U.S. DEPARTMENT OF ENERGY

Office of Energy Efficiency and Renewable Energy

Hydrogen Storage Engineering Center of Excellence Pre-Solicitation Meeting

ACTION: Document for discussion at pre-solicitation meeting on October 15, 2007 in San Antonio, Texas.

BACKGROUND

In 2006, President Bush announced the Advanced Energy Initiative (AEI).[1] The AEI accelerates research on technologies with potential to reduce near-term oil use in the transportation sector, including advanced batteries for hybrid electric vehicles and cellulosic ethanol, and reinforces the President's Hydrogen Fuel Initiative, which aims to make hydrogen fuel cell vehicles and fueling stations available to consumers in the long term. The AEI also supports research to reduce the costs of advanced electricity production technologies in the stationary sector such as clean coal, nuclear energy, solar photovoltaics, and wind energy.

The President's Hydrogen Fuel Initiative (HFI), launched in 2003, accelerates research and development of technologies needed to commercialize hydrogen fuel cells for transportation and electricity generation.[2] In support of the HFI, the US Department of Energy (DOE) Hydrogen Program:

- Conducts basic and applied research, technology development and learning demonstrations, and education and outreach activities.
- Focuses on addressing key technical challenges for fuel cells and hydrogen production, delivery, and storage, as well as overcoming institutional barriers through public awareness, training and development of appropriate hydrogen codes and standards that ensure safety.
- Works with public and private-sector partners including automotive and energy companies, power equipment and component manufacturers, electric and natural gas

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1 Bush, George W. "2006 State of the Union Address By the President." U.S. Capitol, Washington, D.C.. 31 Jan. 2006. Available on the Web at <http://www.whitehouse.gov/stateoftheunion/2006/>.

2 Office of the President. "Hydrogen Fuel: A Clean and Secure Energy Future." 30 Jan. 2003. Available on the Web at <http://www.whitehouse.gov/news/releases/2003/01/20030130-20.html>.

utilities, standards development organizations, other federal agencies, state and local government agencies, universities, Federal laboratories and other national and international stakeholder organizations.

- Integrates hydrogen activities in the DOE Offices of Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, and Science.

In support of the HFI, the DOE Office of Energy Efficiency and Renewable Energy (EERE) is planning to solicit applications from multidisciplinary teams with the objective of advancing on-board hydrogen storage systems, a key enabling technology for hydrogen fueled vehicles. The planned DOE EERE Hydrogen Program Funding Opportunity Announcement (FOA) seeks to fund a virtual Center of Excellence in Hydrogen Storage Engineering that supports the research and development of viable hydrogen storage systems for on-board vehicular applications to meet DOE performance and cost targets.

The original DOE Hydrogen Storage “Grand Challenge” solicitation launched in 2003 was planned for approximately $150 million over 5 years, subject to appropriations, and forms the basis for the bulk of DOE’s National Hydrogen Storage Project. Including awards in basic research by the DOE Office of Science announced in 2005 and 2007, the DOE “National Hydrogen Storage Project” includes approximately 40 universities, 15 companies and 10 federal laboratories.

The planned Program Funding Opportunity Announcement for a new Center of Excellence in Hydrogen Storage Engineering is intended to fund one team to complement the existing National Hydrogen Storage Project activities. The announcement would offer an opportunity for one team led by a US organization, including a national laboratory, an institution of higher education, or a nonprofit or for profit private/public entity, to submit applications. Team partners may include national laboratories, non-DOE laboratories, institutions of higher education, nonprofit or for profit private/public entities, non-US institutions, and state and local governments. Non-US institutions may participate as a sub-contractor to US institutions, subject to requirements that will be described in the FOA. The total funding ceiling for this FOA will be approximately $25 to 30 million over 4 to 5 years, subject to appropriations. Non-federal cost share will be required and will be described in the planned FOA.

HYDROGEN STORAGE ENGINEERING CENTER OF EXCELLENCE

1.0 Center of Excellence Objectives

Hydrogen storage systems, particularly materials-based systems, are complex and have a multitude of design parameters, sub-systems, and input/output variables that impact overall system performance. System issues include, but are not limited to, thermal management, mass diffusion, material handling, refueling, cost, start-up/shut-down, transient control, manufacturability, geometric constraints/packaging and safety. Examples of material issues that impact system performance include packing density, kinetics, thermodynamics and operating temperature and pressure. Off-board regenerable materials (e.g., chemical hydrogen carriers or hydrides) also require additional considerations for handling of spent material(s) within the on-board system and vehicle inventory and components for “re-filling” and removal. Such system issues require a new comprehensive engineering effort to meet DOE’s goals.

The new Hydrogen Storage Engineering Center of Excellence (CoE) would complement the work of the current materials-based CoEs and independent projects by addressing these on-board system concerns, providing both assessments of realistic on-board system performance and important feedback to the materials developers.

Specific objectives of the new CoE are to:

(a) Develop and utilize an understanding of storage system requirements for light-duty vehicles to design innovative components and systems with the potential to meet DOE performance and cost targets;

(b) Develop innovative on-board *system* concepts for materials-based storage technologies;

(c) Develop and test innovative concepts for storage sub-systems and component designs;

(d) Develop engineering, design and system models which address both on-board subsystems and the fuel cycle, including refueling, thermal management and the storage-delivery interface; and

(e) Design, fabricate and test subscale (~1 kg material) prototype fixtures, components and/or systems based on adsorbents, advanced metal hydrides and/or chemical hydrogen storage, based upon a Go/No-Go decision to be made by DOE. The Go/No-Go decision will be made on whether to fabricate and test specific prototypes during phase 3 work.

NOTE: Engineering of the off-board regeneration of spent chemical hydrogen storage materials is not within the scope of the planned funding opportunity announcement.

2.0 Center of Excellence Structure

To address the objectives and expected outcomes of this engineering CoE, a multi-institution team covering many scientific, engineering, manufacturing and project management disciplines is considered optimal. DOE is not prescribing any predetermined number of team members, team structure or mix of types of organizations. The team lead determines the mix of technical partners to best address DOE's specified technical scope of work, management needs and the associated review criteria. Existing members of materials-focused CoEs or other DOE independent projects may apply. An applicant can apply as a partner to more than one CoE team, as appropriate, but must submit separate applications for each proposed CoE. It may be desirable for a team to include partner(s) with tank/commercial system development experience.

To be eligible, the proposed center of excellence (CoE) team is required to submit two types of applications, Category 1 and Category 2. The CoE team consists of a team lead and multiple individual technical team partners. The team lead and each individual technical team partner must submit their own stand alone application under the FOA.

The team lead application, focusing on coordination and management, is henceforward labeled "Category 1." The Category 1 or "Team Lead" application describes the strategy and approach of the entire center and how its operations and outcomes are going to be managed and coordinated. The proposed team lead is responsible for submitting the Category 1 team lead application. The Category 1 application cover page will include the names of all the organizations participating on the team (see Appendix A). The team determines the mix of technical partners to best address the objectives of this FOA. The team lead Category 1 application will not contain detailed descriptions of technical scope of work; this is contained in the category 2 applications.

