Hydrogen Storage Engineering
CENTER OF EXCELLENCE

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

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May 20, 2009

DOE Hydrogen Program

Jet Propulsion Laboratory
California Institute of Technology

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

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Project ID
 # stp_10_reiter

Overview:
Project Details

Timeline

- Project start date: February, 2009
- Project end date: January, 2014
- % complete: 3% (Duration)

Budget

- Expected total project funding:
  - $3.195M (DOE)
  - $0.03M (Caltech)
- Funding received in FY08:
  - $0K (DOE)
- Funding received for FY09:
  - $0K (DOE)

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

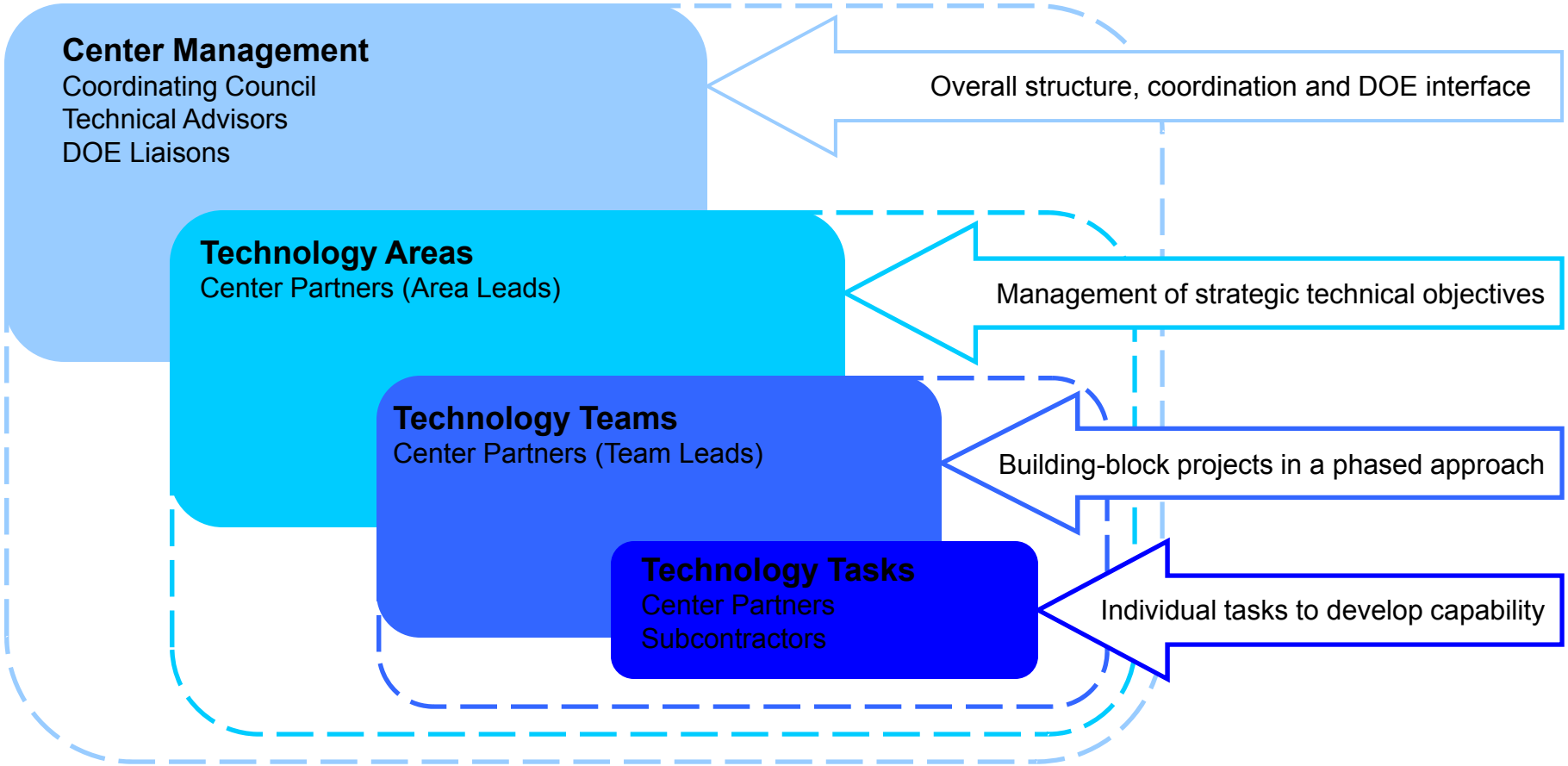
Partners

- Caltech (subcontract)

