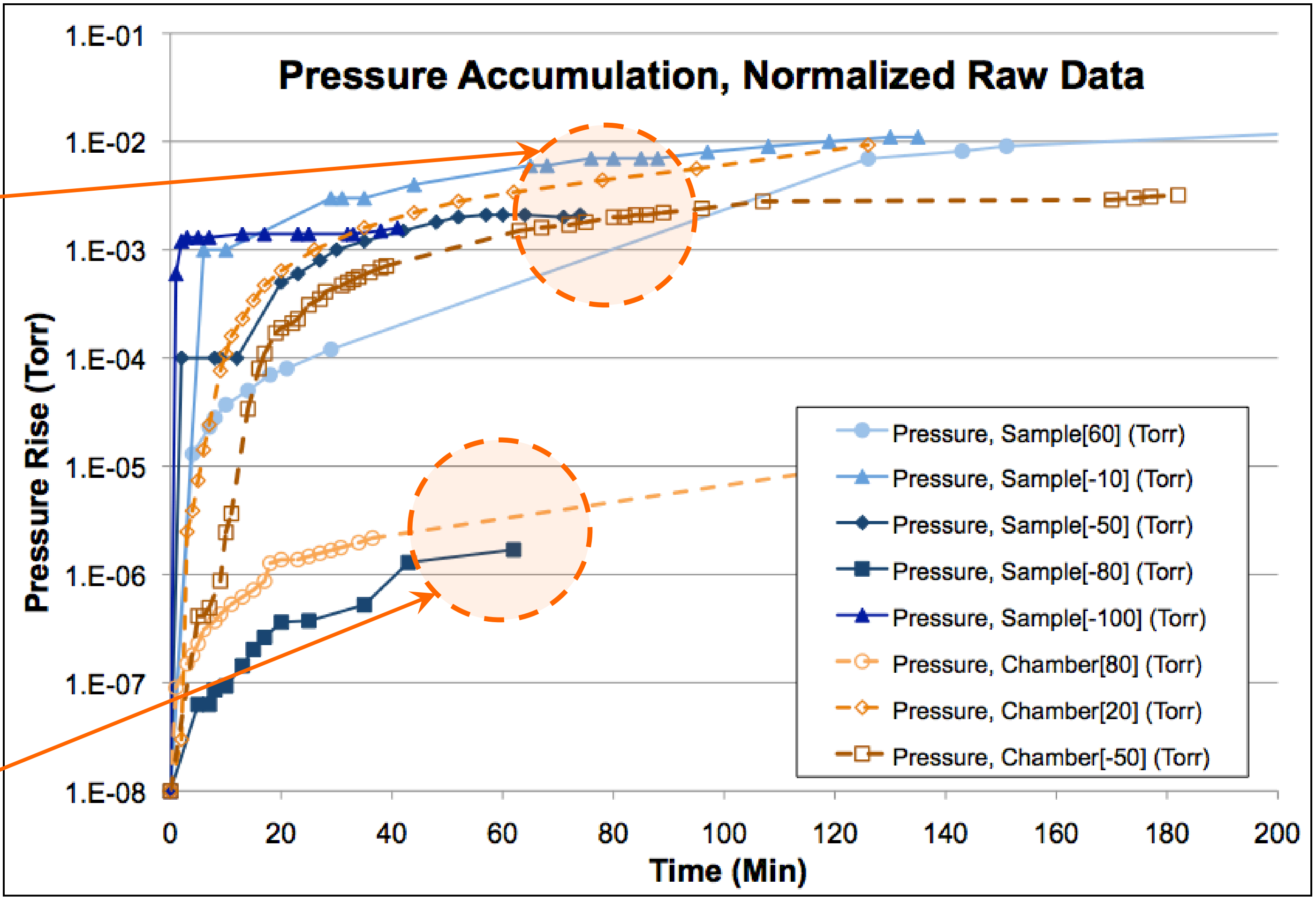
Schematic of experimental chamber setup, showing thermal control

Initial Vacuum Outgassing Data
Accomplishments

Initial measurements of outgassing from COPV materials made at relevant pressures, temperatures (170-350 K); lessons learned

Lack of resolution in time and pressure, along with some inconsistent results

Data outliers suggest inconsistent instrumental accuracy



Plotted curves illustrate normalized pressure rise data. Although exponential trends are seen, some inconsistency is noted regarding expected temperature dependencies; data show poor resolution in time. Atmospheric contamination of chamber and sample is also suspected.

Downstream HX Detailed Model Design
Accomplishments

★ Detailed, fully-coupled model predicts 1.1 kg, 1.0 L for Downstream HX in cryo system architecture

- *Coolant-coupled HX* design was selected at 2011 AMR to utilize existing radiator and large FC coolant flow rate to mitigate frost formation while pre-heating H_2 fuel

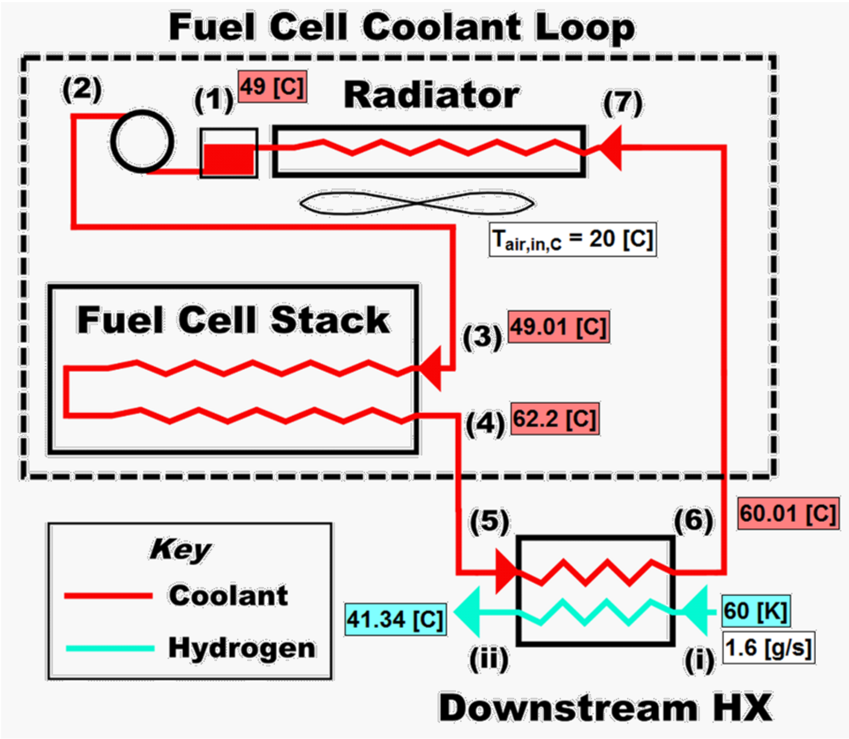
- HX model predicts coupled inlet and outlet temperatures of (3) fluid streams
  - H_2, Glycol-water (55/45) coolant, Air

- Technical targets[1]
  - T_{min}:-40°C; flow: 1.6 $g \cdot s^{-1}$;T_{amb}: -40 to 60°C

- Assumptions
  - T_{FC} = 80 °C assumed constant for FC efficiency calculations; *minimizes* available waste heat
  - Flow mal-distribution is minimal for all streams
  - Full tank, isenthalpic expansion (conservative)