Each technical team partner must submit a Category 2 application that includes the partner's detailed technical scope of work description. The Category 2 or "Individual Technical Application," contains the detailed partner technical work description, partner work plan, partner milestones and expected outcomes, and partner capabilities and facilities. **Note that if a team lead proposes technical work, the team lead must also submit a separate application under Category 2.** Similarly, if a technical team partner proposes technical work under two different proposed Centers, the technical partner must submit two separate Category 2 applications. As part of the merit review process, the team's Category 1 score and Category 2 scores will determine the overall Engineering Center of Excellence team score. Upon team selection, DOE will negotiate a separate award with each partner.

NOTE: All partners should include one or more Go/No-Go decision points in the applications. DOE may hold an annual solicitation to add future partners and work scope into the Engineering Center of Excellence.

The Category 1 application counts for 40% of the score for the proposed CoE. The set of Category 2 applications accounts for the other 60% of the score for the proposed CoE. The scoring will be explained further in section 5.0 Evaluation.

3.0 Hydrogen Storage Engineering Center of Excellence Scope of Work

To address the objectives of the Engineering CoE, the following topic areas will be critical in the technical approach and work plan:

- **Systems engineering for hydrogen storage systems for vehicular applications.** Understand interactions of key components and subsystems; interfaces to power plant (e.g. fuel cell or ICE) and other subsystems; refueling issues; and storage-delivery interface. Note: fuel cell power plants are the emphasis of the DOE Hydrogen Program.
- **Energy management.** Understand impact on subsystems of required heat and/or mass transport. Develop operating requirements for materials based upon system requirements. Understand impact of transients; refueling and dispensing issues; and shutdown and startup at various temperature conditions.
- **Novel component & reactor designs.** Stress conformable designs that are compact and light-weight. Understand impact of designs on manufacturability to select options that lend themselves to low-cost, high-volume manufacturing methods. Model and understand integration and packaging issues of major sub-systems.
- **Concept evaluation & sub-scale prototype testing.** Develop up to 3 subscale prototypes (~1 kg material) for each material type, as appropriate (e.g. chemical hydrogen storage, metal hydrides, and adsorbents) based on a Go/No-Go decision(s) to be made by DOE.

The technical topics above will require a multi-disciplinary approach. It is not expected that an individual partner will cover all four topics mentioned above in their Category 2 technical application. It is also not expected that an individual partner will cover all aspects of a single topic. It is up to the CoE team lead to organize how each partner's technical scope of work will integrate into the overall CoE work portfolio to meet DOE's overall objectives described in Section 1 Center Objectives.

The Engineering CoE proposed work plan should be organized into 3 phases of work with Go/No-Go decision points between each phase.

Phase 1: Understand System Requirements and Define Novel Concepts

The objectives of Phase 1 are to develop and utilize an understanding of storage system requirements for light-duty vehicles and to design innovative systems and components with the potential to meet DOE performance targets. Concepts will utilize a fuel cell or ICE powerplant and define novel concepts based on adsorbents, advanced metal hydrides and/or chemical hydrogen storage. Phase 1 should include, but is not limited to, the following:

1. System engineering: Develop system configurations. Considering the storage system as a "black box," define the operating parameters for the storage subsystem to function with the fuel cell (and/or ICE) on-board environment to meet the DOE performance targets. R&D is needed to define the ranges of input and output variables depending on material type (e.g., metal hydrides, adsorbents and/or chemical hydrogen storage) including temperatures, power, flow rates and weight, volume and geometric (shape) constraints. The output of this effort will be system models for a number of scenarios of light-duty vehicles platform/powerplants which define the range of storage system requirements to meet DOE's targets. This information will be transferred to the DOE materials research portfolio, as appropriate.

2. Energy management. Utilizing the DOE system performance targets as well as the information developed by the system engineering efforts, the team will define preliminary sub-system and interface requirements including interface with the refueling station/forecourt. For example, define requirements for "fresh/spent fuel" delivery to and recovery from the vehicle for chemical hydrogen carrier systems. Design, develop and test innovative concepts for components and/or sub-systems such as thermal management and refueling. For hydrogen release, develop concepts for both on-board endothermic and exothermic material approaches. Examples include materials that are reversible above room temperature, reversible below room temperature, and off-board regenerable materials. These designs include consideration of manufacturability issues, cost and safety.

3. Materials Operating Requirements. In collaboration with the three existing materials-focused CoEs and other DOE independent projects, determine and/or compile the "engineering properties" (e.g., packing density, effective thermal conductivity, hydrogen uptake/release kinetics, available hydrogen capacity, durability) and evaluate their impact on the system, subsystem and/or component design and performance. Potentially collaborate with materials-focused CoEs and independent projects to improve material processing (e.g., increased packing density, lower cost material fabrication) leading to better system performance.

4. Perform engineering modeling & validation. Develop software design tools (as appropriate) and develop experimental test fixtures to demonstrate innovative concepts for storage systems and components, including thermal management, material handling/transport for on-board the vehicle (as appropriate), reactor subsystems and fuel recovery. Determine the engineering requirements for the different material classes (e.g., reversible above room temperature, reversible below room temperature, off-board regenerable materials) for the specific components, including reactors and material transport, when needed. Identify research gaps in engineering developments that need to be filled for specific system concepts.

5. System Performance Analysis. Synthesizing the work conducted in Phase 1, provide to DOE and the Hydrogen Storage Systems Analysis Working Group (http://www1.eere.energy.gov/hydrogenandfuelcells/ssawg.html) a report on the system performance projections of volumetric and gravimetric capacity, and transient performance for systems interfacing with a fuel cell and/or ICE powerplant on a limited number of light-duty vehicle platforms. For the most promising scenarios (to meet the DOE targets), conduct preliminary system cost estimates using high volume manufacturing methods. Identify engineering and materials research gaps and propose plans to address prioritized gaps.

The end-product of Phase 1 (~year 2 of work) should include a report to DOE on the system performance projections and assumptions and a recommended prioritized list of next research steps. In addition, the report will document novel concepts developed and demonstrated, such as thermal management concepts/designs or hydrogen release reactors and how they may be applicable to selected materials-based storage technologies. Go/No-Go decision(s) will be made by DOE based upon the quality of the work performed in Phase 1 and the status of materials' performance in the DOE portfolio.

Phase 2: Novel Component and System Concept Designs

The objectives of Phase 2 are to develop novel on-board component and systems designs (including fuel delivery/recovery, as appropriate). Phase 2 may be an extension or expansion of specific promising work identified in Phase 1. Phase 2 should include an updated assessment of the status of state-of-the-art material properties and the implications of these properties on system and component performance. System designs will encompass adsorbents, advanced metal hydrides and chemical hydrogen storage, as appropriate. Phase 2 should include, but is not limited to, the following:

Continue and expand upon Phase 1 work content. Additional work from Phase 1 (items 1-5) may need to be continued into Phase 2 based on Phase 1 results. Applicants should provide clear Go/No-Go decision points and decision criteria to evaluate continuation from Phase 1 to Phase 2.