Overview:
HSECoE Organizational Approach

- The organization of HSECoE is built around a modular, hierarchical concept based on Technology Areas/Teams/Tasks

- This organization will help HSECoE meet objectives by:
  - Maintaining effective tasking within a diverse team
  - Managing technology development in an emerging field



Overview:
JPL's Roles in HSECoE

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

Materials Operating Requirements
D. Herling, 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

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
D. Mosher, UTRC
- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

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**

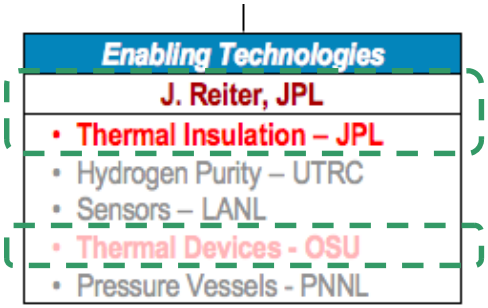
Relevance:
Milestones and Task Breakdown

- JPL Task Plan, including milestones, deliverables, and Go/No-Go points (excerpted from HSECoE Proposal, 2009 Annual Operating Plan, or other materials where appropriate)

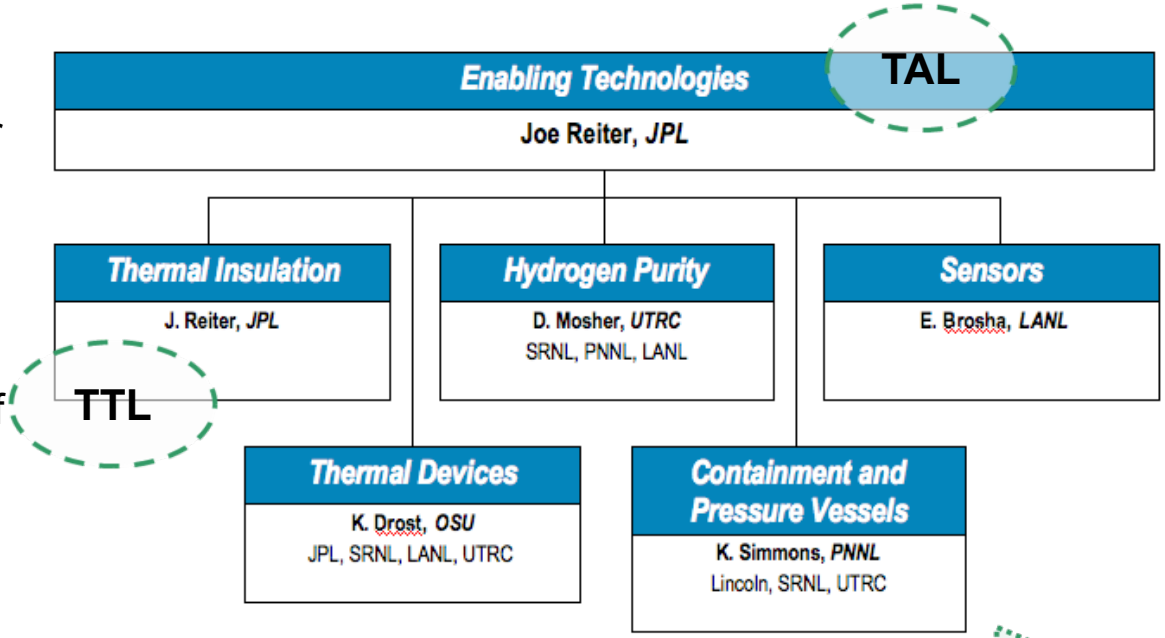
JPL Task No.	Description	Phase 1								Phase 2					Phase 3						
		2009 (Q)			2010 (Q)				2011 (Q)				2012 (Q)				2013 (Q)				
		2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
1a	Media & safety risk identification				M1																
1b	Media & safety evaluation and mitigation													M7							
1c	Identify and address media performance gaps							M2					M8	D3							
1d	Evaluate engineering impact of candidate media													M9							
2a	Evaluate pressure/containment tech.							M3							D4						
2b	Assist evaluation of H2 purity/sep. tech.							M4							D4						
2c	Identify/evaluate/select passive thermal tech.							M5							D4						
2d	Enabling Tech. gap assessment/mitigation							D1	G1												
3a	Model novel HX/MX approaches									M10		G2									
3b	Design and fabricate thermal test articles											M11									
3c	Perform validation test studies												M12								
3d	Model platform evaluation and downselect.												M13								
3e	Provide model tech. gap assessment/mitigation												D5								
4a	Propose/evaluate system engineering concepts								M6												
4b	Develop Go/No-Go criteria for sys. concepts							D2													
4c	Provide tech. gap assessments for sys. concepts												M14								
4d	System concept evaluation and downselect															D6					
4e	Develop draft test plans for prototype testing															M15					
4f	Develop Go/No-Go criteria for prototype plans															D7					
4g	Scale optimization/analysis for prototypes																M16				
4h	Provide eng. oversight for prototype design																M17				
5a	Hazard assessment and mitigation for I&T																D8				
5b	Design/procurement for test facility																M18				
5c	Finalize test plan																	M19			
5d	Assemble prototype system components																	M20			
5e	Software development																		M21		
5f	Construct test facility																		M22		
5g	Integration and Test																			M23	
5h	Analyze, report, and archive data																				D9
5i	Decommission prototype and test stand																				M24