Heat Exchanger	Mass (w/coolant) [kg]	Volume [L]
Herringbone Plate (2011)	**5.0**	**2.0**
Mini S&T (2012)	**1.1**	**1.0^2**

Progress of JPL's Downstream HX technology development from 2/2011-2/2012



Schematic results for 80 K storage case, 20 °C ambient

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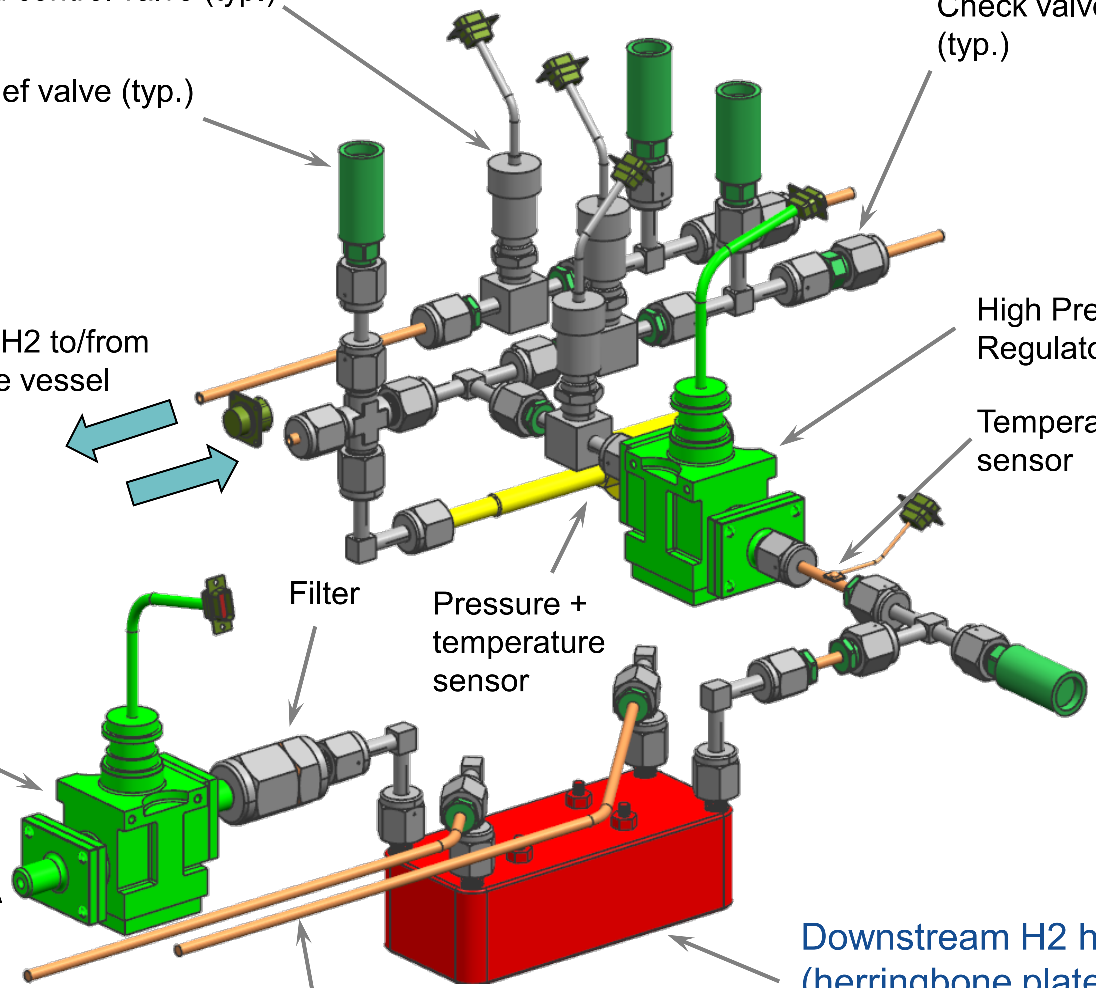
[1] DOE MYPP, Storage Interim Update (2011)

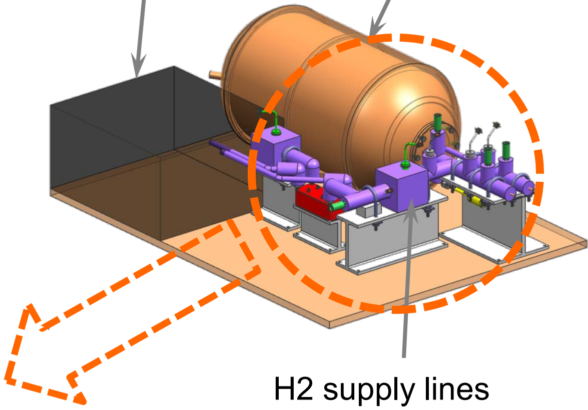
[2] Approximately 60% of this volume is thermal insulation

HX Modeled in Representative System
Accomplishments

Initial design and sizing of downstream HX component included in cryo-adsorbent system CAD visualization



Downstream H2 heat exchanger (herringbone plate configuration; *ca. 2011*, *superseded*)

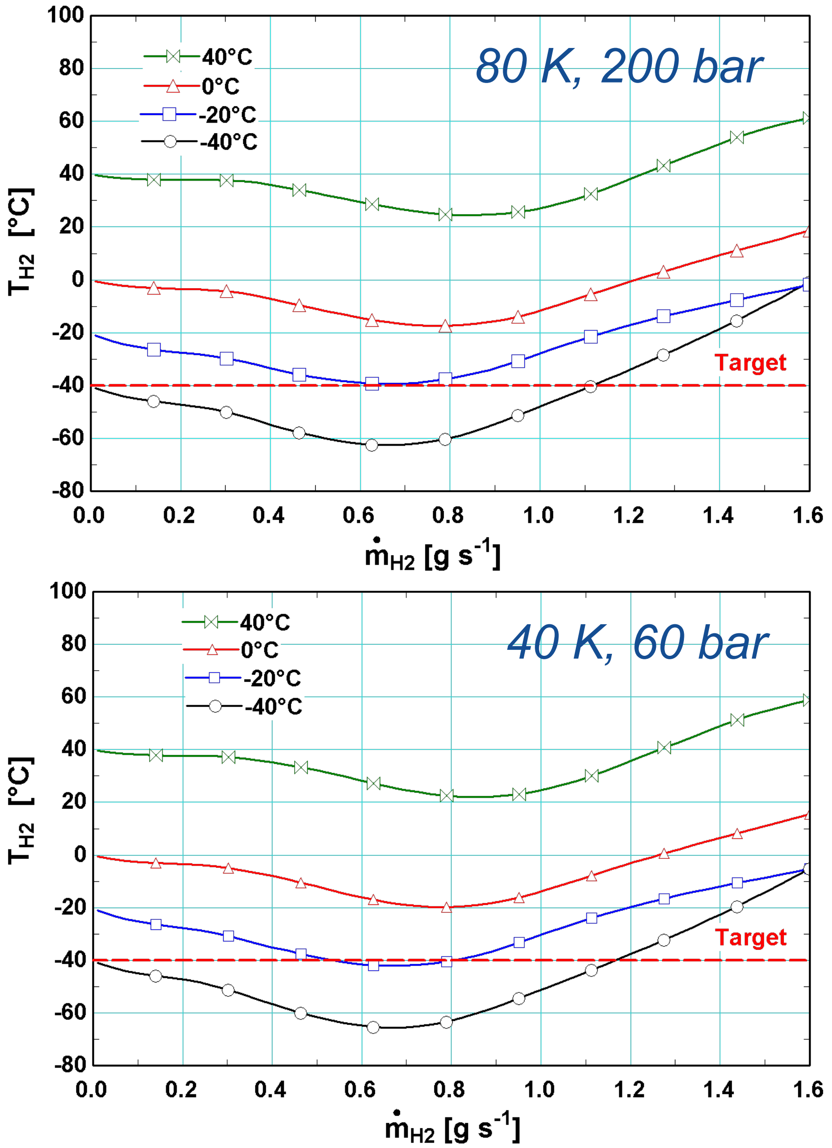


Typical shell/tube configuration (Exergy, LLC)