6. Develop and evaluate concept designs. Fabricate and evaluate test fixtures and sub-system components to demonstrate the viability and performance of specific engineering designs. In some cases, surrogate materials could be used in place of actual storage materials (for example, an intermetallic hydride with rapid hydrogen kinetics, in place of a high capacity hydride with slower kinetics, could be used to isolate engineering factors limiting performance of a component such as a heat exchanger). Evaluate complete system designs using new concepts and include material properties, if available. These designs should include consideration of manufacturability issues, cost and safety.

7. Update system analysis projections and models, as appropriate. Combining the work conducted in Phases 1 and 2, provide to DOE a report on the system performance projections of volumetric and gravimetric capacity, transient performance, projected lifetime, cost and manufacturability for systems interfacing with a fuel cell and ICE powerplant on a limited number of light-duty vehicle platform scenarios. Identify engineering and materials research gaps and propose plans to address identified issues. Propose to DOE a prioritized plan for sub-scale prototype(s) construction, testing and evaluation including recommended quantitative Go/No-Go decision criteria to proceed to Phase 3.

The end-product of Phase 2 (~year 4-5) should include a report to DOE on the updated system performance projections and assumptions and a recommended prioritized list of next research steps. A Phase 3 research, development and test plan and Go/No-Go decision criteria will be proposed by the team for advancement to Phase 3 activities. DOE will determine whether the center performs sub-scale prototype construction and testing activities in Phase 3.

Phase 3: Sub-scale prototype construction, testing & evaluation

One of the objectives of Phase 3 is to deliver to DOE a set of estimated system engineering specifications and performance projections for recommended sub-scale prototypes. The designs should include consideration of manufacturability, safety and cost. Depending on the Go/No-Go decision at the end of Phase 2, the team will construct, test and evaluate up to 3 types of sub-scale (~25-100 g hydrogen) prototypes based upon different material classes (e.g., reversible above room temperature, reversible below room temperature, off-board regenerable materials).

4.0 Center of Excellence Narrative Requirements

Category 1: Team Lead Narrative

Note that the Narrative is only one part of the overall Grants.gov application; the complete application requirements will be provided in the planned FOA. **There is a page limit of 25 pages for the Category 1 narrative, not including resumes and budget information**. There is no proposed limit on the pages for any given section; this is left up to the discretion of the applicant. This narrative will be submitted by the team lead, Category 1 applicant as part of the overall proposed CoE.

The Category 1 narrative should contain the following sections:

Section I: Overall Scope and Management Plan of the CoE

The center management plan should describe the overall structure of the center, how it will operate, coordinate partner efforts, make down-select and other key decisions, and communicate internally and externally. The team lead should discuss in detail the overall CoE strategy, technical approach and work plan. The work plan should define the overall CoE goals, objectives, approach and expected outcomes of each phase of work. The work plan should describe and quantify the potential of the proposed concept(s) to advance the technology and to achieve DOE's specific technical performance and cost targets for on-board storage systems. A key piece of the CoE work plan is how the team lead will combine all the outcomes and work products being produced under the entire center umbrella. Each phase of work should be defined including expected outcomes or major deliverables from each phase of work. The lead applicant should identify the key technical risk areas and how they will be addressed and mitigated. To the extent possible, the team lead application should avoid duplication with the individual technical partner applications.

The team lead should provide a detailed project management plan including:

- Overall CoE strategy, technical approach and work plan, including strategy to combine work outcomes and products generated under the CoE umbrella.
- Overall CoE management and coordination.
- CoE management structure and self-governing/advising entities, as appropriate.
- Liaison and coordination with storage materials projects (e.g. materials-focused CoEs and independent projects).

- Coordination of the Storage Systems Analysis Working Group (SSAWG).[3]
- Proposed guidelines, principles and strategy governing the CoE Intellectual Property (IP) management plan.
- Communications plan, internally within the engineering CoE and with external parties, including the current materials-focused CoEs and independent projects.
- Proposed guidelines and principles governing the CoE safety plan, particularly handling of hydrogen and handling of potentially hazardous materials, and testing of subscale components and systems at low to moderate pressures.
- Overall CoE work breakdown structure broken into 3 phases, including overall high-level CoE task descriptions, major milestones, down-select points and major decision point criteria.
- Project schedule including timing of milestones and Go/No-Go decision points for all 3 phases.
- Coordination of CoE milestones and reporting to DOE.
- Definition and organization of partners' roles & responsibilities.
- Partner coordination plan for subscale prototype construction and testing.
- Table listing all technical partners and the percent contribution (weighting factor) for each Category 2 technical partner (see Appendix A – Cover Letter Template for the Category 1 Team Lead Application).

<u>Section II: Team Lead Qualifications</u>

The team lead should describe the education, professional training, technical skills, and work experience of the team lead Center Director and other key personnel from the team lead organization (including personnel from major subcontractors or co-principal investigators (PIs), as appropriate). The team lead should also include the level of time commitment for the Center Director and other key personnel by year for the entire proposed project.

This section should also include a discussion that addresses the capability of the proposed team lead to address all aspects of the proposed work within the CoE. In brief, summarize the relevant experience of the Center Director and the team lead organization in leading similar projects. The team lead application should also provide a brief contingency plan for replacement of key personnel.

Include a summary of the team lead's existing facilities and those of subcontractors proposed in completing the work. Discuss, as relevant, the complementary nature of facilities and capabilities that could be applied for the team lead's coordination of the work to be conducted within the CoE.

Category 2: Individual Technical Partner Narrative

Note: Per section 2.0 Center Structure, all partners planning on conducting technical work must submit a Category 2 application for review. If the team lead organization proposes to conduct technical work, the team lead must also submit a Category 2 application for their technical work. If

3 http://www1.eere.energy.gov/hydrogenandfuelcells/ssawg.html

the team lead does not propose technical work, the team lead will submit a Category 1 application only.

Note that the Narrative is only one part of the overall Grants.gov application; the complete application requirements will be provided in the planned FOA. **There is a page limit of 10 pages for the Category 2 partner narrative, not including resumes and budget information.** There is no proposed limit on the pages for any given section; this is left up to the discretion of the applicant.

The Category 2 Technical Partner narrative will contain the detailed discussion of the technical partner's objectives, technical approach, work plan, milestones, down-select and decision points and expected outcomes. Ideally, the proposed CoE task structure described in the Category 1 application should be explicitly apparent in the partner application to aid the reviewers in evaluating the context and role of the partner application in the overall CoE work plan. The technical partner application should avoid duplication with the overall team lead application to the extent possible.

Each Category 2 Technical Partner application must include down-select decision points, at least one Go/No-Go decision point and suggested quantitative criteria to determine their continuation in the center of excellence. These decisions will be made by DOE.

The following Sections should be addressed in each Category 2 technical partner narrative:

<u>Section I: Technical Concept of the Individual Technical Partner</u>

The partner should include an overview of the partner's project and the context of how this work contributes towards achieving the overall CoE's objectives. The applicant should describe the proposed technical concept(s) and the research plan that will investigate that technical concept. The partner should define the goals, objectives, approach and expected outcomes and/or work products of each phase of work. The applicant should describe the innovation of the proposed concept. The partner should identify the key technical risk areas of the proposed concept and how they will be addressed and mitigated. The applicant should describe and quantify the potential of the proposed concept(s) to advance the technology and to achieve DOE's specific technical performance targets for on-board storage systems, as applicable.