Approach:
JPL Task Area 1 - Adv. Technology Development

- JPL is the Technology Area Lead (*TAL*) for HSECoE's "Enabling Technologies" strategic technology area *(TA)*
  - This will be a major effort, 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 will also perform as TTL for the "Thermal Insulation" task group, developing approaches for passive thermal management of the storage vessel, thermal devices, and balance-of-plant components of the prototype system



A breakdown of the "Enabling Technologies" TA is provided in the form of **Quad Charts** for each of the Technology Teams led by JPL an other Center Partners within this structure

Approach:
"Enabling Technologies" TAL Quad Chart

Technology Area: Enabling Technologies

Area Lead: J. Reiter, *JPL*

March 2009 (v2)

Objectives:

- Provides a framework for identifying and addressing technology gaps as well as incorporating new technologies into the Center
- Survey and evaluate existing state-of-art technologies for incorporation into Center design activities
- Provide capabilities as a "technology working group" throughout Center operation
- Identify and recommend approaches to technology development in an ongoing fashion in order to meet technical challenges in key areas

Accomplishments:

Key Milestones:

1. Develop technology flow diagram(s) and identify cross-cutting relationships within CoE (5/09)
2. Perform initial criteria evaluations, SOA surveys, gap identification and mitigation approach (8/09)
3. Perform initial testing against trade-space model results for key technologies (3/10)

Issues:

- Will identify efficient collaborative methods for sharing progress quickly across team
- Must work closely with Center modeling teams/partners in order to accomplish some key goals

Approach:
"Thermal Insulation" TTL Quad Chart

Technology Area: Enabling Technologies
Technology Team: Thermal Insulation

Area Lead: J Reiter, *JPL*
Team Lead: J. Reiter, *JPL*

March 2009 (v2)

Objectives:

- Identify notional requirements, capabilities, and gaps for passive thermal management in storage systems
- Develop high-level trade space performance models *f*(geometry,material,temperature,time,etc.) as evaluative tool (interface with HSECoE modeling groups)
- Evaluate, recommend, and incorporate candidate approaches for engineered systems (full- and sub-scale)

Accomplishments:

Key Milestones:

1. Draft CoE info flow/relationships (JPL) (5/09)
2. Complete initial SOA survey/lit search (JPL) (8/09)
3. Initial weighted trade space model results (JPL) (12/09)
4. Initial model validation experiments for MH system (JPL) (3/10)