Steady-state Downstream HX Model Results
Accomplishments

★ Steady-state predictive results predict near-total compliance with targets for the prototype HX design (80 K & 40 K)

- Delivery temperature target met for *all* cases save -40°C ambient
  - Delivered temperature is still within ~20°C of other boundaries (radiator air, fuel cell surface)
  - For this extreme case, auxiliary heating may be necessary; e.g., OSU developing a micro combustor
- *Negligibly* lower H_2 delivery temperature for 40 K storage than 80 K; freezing risk is slightly greater at 40 K
  - Experiments are planned to evaluate extent/impact of this phenomenon (cf. *Future Work*)



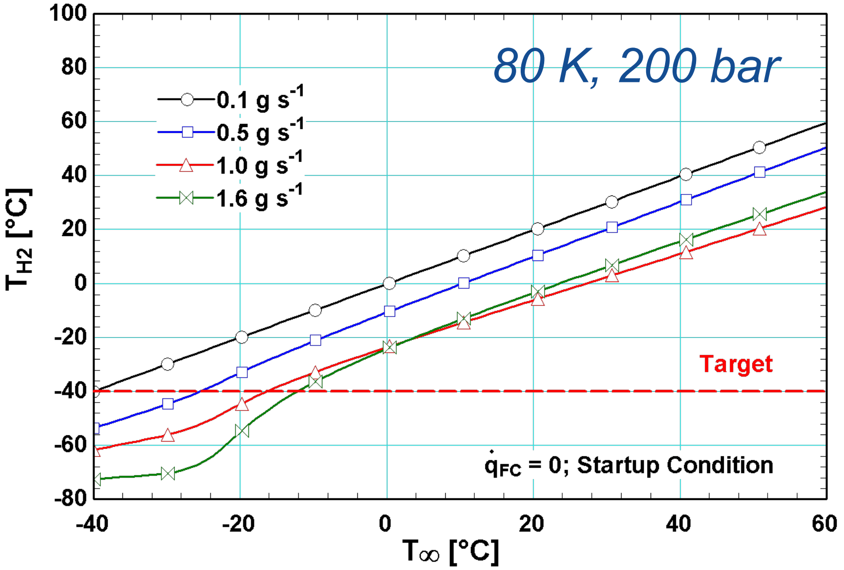
Top: Delivered H_2 T vs. H_2 flow rate (various T_{amb}) for 80 K, 200 bar

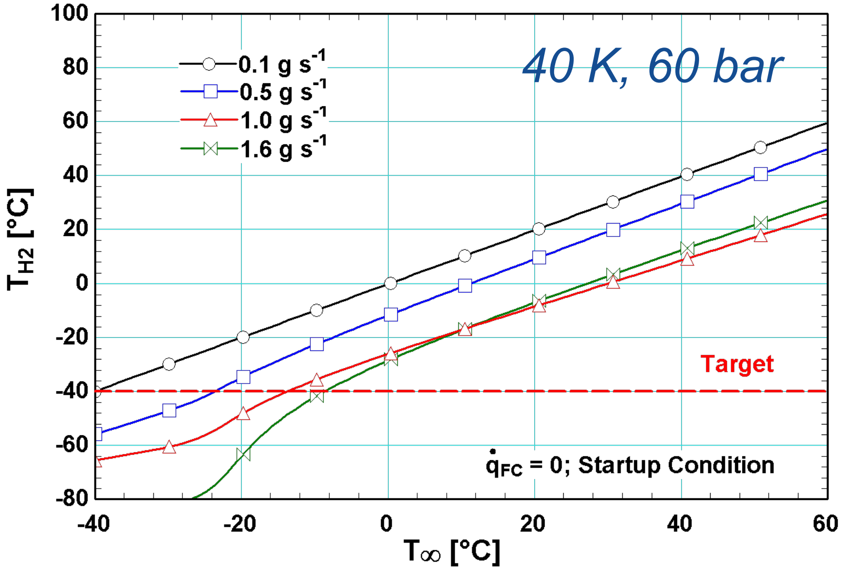
Bottom: Delivered H_2 T vs. H_2 flow rate (various T_{amb}) for 40 K, 60 bar

Startup/Transient Downstream HX Model Results
Accomplishments

★ Transient case analyzed for cold vehicle startup conditions; partial compliance predicted across cases (80 K & 40 K)

- Model predicts that delivery temperature target is met for “moderate” H_2 demand
  - During startup, no waste heat available
  - Low demand coincides with startup
- H_2 tubes may accumulate ice during startup for $T_{amb} < -20^oC$
- Analyzed 40 K storage case:
  - For $T_{amb} > -10^oC$ or lower flow rates, little effect on deliverable H_2 temperature
  - For $T_{amb} < -10^oC$ or large H_2 flow rates, supplemental heating might be required (esp. for startup)





Top: Delivered H_2 T vs.T_{amb} for startup (various H_2 flow rates) for 80 K, 200 bar

Bottom: Delivered H_2 T vs.T_{amb} for startup (various H_2 flow rates) for 40 K, 60 bar