<u>Section II: Work Plan of the Individual Technical Partner</u>

The partner should provide a detailed project management plan for their piece of work including:

- Goals and objectives of the project and how the proposed work plan will successfully meet these goals
- Work plan and project schedule broken into 3 phases with associated Go/No-Go decision points, task descriptions, major milestones (at least 1 per year), and criteria for the decision points
- Technical and adminstrative project deliverables, in conjunction with each phase of the project
- Approach to manage the partner principle investigator's (PI's) team (i.e. team within the partner PI's own organization) and ensuring communication within the PI's team and internally with the CoE
- Describe briefly how safety will be addressed, particularly the handling of hydrogen and handling of potentially hazardous materials

Section III: Qualifications and Facilities of the Individual Technical Partner

The partner should describe the education, professional training, technical skills, and work experience of the PI and other key personnel or major subcontractors, as appropriate. For the PI and other major key personnel, include the level of time commitment by year for the entire project.

The partner should summarize the relevant experience of the PI and major participants in performing similar projects. Summarize the partners' existing facilities, and those of subcontractors proposed for completing the work. Discuss, as relevant, the complementary nature of facilities and capabilities that could be applied to the work to be conducted within the CoE. Describe and substantiate any request for new facilities or equipment.

5.0 Evaluation

Merit Review Criteria

The Category 1 application counts for 40% of the score for the proposed CoE. The set of Category 2 applications accounts for the other 60% of the score for the proposed CoE. The applicant team will pre-determine the percent contribution weighting factors (i.e. percent of total) to be applied to each technical partner application for the review process. For example, some technical partners may have a larger role in the overall CoE than others and the weighting factors should reflect the differences in work scope contribution of each technical partner (See Appendix A – Cover Letter Template for the Category 1 Team Lead Application).

The following evaluation criteria will be used in the comprehensive evaluation of applications. For each criterion, the weighting (out of a total of 100%) is indicated to show the relative importance. As this document is in draft form, note that the criteria below are subject to change.

Category 1: Team Lead Application (40% of the Total Team Score)

Criterion 1: Overall Scope and Management Plan of the CoE (Weight: 60% of Category 1 Score)

Scope of the CoE

- The adequacy with which all portions of the technical objectives of the Funding Opportunity Announcement (FOA) are addressed by the CoE team; i.e. effectiveness of the management lead in assembling the necessary skills and ability that are required to fulfill the engineering CoE objectives as outlined in the FOA

Management Plan of the CoE

- The relevance and clarity of the goals and objectives of the CoE collectively
- Adequacy of the proposed management plan to effectively manage the team and to optimize the synergy and communication among the team members to achieve project success
- The clarity and reasonableness of the roles and responsibilities of the team members within the CoE
- Clarity, reasonableness, and timing of the overall task management plan for the CoE, including overall CoE milestones, Go/No-Go decision points, down-select decision points and deliverables
- The adequacy of the Intellectual Property (IP) management plan for the CoE
- Appropriate logic used to assign the percent contribution of each partner

Criterion 2: Team Lead Qualifications (Weight: 40% of Category 1 Score)

- Demonstrated ability of the managing applicant to organize, lead, and provide technical and programmatic guidance in teaming arrangements similar in scope and size
- Organization qualifications and experience
- Qualifications of the Center Director and other key personnel in the team lead organization and experience of the management personnel

Category 2: Individual Technical Partners Applications (60% of Total Team Score)

Criterion 1: Technical Concept of the Individual Partner (Weight: 45% of Category 2 Score)

- The relevance of the technical concept to the technical objectives of the FOA
- The technical viability of the proposed concept, including evidence of experimental data and prior results and/or the application of sound scientific principles to substantiate the proposed concept
- The innovation of the proposed concept and the extent to which the proposed concept offers advantages over current emerging technologies and methodologies
- The identification of the key technical risk areas of the proposed concept and mitigation strategies to address them
- The potential of the proposed concept to advance the technology and to achieve the DOE specific technical performance and cost targets for on-board storage systems

Criterion 2: Work Plan of the Individual Partner (Weight: 40% of Category 2 Score)

- The relevance and clarity of the goals and objectives of the project
- The likelihood of success of the proposed work plan to meet the project goals
- Clarity, adequacy and reasonableness of the work breakdown structure and task descriptions
- Clarity, reasonableness, and timing of the milestones, Go/No-Go decision points, and deliverables
- The clarity and adequacy of technical and administrative project deliverables, including the specific anticipated end result or product of each phase of the project
- The adequacy of the communication plan to work effectively within this specific project (i.e. with subcontractors or co-PIs) and to work effectively with other CoE partners to meet the project goals
- The adequacy of the plan to address safety, particularly handling of hydrogen and handling of potentially hazardous materials

Criterion 3: Qualifications and Facilities of the Individual Partner (Weight: 15% of Category 2 Score)

Personnel and Organization Qualifications

- The adequacy of the education, professional training, technical skills, and work experience of the Principal Investigator (PI) and other key personnel, including personnel from major subcontractors

- The level and reasonableness of the time commitment of the PI and other key personnel, including personnel from major subcontractors, assigned to the proposed project
- The capability of the proposed personnel to address all aspects of the proposed work

Facilities

- The adequacy of the applicant's existing facilities, and those of subcontractors, proposed for completing the work
- The reasonableness of any request for new facilities or equipment

Appendix A – Project Narrative Cover Page Template for Category 1 Applicant

Category 1: Team Lead Organization Narrative in Response to Funding Opportunity Announcement DE-PS36-08GOxxxxx, Hydrogen Storage Engineering Center of Excellence

Title of the Project

Team Lead Organization Name

Lead PI Name, Title	Business Contact Name, Title
Phone Number	Phone Number
Fax Number	Fax Number
Address Line 1	Address Line 1
Address Line 2	Address Line 2
City, State Zip Code	City, State Zip Code
E-Mail	E-Mail

Example Team Table

Partner Organization Name	PI Name	Percent Contribution to the Success of the Team
Category 1 / Team Lead Application (Name)		**40% (fixed)**
Category 2 / Technical Partner #1 Name		15%
Category 2 / Technical Partner #2 Name		10%
Category 2 / Technical Partner #3 Name		10%
Category 2 / Technical Partner #4 Name		10%
Category 2 / Technical Partner #5 Name		5%
Category 2 / Technical Partner #6 Name		5%
Category 2 / Technical Partner #7 Name		5%
	Total	100%

Note 1: As part of the merit review process, the team's Category 1 score and Category 2 scores will determine the overall CoE team score.
Note 2: The total must add to 100%.
Note 3: Weighting for Category 1, team lead partner application must remain at 40%.
Note 4: All technical team partners must be included in the table.
Note 5: DOE is not instituting any predetermined number of team members so the table above is simply an example.