Issues:

- Identify model framework for trade space study

Approach:
"Hydrogen Purity" TTL Quad Chart

Technology Area: Enabling Technologies
Technology Team: Hydrogen Purity

Area Lead: J. Reiter, *JPL*
Team Lead: D. Mosher, *UTRC*

March 2009 (v2)

Objectives:

- Develop system methods to improve discharged hydrogen purity / quality for acceptable PEM fuel cell durability.
- Establish procedures for assessing hydrogen purity – moderate level & PEM FC durability level.
- Collaborate with material CoEs to identify existing purity data / concerns & gaps for future testing.
- Evaluate and advance separation method concepts (gas/gas and gas/particulate).
- Incorporate top separation candidate(s) into storage system designs.

Accomplishments:

Key Milestones:

1. Determine current purity concerns in materials CoE and select top 2 to 3. (All) (6/09)
2. Compare initial evaluations of separation approaches. (All) (12/09)

Issues:

- Confirm partner differentiation / roles
  - –UTRC: composite Pd membranes
  - –HSM: polymer membranes
  - –SRNL: metallic membranes
  - –TBD: molecular sieves & adsorbants.
  - –Measurement: LANL & PNNL
- PEM FC can be affected by very low levels of impurities.
- Storage materials & impurities are TBD; performance of some separation methods can be highly influenced.

Approach:
"Sensors" TTL Quad Chart

Technology Area: Enabling Technologies
Technology Team: Sensors

Area Lead: J. Reiter, *JPL*
Team Lead: E. Brosha, *LANL*

March 2009 (v2)

Objectives:

- Identify and evaluate novel devices and methods and for storage system instrumentation (SOC, fluidic, thermal, structural, etc.)
- Interface with other CoE TAs as necessary for engineering impact of sensor devices (compatibility, etc)
- Recommend sensor technologies and instrumentation approaches for engineering design (full- and sub-scale)

Accomplishments:

Key Milestones:

1. Identify initial criteria matrix: data type,technology class, etc. (LANL) (5/09)
2. Complete initial SOA survey/lit search (LANL) (8/09)
3. Provide candidate list for SOC sensors (LANL) (12/09)

Issues:

- Need to identify additional collaborators/contributors
- Must be able to rapidly evaluate sensor technologies across a broad tech base by evaluating literature search results

Approach:
"Thermal Devices" TTL Quad Chart

Technology Area: Enabling Technologies
Technology Team: Thermal Devices

Area Lead: J. Reiter, *JPL*
Team Lead: K. Drost, *OSU*

March 2009 (v3)

Objectives:

- Evaluate novel heat exchange/transfer technologies and devices required for operation of an H_2 storage system
- Identify/develop tools for assessing performance and fitness of candidate technologies and devices (mass, volume, power, cost, complexity)
- Evaluate, recommend, and incorporate candidate devices for engineered systems (full- and sub-scale)
- Provide ongoing evaluative capability for emergent technologies/requirements

Accomplishments:

Key Milestones:

1. Compile initial list of potential implementations (All) (5/09)
2. Complete initial SOA survey/lit search (All) (8/09)
3. Initial weighted trade space model results (SRNL) (12/09)
4. Initial model validation experiments (OSU, JPL) (3/10)

Issues:

- Must develop an understanding of scale issues with regard to thermal performance at an early stage in the scoping study

Approach:
"Pressure Vessels" TTL Quad Chart

Technology Area: Enabling Technologies
Technology Team: Pressure Vessels

Area Lead: J. Reiter, *JPL*
Team Lead: K. Simmons, *PNNL*

March 2009 (v2)

Objectives:

- Develop tank designs for retaining storage material structured beds: Absorber (cryogenic), Metal Hydride (pressurized); Chemical hydride (ballast)
- Develop model(s) and evaluate designs for cylindrical and conformal tank concepts
- Assess manufacturability and assembly w/ or w/o integrated thermal management (i.e. heat exchange function), including open/split tank designs
- Identify and test novel resin/fiber/liner systems
- Build and assemble prototype tanks

Accomplishments:

Key Milestones:

1. Establish modeling approach and platform(s) (All) (6/09)
2. Determine basic operational parameters (boundary conditions) for each system (PNNL, Lincoln) (9/09)
3. Complete initial design concept analysis w/o internal thermal management function (All) (12/09)

Issues:

- Availability of high strength low cost fibers
- Toughened resin systems that cures below the liner softening point
- Material compatibility
- Install/recharge tank
- Disposition of draft US standards for H_2 storage vessels

Approach:
JPL Task Area 2 - Media/Material Evaluation

- JPL has a role in the evaluation of material properties under the Technology Area led by Center Partner PNNL
  - Within the context of compatibilities, reactivities, and the engineering properties of candidate materials, JPL can contribute assessments and expertise

- Close collaboration with SRNL, UTRC, and other CoE partners to respond to assessment needs, especially as they shift (Phase 1/2)
  - Some direction from DOE/CoE expected regarding this effort

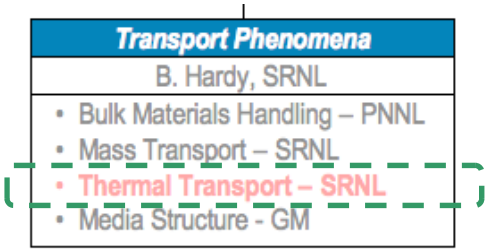
- Will assess relevant data regarding issues relating to safety, risk, compatibility, etc. as R&D requirements drive the "feedback loop"

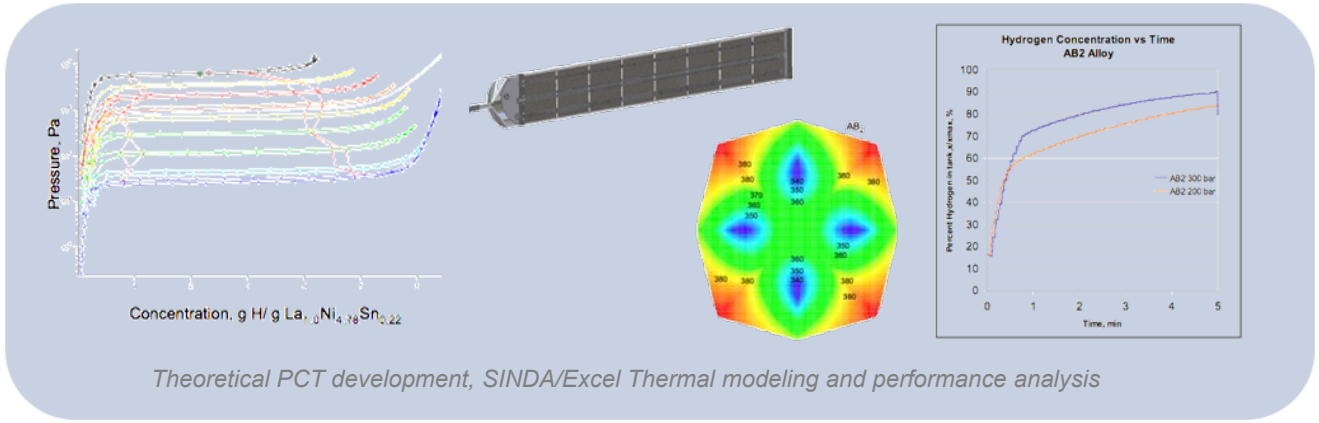
- May leverage expertise with metal/complex hydrides as well as hydrogen sorption materials via collaboration with Caltech

500 MHz NMR spectrometer at Caltech

Approach:
JPL Task Area 3 - Thermal Modeling & Validation

- JPL will utilize current in-house modeling capabilities to support overall Center activities to evaluate an predict heat-exchange (HX) characteristics of component designs
- SINDA/FLUINT model platform with custom capabilities (charging/discharging, non-equilibrium PCT curves, H2 flow enthalpy accounting, alloy properties, etc.)
  - Originally developed during engineering activities within the Metal Hydrides Center of Excellence (MHCoE)





Theoretical PCT development, SINDA/Excel Thermal modeling and performance analysis