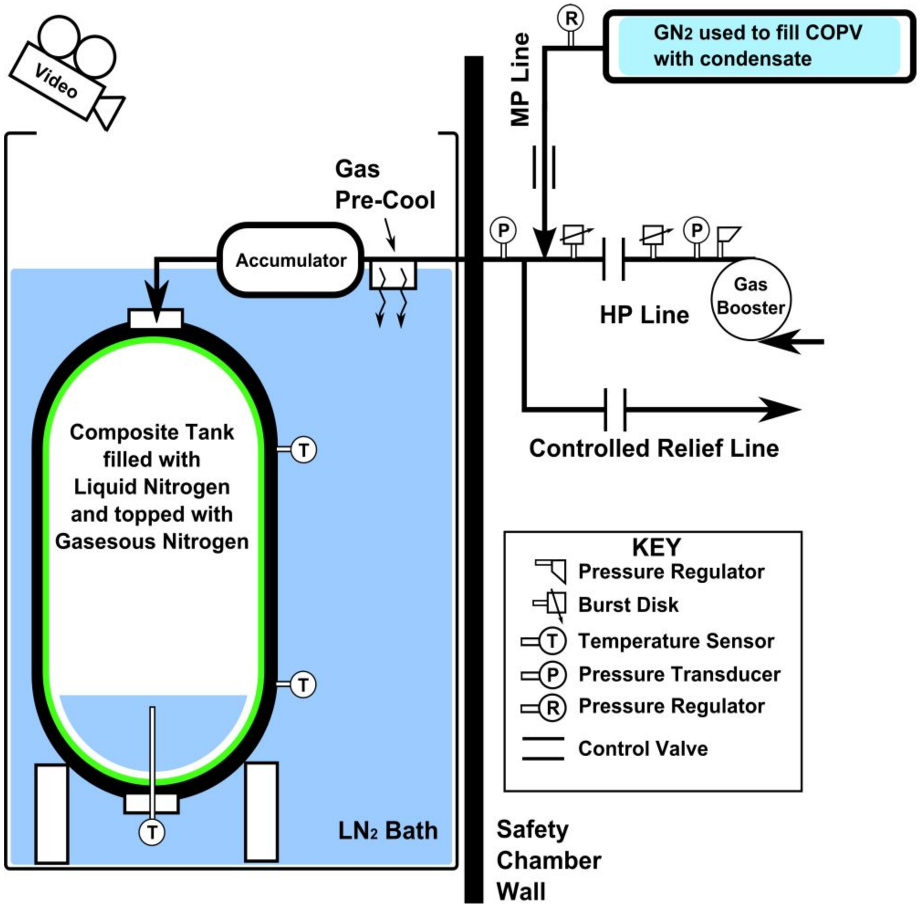
Cryo-Burst Facility Design
Accomplishments

★ Completed facility design for 15 kpsi burst of < 20 L COPV at 77 K; procurements begun

- Sizing accounts for worst case (BLEVE)
- Ear damage perimeter: 2.6 m
  - Nearly exceeded by building perimeter, muffled by brick walls
- Projectile safe distance: 34.5 m
  - Blast shielding gives margin
- Fragmentation not observed for COPVs tested by NASA at LN_2 temperature

Filament wound Zylon®/urethane composite tank burst in LN_2. Note, Zylon has higher elastic modulus and yield strength than carbon being tested.

Source: Black, S. (2005) An update on composite tanks for cryogens. www.compositesworld.com. Accessed June 21, 2011.



Schematic illustration of the JPL cryo-burst facility layout.

HSECoE

Roles and Relationships – *Collaborations*

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– UM
- 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**

JPL's Phase 3 roles descoped and shifted during FY11

JPL Partnerships – *Collaborations*

- General
  - SSAWG, HSECoE-at-large
  - D. Siegel (Michigan): Cryo-system Architect

  Center collaborations are constantly leveraged within the matrix structure & function

- System Design
  - D. Tamburello (SRNL): cryo system models, performance metrics, flowsheets
  - C. Ahn (Caltech): CA materials performance and testing approaches
  - K. Drost (OSU): micro-combustor and HX design elements
  - D. Kumar (GM): CA vessel design approach, testing/performance
- Technology Area discussions/regular technical interchanges
  - K. Simmons (PNNL): Pressure Vessels Team Lead/tank design and costing, BoP studies
  - N. Newhouse (Lincoln): tank design criteria, novel approaches, prototype vessels
  - D. Tamburello, B. Hardy (SRNL): cryo-system thermal management

The collaborations listed above are selected from the reporting period, and are *non-exhaustive*

2012 S.M.A.R.T. Milestones
Future Work

- In late FY2011, the Center and DOE developed "S.M.A.R.T." milestones for all partners to align and coordinate technical work in Phase 2
  - Evolved JPL Milestones shown in table below; others may be added if Center needs shift
  - JPL's FY2012-2013 progress will be measured against these metrics

Date	Milestone	Status	Comments
6/2012	Report on ability to develop a cryo-adsorbent vessel thermal insulation design having less than a 5 W heat leak at 40 K and having a mass < 11 kg and volume < 35 liters.	Experimentally validated model (coupon-scale) predicts < 2 W @ 77 K	Outgassing activity is merged into this milestone; predictions will be extrapolated to 40 K; "subscale" 77 K dormancy experiments expected 5/2012
9/2012	Report on ability to develop testing capability to burst test Type 4 (COPV) and Type 1 (metallic) tanks at 77 and 40 K and demonstrate tanks meeting minimally 2.5x nominal operating burst pressure.	*No experimental results yet*	COPV tank articles are in manufacture at Lincoln Composites; initial burst at 77 K expected mid FY2012
12/2012	Report on ability to develop and demonstrate a Downstream HX capable of heating a 40 K, > 1.4 g/s hydrogen stream to 233 K with no external icing at 50% RH with mass < 2.5 kg and volume < 1.5 liters.	Modeling indicates requirements can be met at 1.1 kg / 1.0 L	Benchtop experiments in planning stage; expected operation early FY12

- JPL is also participating in the following Center-wide Go/No-Go decisions:
  - Cryo-sorbent surrogate material upselect (Mar-Apr 2012)
  - Phase 3 demonstrator system design upselect (Q2 FY2013)

JPL’s 2012 Task Breakdown
Future Work

- Task Area: Advanced Thermal Isolation Design
  - validate performance models at appropriate scales and environmental conditions, and provide performance data to Center framework team
  - demonstrate manufacturable assembly methods for isolation system
  - fabricate final components for Phase 3 demonstrator system
  - measure vacuum outgassing for relevant materials at high resolution and sensitivity
  - demonstrate potential mitigations to outgassing effects

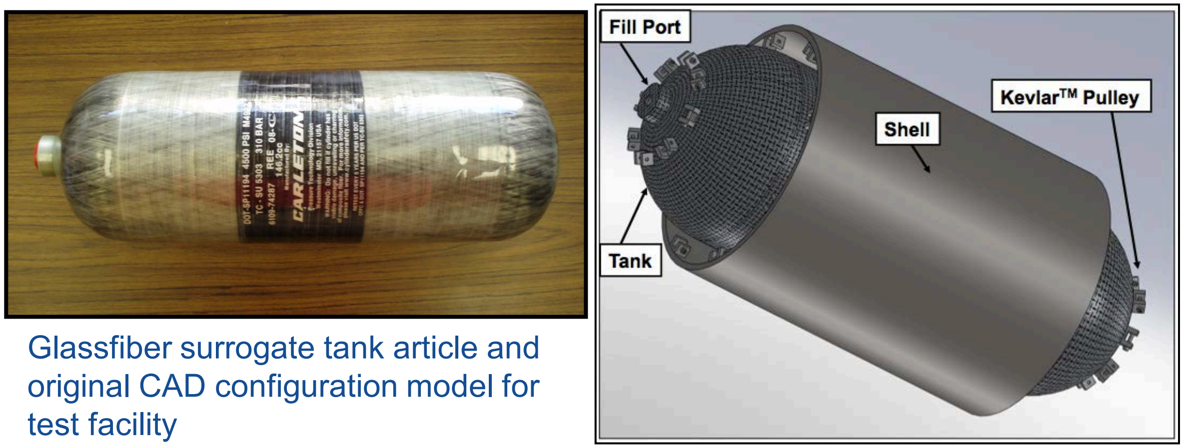
- Task Area: Downstream HX
  - perform benchtop experiments to validate HX model
  - demonstrate performance at cryogenic temperatures and appropriate flowrates (preferably using full-scale article)