Date Submitted

Appendix B - Project Narrative Cover Page Template for Category 2 Applicant

Category 2: Technical Partner Narrative in Response to Funding Opportunity Announcement DE-PS36-08GOxxxxx, Hydrogen Storage Engineering Center of Excellence

Title of the Project*
(*Every project within a team should have an individual title)

Organization Name

Lead PI Name, Title	Business Contact Name, Title
Phone Number	Phone Number
Fax Number	Fax Number
Address Line 1	Address Line 1
Address Line 2	Address Line 2
City, State Zip Code	City, State Zip Code
E-Mail	E-Mail

Key Participants (if there are any subrecipients to Category 2 applicant)

Corresponding Category 1 Team Lead Organization Name

Date Submitted

APPENDIX C: SUPPLEMENTARY INFORMATION

Introduction

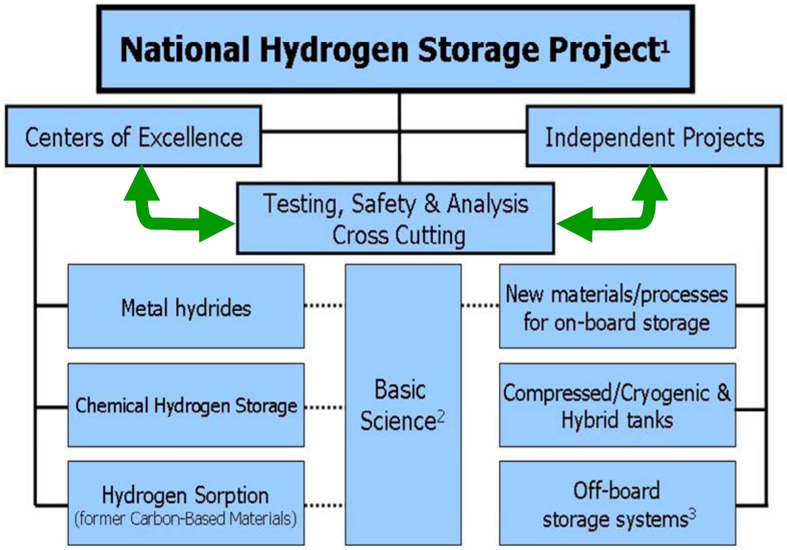
The DOE Office of Energy Efficiency and Renewable Energy is soliciting team applications for a Center of Excellence in Hydrogen Storage Engineering with the objective of supporting the President's Hydrogen Fuel Initiative. This Announcement seeks to fund engineering research and development to support viable hydrogen storage systems for on-board vehicular applications to meet DOE performance targets. DOE intends to provide financial support for this effort under authority of the Energy Policy Act of 2005, Public Law 109-58, in particular the Spark M. Matsunaga Hydrogen Act of 2005, Title VIII – Hydrogen.

Background

Hydrogen storage for on-board transportation applications is one of the most technically challenging barriers to the widespread commercialization of hydrogen fueled vehicles. The DOE Hydrogen Storage activity focuses primarily on the research and development of low pressure, materials-based technologies to allow for a driving range of greater than 300-miles while meeting packaging, cost, safety, and performance requirements to be competitive with current vehicles.

Figure 1 shows the framework for DOE's National Hydrogen Storage Project, which includes independent projects and three existing materials-focused Centers of Excellence (CoEs) in applied hydrogen storage R&D as well as basic science in hydrogen storage (funded by DOE Office of Basic Energy Sciences). Projects are focused in three main areas: metal hydrides, chemical hydrogen storage, and hydrogen sorption. In addition, a cross-cutting area addresses material and system safety, systems analysis, testing and advanced tank R&D. The storage portfolio is comprised of approximately 40 universities, 15 companies and 10 federal laboratories, including 17 basic science projects started in FY 2005 and 7 basic science projects awarded in FY 2007.

Figure 1. Framework for the US National Hydrogen Storage Project



1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

The Program's overarching goal is to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications. The focus of the efforts has been on the 2007 system targets of 1.5 kWh/kg (4.5 wt.%), 1.2 kWh/L (36 g/L) and $6/kWh as well as the 2010 targets of 2.0 kWh/kg (6.0 wt.%), 1.5 kWh/L (45 g/L) and $4/kWh. Research also addresses all other system requirements such as durability/operability, charge/discharge rates, efficiency, fuel purity and environmental health and safety. The 2010 targets would allow some light-duty vehicles to achieve a 300-mile driving range to enable limited market penetration. The 2015 targets of 3 kWh/kg (9 wt.%), 2.7 kWh/L (81 g/L), and $2/kWh would enable mass market penetration across all light-duty vehicle platforms.

See Table 1 in Appendix C for a complete list of the system technical performance targets for on-board hydrogen storage systems. The key technical challenges are also described in Appendix C.

FY 2007 Technology Status

On-board hydrogen storage approaches under investigation include high capacity metal hydrides, high surface area adsorbents, chemical hydrogen storage carriers, low-cost and conformable tanks, compressed/cryogenic hydrogen tanks, and new materials or processes, such as conducting polymers, metal organic frameworks (MOFs), ionic liquids and nanostructured materials. Physical storage systems, such as compressed/cryogenic tanks, and reversible material systems, such as metal hydrides and high surface area adsorbents are classified as "on-board reversible" systems because they can be refueled on-board the vehicle from a gaseous (or liquid) hydrogen supply. For chemical hydrogen storage, as well as certain metal hydrides, material regeneration with hydrogen is not possible on-board the vehicle; thus, these systems must be regenerated off-board and are termed "off-board regenerable".

During FY 2007, new materials were developed and the performance of existing materials was improved through the materials-focused Centers of Excellence and independent projects.

Figure 2 shows gravimetric and volumetric material-based capacity data for materials under development in FY 2007. Note that these values do not include any balance-of-plant components needed to estimate system values. Although these results show potential materials-based capacities of over 5 to 9 wt.% and over 45 g/L, it must be reiterated that the targets are system-level capacities that include the storage media, tank and all balance-of-plant components needed for a vehicular system[4].

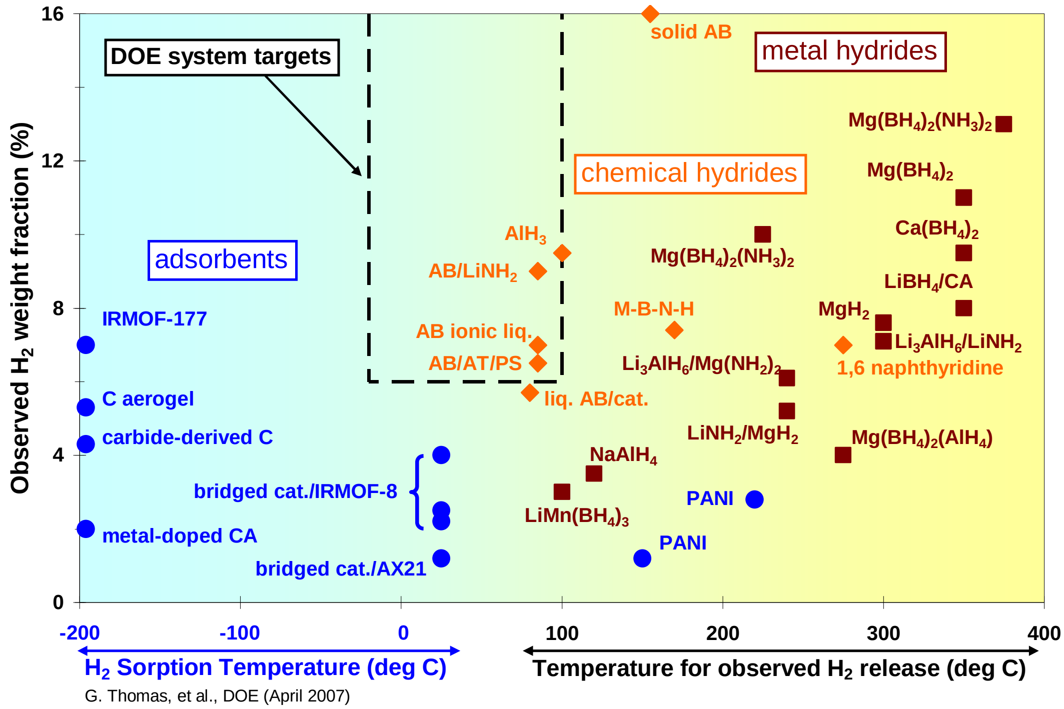
Figure 2. Selected Examples of Progress in Applied Materials R&D in FY2007 (Note: Material capacities only, not system values)