- Activity includes capabilities for model/sub-model validation via bench-testing of discrete HX/MX components made at JPL with rapid turnaround
  - Can provide validation paths for models developed either at JPL or by other Center Partners
- This is a gated activity; a Go/No-Go milestone exists in Phase 2 for downselecting candidate approaches based on their performance
  - Criteria and candidate list is expected to evolve based on Phase 1 milestoning

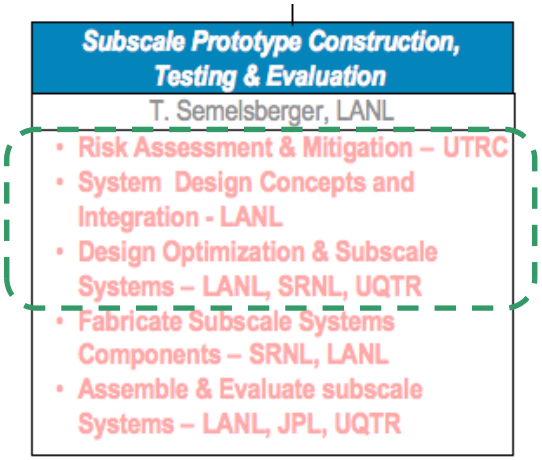
Approach:
JPL Task Area 4 - Prototype Concept Engineering

- Activity focuses on metal/complex hydride and hydrogen sorption systems

- JPL will collaborate with LANL as Technology Area Lead and other Center Partners in Phase 2, in advance of overall DOE/CoE downselect

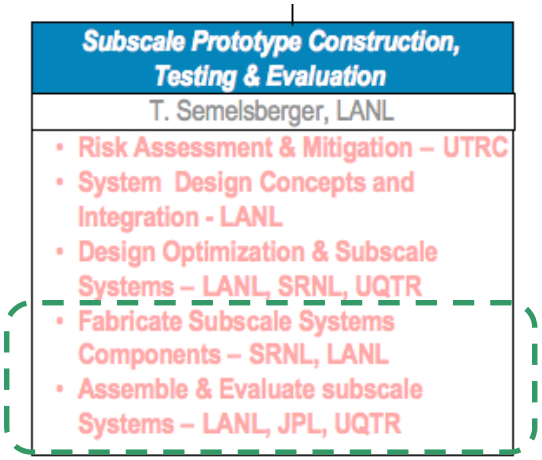
- Will provide system engineering support:
  - Scale optimizations for candidate system approaches, as well as component designs
  - Risk assessment studies (construction, assembly, test, operation, etc.)
  - Propose risk mitigation in advance of system concept downselect

- Will contribute much of the output of the Enabling Technologies team toward assisting DOE and the Center with the Phase 2 system concept downselect; *much of this activity will be in an emergent/evolving mode*



Approach:
JPL Task Area 5 - Prototype Testing and Evaluation

- This activity is JPL's main role in Phase 2/3 and supports the entire Center
  - Presupposes the selection of a metal-hydride based prototype demonstrator, although some contributions may be made in the event a sorption system is still selected



- Utilizes a currently active fabrication/testing/characterization laboratory at JPL with available space for ~2 test-stands
  - Hydrogen Storage Engineering Laboratory (HSEL)
- Tasks aligned under this objective are currently scoped to run from Q2FY2012 through Q4FY2013; 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)

Accomplishments

- **JPL HSECoE effort is organized and off to a successful start**

- **Center Kick-Off Meeting held in Washington DC (12/08)**
- **Tech Team Meeting attended by Center Partners in Washington DC (12/08)**
- **Initial Center Face-to-Face Meeting held in Golden, CO (2/09)**
- **JPL Task Plan and draft milestones completed for Phase 1; "100-day" scope finalized during F2F meeting**

Proposed Future Work

- JPL efforts on Thermal Insulation task are already underway; the next steps are to complete initial state-of-art assessments and propose approaches to gap determination and mitigation

- Define communications plan and information flow for “Enabling Technologies” TA, as compelled by 100-day plan; obtain initial status of collaborating Center Partners in charge of sub-Teams

- Determine current status of SINDA modeling/validation effort as originally put “on-hold” during the cessation of engineering “Task E” under MHCoE, and adopt plan forward for model efforts during HSECoE Phase 2