- Task Area: Vessel Cryo-Burst Testing
  - continue to work toward cryo-burst operations for Center test articles; provide rapid turnaround for need-based testing
  - evaluate possibility of cryogenic cycle-testing using cryo-burst facility

“Scaled” Dormancy Experiment
Future Work

- Mid-scale experimental facility nearing completion; results expected 5/2012
  - High-similitude configuration to test advanced thermo-mechanical design
  - Approximately 1:4 scale, utilizing glassfiber (SCUBA) tank for simplicity
  - Designed to operate at LN_2 temperature (77 K)
- Actual heat transfer will be measured relative to LN_2 boil-off rate
  - Detailed validation of parasitic thermal model at relevant temperatures, architecture, and near-scale

Image shows initial fill and testing of suspended tank article at LN_2 temperatures



Glassfiber surrogate tank article and original CAD configuration model for test facility

High-Resolution Outgassing Facility
Future Work

- New facility will utilize *throughput* method of measurement instead of *pressure rise* method
  - smaller chamber volumes
  - better accuracy and sensitivity at steady-state operation
  - simpler to account for readsorption of species on chamber walls
- High resolution data capability
  - temperature measurement by Lakeshore Si-diode
  - pressure measurement via cold-cathode gauge
  - species ID via RGA mass spec
- Purpose-designed to reach 77 K and low initial pressures
  - better coupling to cold stage, better shrouding in chamber
  - close-coupled turbopump with high throughput
- Quick turnaround
  - easy access to sample platform
  - facility built for easy maintenance

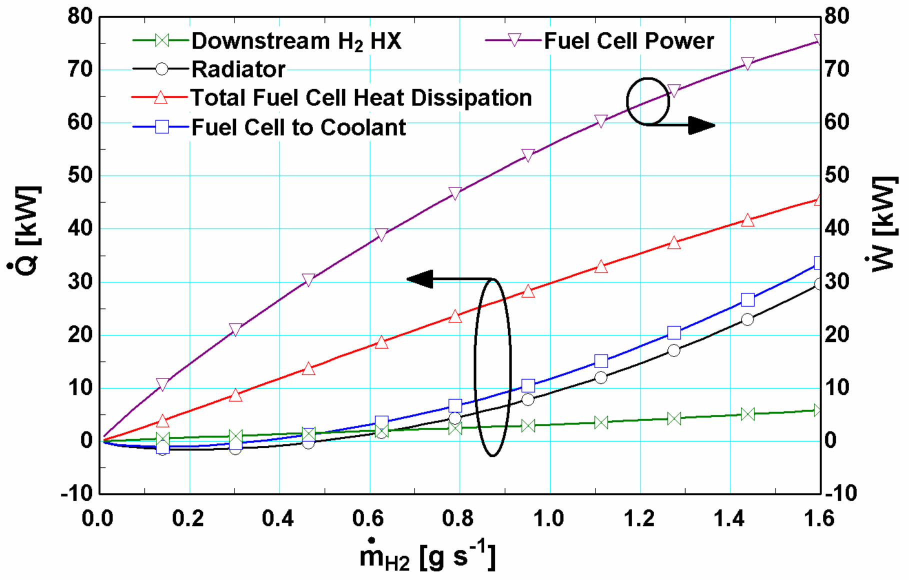
Outgassing facility under construction in JPL’s H_2 Storage Engineering Laboratory. Sample stage can just be seen inside 8” chamber mouth. Facility has been assembled largely from existing hardware at minimal cost.

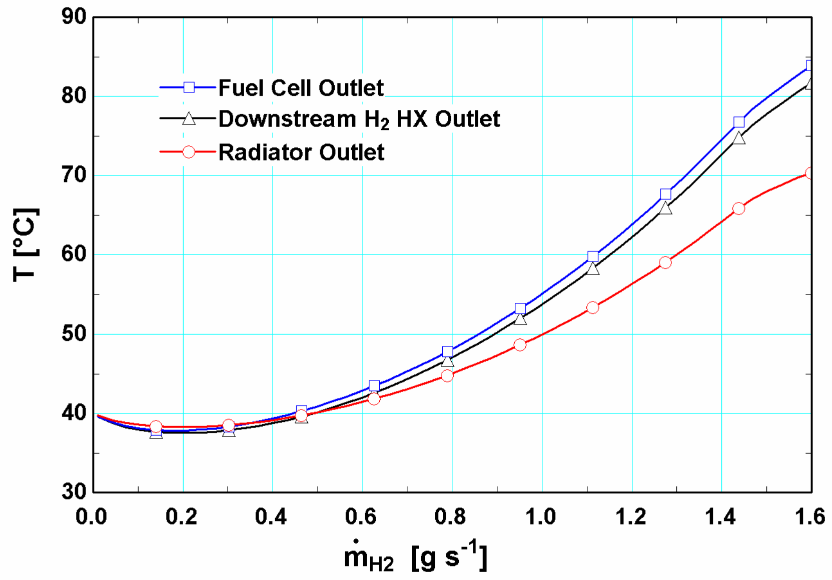
Facility will address shortcomings of 2011 experimental effort:

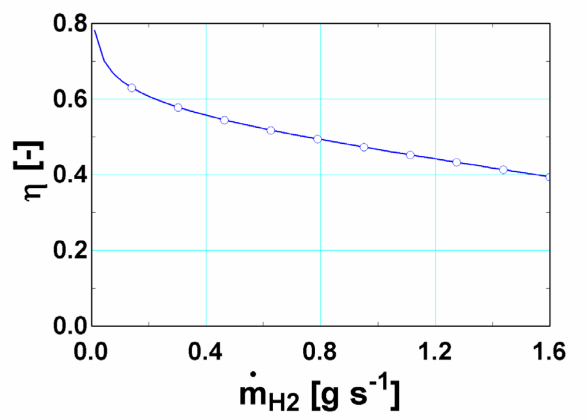
- effects of chamber and sample were not separable
- calibration was difficult
- unsystematic setup procedures yielded long turnaround time
- apparatus could not reach 77 K, and temperature control was poor
- facility not built for this purpose; much more sensitivity required
- time resolution was poor; dedicated data acquisition required

Advanced HX Model With Validation Experiments
Future Work

- Detailed model results show that coupling is very complex; e.g., coolant may *heat* FC for certain flow rates and ambient temperatures
  - At low H_2 flow rate, FC efficiency is great: less waste heat
  - Less waste results in lower H_2 outlet temperature (downstream HX)
  - Injecting cold H_2 cools fuel cell
- No active FC thermal control on present model: planned next step
- Benchtop experiments will validate model results at cryogenic temperatures and valid flowrates







Top: Coolant heat transfer and FC power (40°C ambient)

Bottom: Local fluid temperatures for radiator

Left: Fuel cell efficiency (HHV) calculated in model

Cryo-Burst Facility Operations
Future Work

- COPV terminal performance at cryogenic temperatures and medium-high pressures is not well known
  - cryo temperatures, ~5 bar (NASA)
  - room temperature, ~200 bar + cycling (CNG)
  - cryo temperatures, >50 bar + cycling (?)
- HSECoE cryo-adsorbent experiments will utilize “full scale” pressure/temperature profiles on the Phase 3 prototype; JPL and HSECoE see cryo-burst as a both a safety issue and an engineering issue
  - experimenter safety is paramount
- At the conclusion of this program, the Center will have
  - data that evaluates fitness/safety of COPV design/types for implementation in Center work
  - test facility for further follow-on testing for different COPV tank types, including “optimized” low-mass tank (that might not otherwise be tested in a partner lab)
  - with some extra work, *cryo-cycling* is a possible enhancement of this facility