	Metal Hydrides	Chemical H_2 Storage	Adsorbents
2006	• **Alane:** ~8-10 wt%,~150 g/L *(<150 C)* • **Borohydrides:** >9 wt%,~100 g/L *(~250 - 350 C)* • **Destabilized Binary hydrides:** ~5-7 wt%, ~60-90 g/L *(~250 C)* • **Li Mg Amides:** ~5.5wt%,~80 g/L *(>200 C)*	• **4,7 Phenanthroline (organic liquids):** ~7 wt%, ~65 g/L *(<225 C)* • **Seeded Ammonia Borane** ~9 wt%,~90 g/L *(>120 C)* • **Ammonia Borane/Li amide** ~7 wt%, ~54 g/L *(~85 C)*	• **Metal-Organic Frameworks-IRMOF-177:** ~7 wt%,~30 g/L *(77K)* • **Bridged catalysts – IRMOF-8:** ~1.8 wt.%,~10 g/L *(room temp.)* • **Metal/carbon hybrids--** ~6-8 wt%*,~39 g/L* (*theory)
2007	• **Alane (AlH3) regeneration:** *Chemical, electrochemical, supercritical fluids* • **LiBH4/C aerogels:** 6-8 wt.%, ~55-75 g/L *(~300 C)* • **Reversible Ca(BH4)2:** ~9.6 wt.%, ~105 g/L *(~350 C)* • **Mn(BH$_4$)2:** 9-13 wt.% *(>100 C)* • **Mg(BH$_4$)$_2$:** 9-12 wt.%, ~110 g/L *(~350 C)* • **Destabilized hydrides:** *DFT Identified new reactions; LiBH4/MgH2; CaH2/LiBH4; LiNH2/LiH/Si*	• **1,6-Naphthyridine:** ~7 wt.%, ~70 g/L *(275 C); Surface supported catalyst* • **AMINE BORANES:** • **Ionic liquids:** ~7 wt.%, 39 g/L *(85 C)* • **AB/LiNH2, AB/LiH:** ~9 wt.%, ~70 g/L *(85 C)* • **Solid AB:** >16 wt.%, >199 g/L *(155 C) (>3g/s/kgAB)* • **Liquid AB/catalyst:** ~ 6 wt.% *(~ 80 C)* • **Regeneration:** *2-step process, est.>50% eff.*	• **Bridged cat./IRMOF-8:** >3 wt.%, 100 bar (25 C); ~20 kJ/mol; • **Bridged cat./AX-21:** >1 wt.%, 100 bar (25 C) • **C aerogels:** ~5 wt.%, ~30 g/L (77 K) • **Metal-doped C aerogels:** ~2 wt.% (77 K); ~7-7.5 kJ/mol • **PANI:** 2.8 wt.%, 25 bar (25 C); Release at ~100-220 C

Significant work is needed to modify or "tune" the properties of high hydrogen capacity materials toward the required range of operating temperatures and pressures. While most technical articles contain plots of storage capacity (weight versus volume), an informative alternative is to show capacity as a function of temperature. Figure 3 shows the current status of materials development from the Storage subprogram in terms of hydrogen capacity (material-based capacity on a weight basis) as a function of release or uptake temperature. The system level targets for weight and temperature are defined by the dashed lines to put the material-based capacities in perspective. The limitations in temperature are due, in some materials, to thermodynamic properties (e.g., enthalpies or binding energies are either too high or too low) and, in others, the kinetics (e.g., hydrogen absorption or release rates are too slow at the required operating temperatures). There is typically a range of temperature across which hydrogen is discharged (or charged) and the values shown will be updated by DOE as advancements are made in this field.

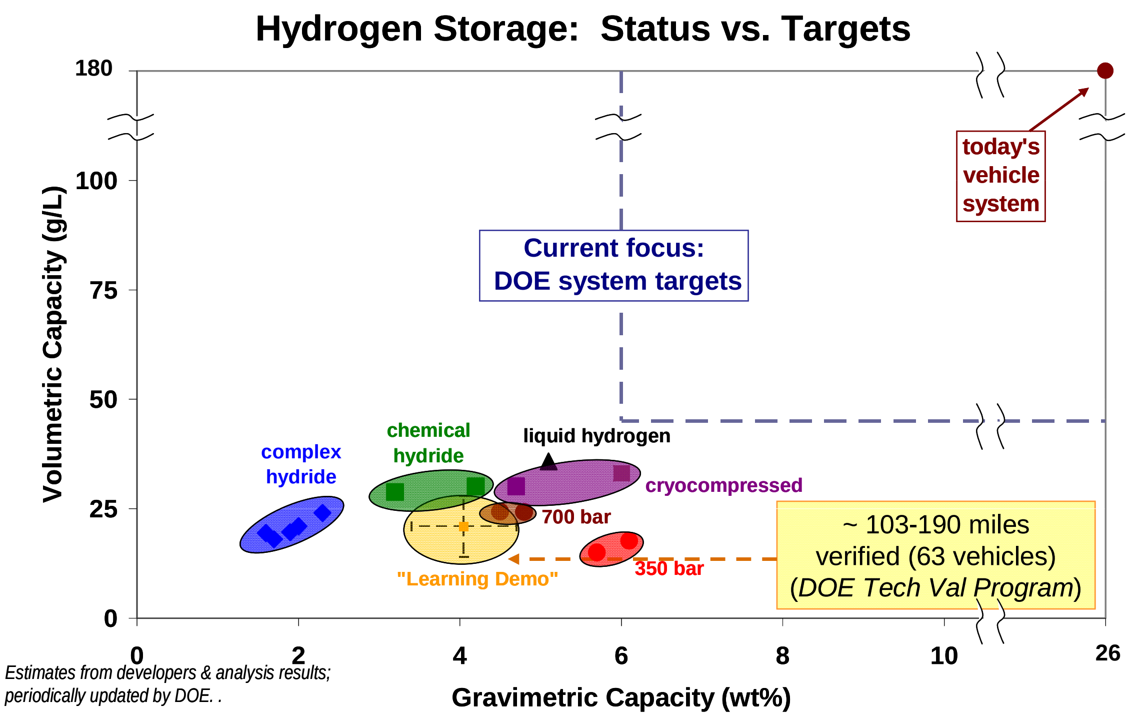
[4]Please see the DOE Hydrogen Program Annual Progress Report for details on sponsored R&D projects: http://www.hydrogen.energy.gov/annual_progress.html.

Figure 3. Hydrogen Storage Capacity for Materials as a Function of Temperature



The current storage system status values, as shown in Figure 4, are estimates provided by developers and by the R&D community. Since a limited number of full-scale complete systems have been fabricated, most of the data shown are projections based on system designs or on laboratory sub-scale prototypes. One highlight of Figure 4 is the circle showing the range of “real world” system data from the DOE Technology Validation subprogram through which more than 70 hydrogen fuel cell vehicles have been independently validated. The majority of these vehicles used 5,000 psi (350 bar) hydrogen tanks (a small number used 10,000 psi or liquid tanks) and the storage system capacity ranged from 3.5 to 4.7 wt.% and 14 to 28 g/L. The driving range, based on EPA cycle data, was 103 to 190 miles. It is clear that none of the current systems meets the combined gravimetric, volumetric, and system cost targets. It should also be reiterated that there are several other requirements such as hydrogen charging and discharging rates that are not illustrated in Figure 4 and that must be met simultaneously with all other targets such as capacity.

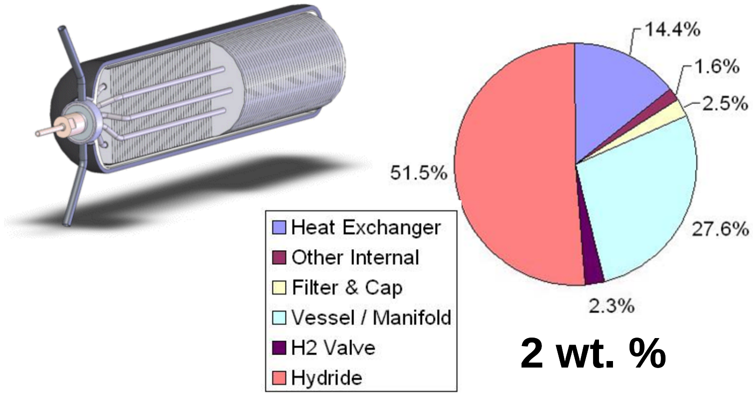
Figure 4. Current Status of Hydrogen Storage Systems versus Targets



As noted in http://www1.eere.energy.gov/hydrogenandfuelcells/storage/doe_rd.html, the DOE Hydrogen Program has funded a limited number of engineered hydrogen storage prototypes. One example project, conducted by United Technologies Research Center, designed and tested 1st and 2nd generation prototypes based on titanium-catalyzed sodium alanate (Ti-$NaAlH_4$) metal hydride.[5] Using improved internal heat exchange design and material packing methods, the 2nd generation prototype achieved 2 wt.% and 21 g/L hydrogen assuming sufficient hydrogen recharge time. Based on the as built 2nd generation model, it is projected that a system could be built with 2.3 wt.% and 24 g/L using the same sodium alanate material and nominal system design and material packing improvements. Figure 5 shows a break-out of how the weight of the system is distributed among the material and major balance of plant components. One important outcome of this work was identifying key engineering issues that impact the overall system volumetric and gravimetric capacity and overall performance. Examples include: hydrogen re-fill and discharge kinetics; impact of "depth of discharge"; thermal integration, especially heat removal during hydrogen re-fill; material packing density; reversible or available hydrogen at low operating temperature; design for assembly and manufacturability and compact heat exchange design.

5 "High Density Hydrogen Storage System Demonstration Using NaAlH4 Complex Compound Hydrides," United Technologies Research Center, agreement number DE-FC36-02AL67610 at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/storage_system_prototype.pdf

Figure 5. Weight Distribution for As-built 2nd Generation Ti-$NaAlH_4$ Prototype



Current EERE Storage Portfolio

DOE communicates to its stakeholders and the public the results of the taxpayer's investment in the DOE Hydrogen Program Annual Progress Report. Each DOE-funded project submits annually a 3-5 page technical progress report. Links to these progress reports are given below.

2007: http://www.hydrogen.energy.gov/annual_progress.html

2006: http://www.hydrogen.energy.gov/annual_progress06.html

2005: http://www.hydrogen.energy.gov/annual_progress05.html

2004: http://www.hydrogen.energy.gov/annual_progress04.html.

Further information on the plans of the DOE Hydrogen Program can be obtained from the Multi-Year Program Plan at www.eere.energy.gov/hydrogenandfuelcells/mypp.

The existing three materials CoEs (in metal hydrides, chemical hydrogen storage and adsorption materials) initiated work in FY 2005. The current materials-focused CoE's objectives are given below.

DOE Metal Hydride Center of Excellence:

The Metal Hydride Center seeks to develop improved lightweight, high-capacity hydride-based materials for vehicular applications. Projects focus on the development of advanced metal hydride materials, including: 1) advanced complex hydrides of the light elements Li, Na, Mg, Ti, Ca, B, Al, Si; 2) destabilized binary hydrides; 3) novel intermetallic hydrides (e.g. Mg-M-H alloys); and 4) other hydride materials, such as alane and the N-H-Li-X systems.

DOE Chemical Hydrogen Storage Center of Excellence:

The DOE Chemical Hydrogen Storage Center of Excellence focuses on developing advanced chemical hydrogen storage materials and carriers and studying their associated engineering requirements for on-board vehicular applications. The goal of the center is to develop an advanced hydrogen storage system by pursuing three "tiers" of R&D for chemical hydrogen storage that will likely require off-board regeneration.

Tier 1, Borohydride/Water, concentrates on the chemistry required for the reaction of borohydride, BH_4^-, compounds such as $NaBH_4$ with water to release hydrogen, and for lowering the cost of converting the resulting borates back to BH_4^-. Tier 2, Novel Boron Chemistry focuses on chemical processes that release hydrogen from other B-H bonded species that may be less energy-intensive and less expensive to regenerate than borohydride. Tier 3, Innovation beyond Boron, examines materials comprising light elements other than boron that could satisfy non-toxicity and mass/volume-storage requirements, while at the same time requiring minimal energy cost of recycling/regenerating.

<u>DOE Hydrogen Sorption Center of Excellence:</u>

The DOE Hydrogen Sorption CoE focuses on developing high surface area adsorbents and hybrid materials for vehicular hydrogen storage systems that enable near room temperature storage of hydrogen at nominal pressure. Through parallel efforts, the Center proposes to determine the limits of performance for specific material systems and extract mechanistic information that can be used for further design and optimization. A key effort is to determine the relationship between nanoscale structure and the energetics of hydrogen binding using a variety of experimental and theoretical tools and well-defined nanostructured materials. Materials of interest include MOFs, polymers, B-C containing materials, C-metal hybrids, graphite nanofibers, alkali metal intercalated carbons and nanotubes, carbon nanohorns, and metal decorated and substitutionally doped versions of these materials.