Summary

- **Relevance & Approach:** JPL has identified a need for *critical cryo-system engineering* in Phase 2; this renewed effort has allowed efficient use of manpower and resources following the de-scope of the metal hydride system in 2011. 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

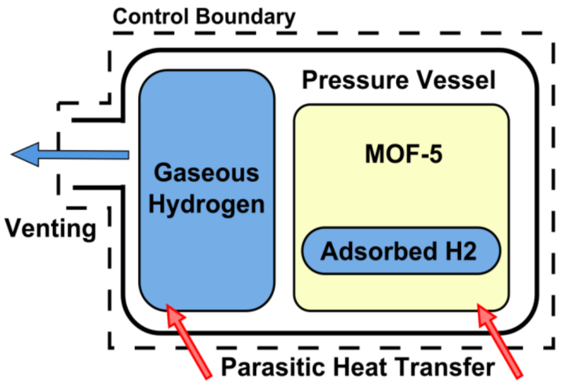
- **Technical Accomplishments**: JPL is actively developing technologies with an eye on *benchtop component testing and model validation* in Phase 2:
  - performed detailed thermo-mechanical design of advanced isolation system for automotive use, and experimentally validated thermal isolation model (coupon-scale) at 80 K
  - obtained initial cryogenic outgassing data for carbon fiber tankwall materials and developed plans for follow-on testing
  - developed fully-coupled Downstream HX model and obtained refined results showing mass/volume reductions; this design was visualized using a CAD model in a representative storage system
  - developed initial cryo-burst facility design, including safety reviews, burst energy, facility use; developed test procedure with assistance from industry (Lincoln Composites, NASA, etc.) and began procurements

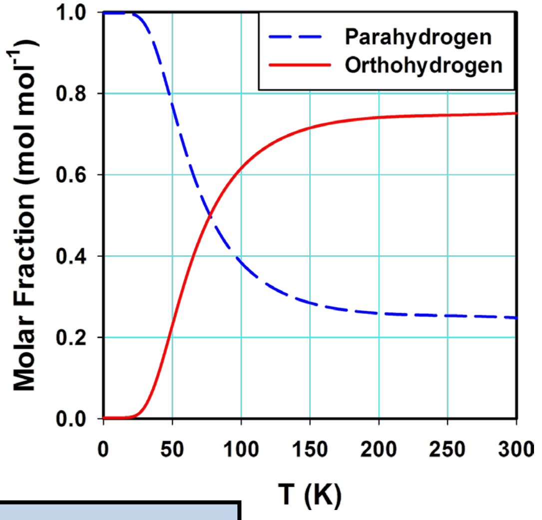
- **Future Work in Phase 2**: Experimental data from dedicated facilities will aim to validate existing model architectures, with a focus on testing designs at cryogenic temperatures
  - validate advanced cryogenic vessel architecture (scaled dormancy experiment)
  - demonstrate H_2 fuel conditioning HX design, validate model (benchtop HX experiment)
  - composite material outgassing measurements (high resolution outgassing facility)
  - cryo-burst facility initial operation

Technical Back-Up Slides

Dormancy Model Details
Technical Backup

- *Dormancy* is the maximum duration that a cryo-storage system can remain quiescent before venting its contents to relieve pressure[1], and is influenced by four related issues
  - design of thermal isolation system
  - mechanical performance of thermal isolation
  - vacuum degradation via outgassing effects
  - vacuum degradation via permeation effects
- MOF-5[2] adsorbent, Type III COPV @ 80 K, 20 MPa fill
- 5.6 kg useable H_2; catalyzed para/ortho conversion included[3]
- Lumped-parameter simulation





Equivalent Biot number for cryo-sorbent tank dormancy: $Bi = U_{\mathrm{eff}} L_{\mathrm{c}} / k_{\mathrm{eff}} \approx 7 \times 10^{-3}$

$$U_{\mathrm{eff}} = A^{-1}\left[\frac{1}{R_{\mathrm{ins}}} + \frac{1}{R_{\mathrm{fit}}} + \frac{1}{R_{\mathrm{sup}}}\right]^{-1} = 0.007\ \mathrm{W\ m^{-2}\ K^{-1}}$$

$$\Bigg\{(mc)_{\mathrm{CF}} + (mc)_{\mathrm{Al}} + m_{\mathrm{s}}\Bigg[V_{\mathrm{g}}\rho_{\mathrm{g}}\frac{\partial}{\partial T}\left(\omega u_{\mathrm{g,o}} + \psi u_{\mathrm{g,p}}\right)_{\mathrm{P}} + \left(\frac{\partial \Delta U_{\mathrm{a}}}{\partial T}\right)_{\mathrm{P,V}} + n_a\frac{\partial}{\partial T}\left(\omega u^0_{\mathrm{g,o}} + \psi u^0_{\mathrm{g,p}}\right)_{\mathrm{P}} + \left(\omega u^0_{\mathrm{g,o}} + \psi u^0_{\mathrm{g,p}}\right)\left(\frac{\partial n_{\mathrm{a}}}{\partial T}\right)_{\mathrm{P,V}}$$
$$+ c_{\mathrm{s}}\Bigg]\Bigg\}\frac{dT}{dt} + m_{\mathrm{s}}\left[V_{\mathrm{g}}\rho_{\mathrm{g}}\frac{\partial}{\partial P}\left(\omega u_{\mathrm{g,o}} + \psi u_{\mathrm{g,p}}\right)_{\mathrm{T}} + \left(\omega u^0_{\mathrm{g,o}} + \psi u^0_{\mathrm{g,p}}\right)\left(\frac{\partial n_{\mathrm{a}}}{\partial P}\right)_{\mathrm{T,V}} + \left(\frac{\partial \Delta U_{\mathrm{a}}}{\partial P}\right)_{\mathrm{T,V}}\right]\frac{dP}{dt} = \dot{q} - \dot{n}_{\mathrm{out}} h_{\mathrm{out}}$$

[1] [W d] is an alternate unit of measurement

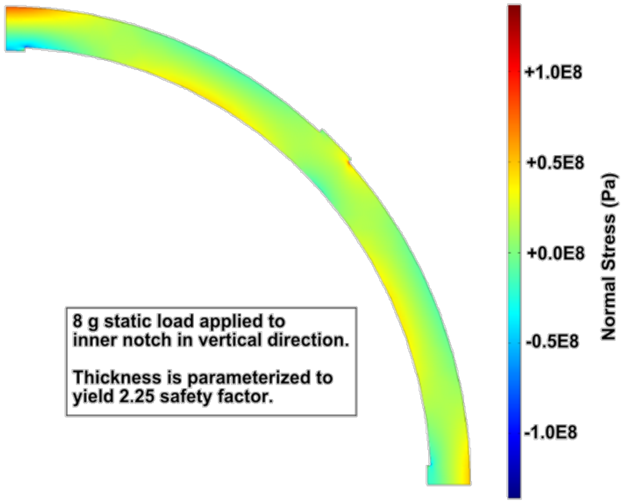
[2] MOF-5 properties from Purewal et al. (2010) AIChE Meeting

[3] Meagher (2008) SUNY Buffalo

Advanced Isolation Design Model Details
Technical Backup

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

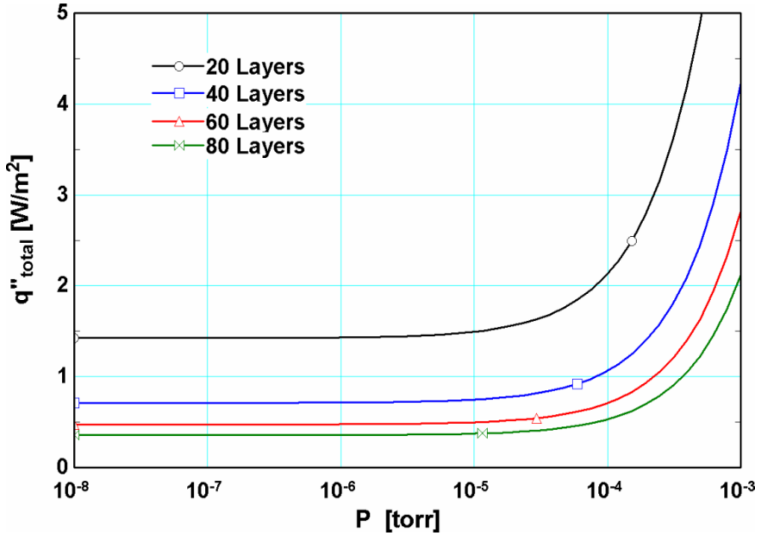


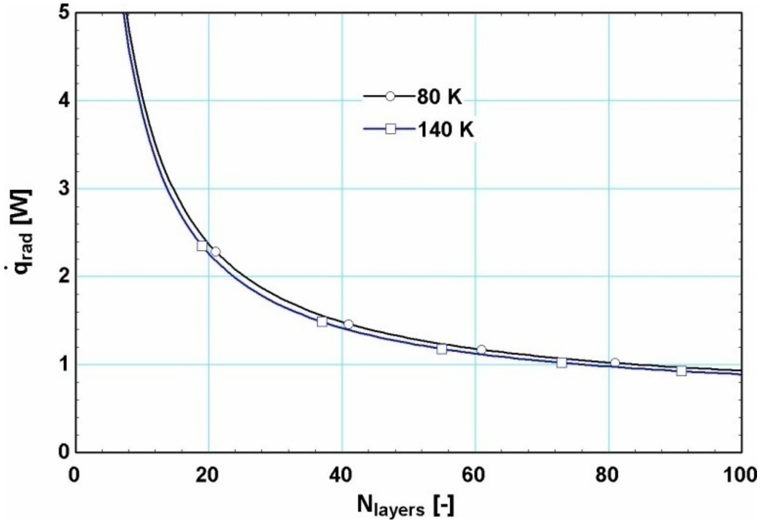
8 g static load applied to inner notch in vertical direction.

Thickness is parameterized to yield 2.25 safety factor.

Parasitic Radiation

- Model for specular-diffuse reflections, two-band approximation
  - MLI: 60 layers, seam effects included





Top Right: MLI effectiveness as a function of vacuum pressure and # layers (Lockheed eqn.)

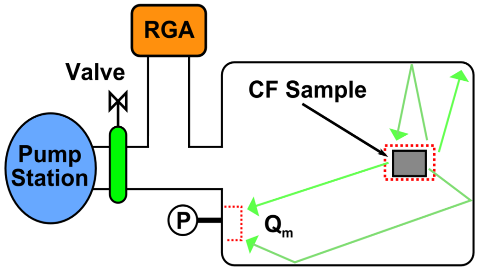
Bottom Left: Mechanical modeling used to size G-10 and Kevlar™ supports (8 g loads)

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

Outgassing: Readsorption Theory
Technical Backup

- Known difference between measured outgassing flux and intrinsic outgassing flux
  - Q_i ~ outgassing flux, quantity of gas leaving sample per unit time per unit exposed geometric surface at a specific instance in absence of readsorption
  - Q_m ~ measured outgassing flux
  - A ~ adsorbing area
  - K ~ number of molecules in a Torr-liter
  - s ~ sticking probability
  - v ~ specific arrival rate
  - V ~ test chamber volume

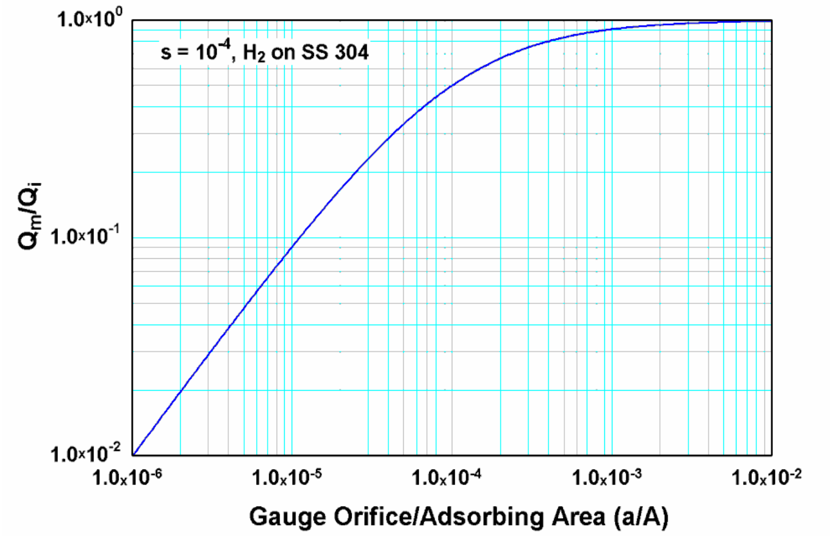
$$\boxed{Q_i = Q_m + pvs + \frac{KV}{A}\frac{dp}{dt}}$$



- Throughput method and pressure-rise method both subject to readsorption:

$$Q_m / Q_i < 1$$

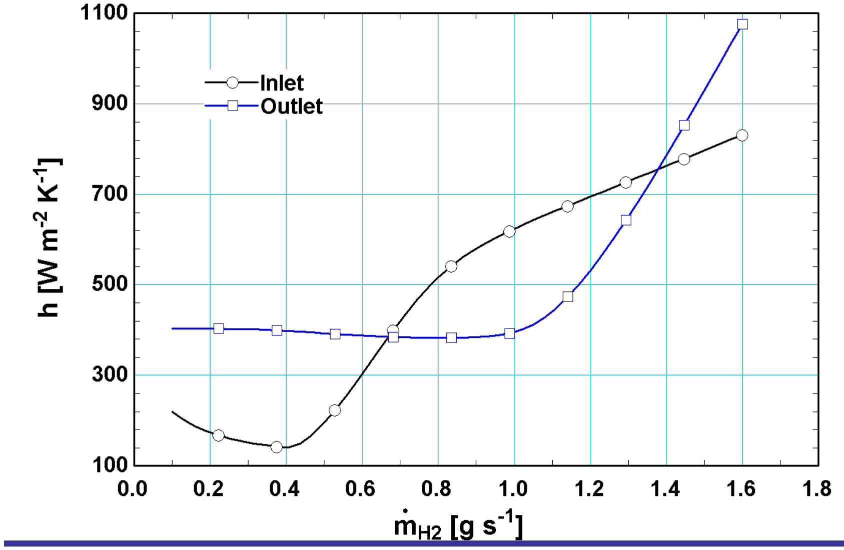
- Pumping speed (S), adsorbing area (A) and sticking probability (s) all affect measured flux
- Varying these parameters between systems can lead to non-repeatability
- Redhead (1996) J. Vac. Sci. discusses implications of readsorption for throughput and pressure-rise



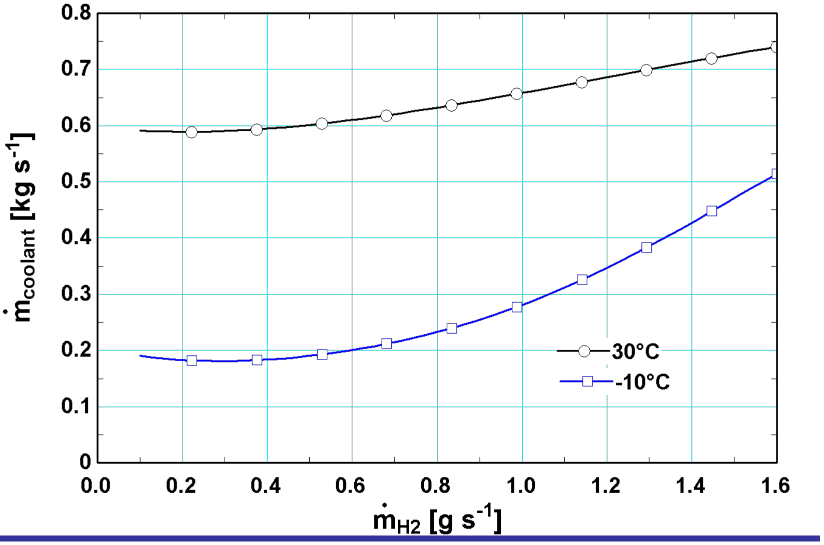
Downstream HX Coupled Model Details
Technical Backup

- HX/radiator represented by segmented model with both gas and liquid sides; model calculates pressure drop and fluid temperature at each node
- Downstream HX sized using data from Center's modeling framework; H_2 flow rate was selected based on Center results for US06 drive cycles
- Total fuel cell waste heat calculated using first order electrochemical model, and waste heat to coolant estimated using reaction enthalpies; we assume $H_2O_{(l)}$ product & well-insulated stack
- FC/vehicle radiator sized to dissipate 36 kW of waste heat from a fuel cell in 60^{o}C ambient environment (within typical range for a louver-finned vehicle air-hydronic radiator)
- Modeling challenges related to wide temperature ranges; coolant (glycol-water) flow rate varies substantially with operating temperature
- *Re* for is transitional for relevant flow rates and geometries
  - Churchill (1977) correlation for laminar, transition, and turbulent regimes

Film coefficient vs.H_2 flow rate at downstream HX inlet/outlet

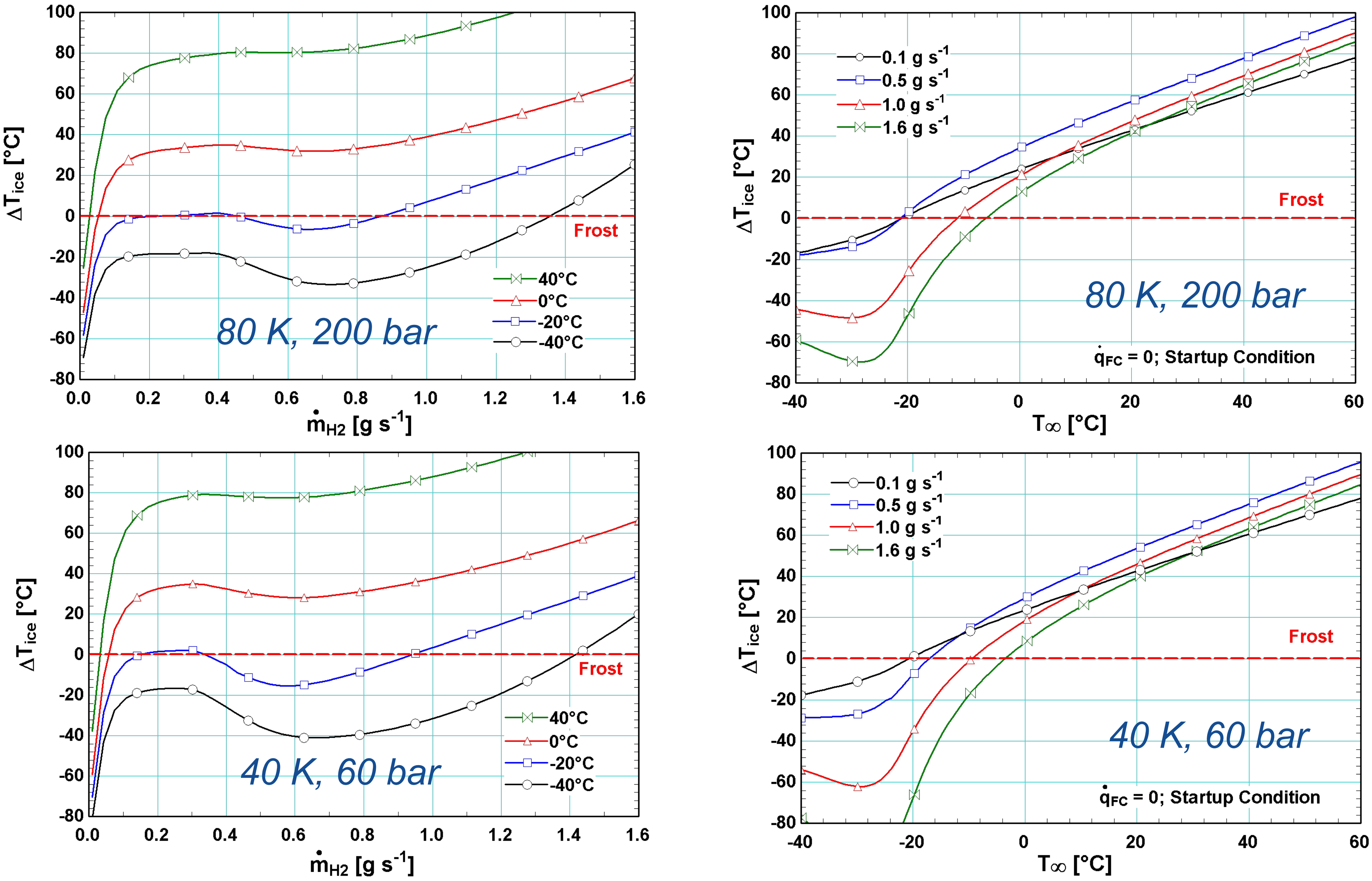


Coolant mass flow rate vs. H_2 flow rate over T_{amb} range



Downstream HX Freezing Margin Plots

Technical Backup



Left Column: Margin above coolant T_{frost} vs. H_2 flow rate for steady-state; *Right Column:* Margin above coolant T_{frost} vs. T_{amb} for startup (all for various H_2 flow rates, storage conditions)

$$\Delta T_{\mathbf{ice}} = T_{\mathbf{tube,o}} - T_{\mathbf{frost,c}}$$