Barriers and Targets

For transportation, the overarching technical challenge for hydrogen storage is how to store the amount of hydrogen required for a conventional driving range (greater than 300 miles), within the vehicular constraints of weight, volume, efficiency, safety, and cost. Durability over the performance lifetime of these systems, as well as acceptable refueling times and hydrogen delivery flow rates must be achieved. The applicants are encouraged to refer the Hydrogen, Fuel Cells, & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan at http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/.

On-Board Hydrogen Storage Technical Barriers

General to All Storage Approaches

A. System Weight and Volume. The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum fueled vehicles. Storage media, materials of construction and balance-of-plant components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms. Reducing weight and volume of thermal management components is also required.

B. System Cost. The cost of on-board hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost media, materials of construction and balance-of-plant components are needed, as well as low-cost, high-volume manufacturing methods.

C. Efficiency. Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to transfer hydrogen into and out of the storage media or material is an issue for all material options. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent media and by-products are typically regenerated off-board the vehicle. In addition, the energy associated with compression of and liquefaction of hydrogen must be considered for compressed and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency for all approaches.

D. Durability/Operability. Durability of hydrogen storage systems is inadequate. Storage media, materials of construction and balance-of-plant components are needed that allow hydrogen storage systems with a lifetime of at least 1500 cycles and with tolerance to hydrogen fuel contaminants. An additional durability issue for material-based approaches is the delivery of sufficient quality hydrogen for the vehicle power plant.

E. Charging/Discharging Rates. In general and especially for material-based approaches, hydrogen refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes for a 5-kg hydrogen charge, over the lifetime of the system. Thermal management that enables quicker refueling is a critical issue that must be addressed. Also, all storage system approaches must be able to supply sufficient flow rate of hydrogen to the vehicle power plant (e.g. fuel cell or internal combustion engine) to meet the required power demand.

F. Codes and Standards. Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. Materials of Construction. High-pressure containment for compressed gas and other high-pressure approaches limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required. Research into new materials of construction such as metal ceramic composites, improved resins, and engineered fibers is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed.

H. Balance of Plant (BOP) Components. Light-weight, cost-effective balance-of-plant components are needed for all approaches of hydrogen storage, especially those requiring high-pressure or extensive thermal management. These include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, heat exchangers, and sensors. System design and optimal packaging of components to meet overall volumetric targets are also required.

I. Dispensing Technology. Requirements for dispensing hydrogen to and from the storage system have not been defined. This includes meeting heat rejection requirements during fueling especially for on-board reversible material-based approaches. For chemical hydrogen approaches, methods and technology to recover spent material from the fuel tank for regeneration during "refueling" are needed.

J. Thermal Management. For all approaches of hydrogen storage; compressed gas, cryogenic and materials-based, thermal management is a key issue. In general, the main technical challenge is heat removal upon re-filling of hydrogen for compressed gas and on-board reversible materials within fueling time requirements. On-board reversible materials typically require heat to release hydrogen on board the vehicle. Heat must be provided to the storage media at reasonable temperatures to meet the flow rates needed by the vehicle power plant, preferably using the waste heat of the power plant. Depending upon the chemistry, chemical hydrogen approaches often are exothermic upon release of hydrogen to the power plant, or optimally thermal neutral. By virtue of the chemistry used, chemical hydrogen approaches require significant energy to regenerate the spent material and by-products prior to re-use; this is done off the vehicle.

K. System Life-Cycle Assessments. Assessments of the full life cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking. An understanding of infrastructure implications, particularly for chemical hydrogen storage, and approaches to reduce primary energy inputs, is lacking.

Compressed Gas Systems

L. High-pressure Conformability. Conformable high-pressure tanks will be required for compressed gas and other high-pressure approaches for hydrogen storage to meet the space constraints of light-duty vehicle applications.

M. Lack of Tank Performance Data and Understanding of Failure Mechanisms. An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Research on tank performance and failure are needed to optimize tank structure for performance and cost. In addition, sensors and associated prediction correlations are needed to predict lifetime and catastrophic tank failure.

Cryogenic Liquid Systems

N. Liquefaction Energy Penalty. The energy penalty associated with hydrogen liquefaction, typically 30% of the lower heating value of hydrogen, is an issue. Methods to reduce the energy requirements for liquefaction are needed.

O. Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting, reduces driving range and presents a potential safety/environmental hazard, particularly when the vehicle is in an enclosed environment. Materials and methods to reduce boil-off in cryogenic tanks are needed.

Reversible Materials-Based Storage Systems (Reversible On-Board)

P. Lack of Understanding of Hydrogen Physisorption and Chemisorption. Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of adsorption/absorption and desorption kinetics is needed to optimize hydrogen uptake and release capacity rates. An understanding of chemical reactivity and material properties, particularly with respect to exposure under different conditions (air, moisture, etc.) is also lacking.

Q. Reproducibility of Performance. Standard test protocols for evaluation of hydrogen storage materials are lacking. Reproducibility of performance both in synthesis of the material/media and measurement of key hydrogen storage performance metrics is an issue. Standard test protocols related to performance over time such as accelerated aging tests as well as protocols evaluating materials safety properties and reactivity over time are also lacking.

Chemical Hydrogen Storage Systems (Typically Regenerated Off Board)

R. Regeneration Processes. Low-cost, energy-efficient regeneration processes have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency and environmental impacts.

S. By-Product/Spent Material Removal. The refueling process is potentially complicated by removal of the by-product and/or spent material. System designs must be developed to address this issue and the infrastructure requirements for off-board regeneration.

TECHNICAL TARGETS

The DOE EERE hydrogen storage activity funds applied research and development of viable hydrogen storage technologies primarily for on-board vehicular applications. The major objective for on-board vehicular hydrogen storage is:

- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt.%), 1.5 kWh/L (45 g H_2/L), and $4/kWh

- By 2015. develop and verify on-board hydrogen storage systems achieving 3 kWh/kg (9 wt.%), 2.7 kWh/L (81 g H_2/L), and $2/kWh

Table 1 shows the technical targets for on-board hydrogen storage systems. The technical targets for on-board hydrogen storage systems[6] were established through the FreedomCAR partnership between DOE and the US Council of Automotive Research (USCAR). The partnership was recently expanded to include the major energy companies and renamed the FreedomCAR and Fuel Partnership[7]. A detailed target explanation document can be found at http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf.

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6 See the following websites for details on the targets: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/freedomcar_targets_explanations.pdf and www.eere.energy.gov/hydrogenandfuelcells/mypp

7 The FreedomCAR and Fuel Partnership includes US Department of Energy, USCAR (DaimlerChrysler Corporation, Ford Motor Company and General Motors Corporation), BP America, Chevron, ConocoPhillips, ExxonMobil Corporation and Shell Hydrogen US

Technical Targets: On-Board Hydrogen Storage Systems

Storage Parameter	Units	2007	2010	2015
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)[a]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	2 (0.06)	3 (0.09)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost [b] (& fuel cost)[c]	\$/kWh net (\$/kg H_2) \$/gge at pump	6 (200) ---	4 (133) 2-3	2 (67) 2-3
Durability/Operability • Operating ambient temperature [d] • Min/max delivery temperature • Cycle life (1/4 tank to full) [e] • Cycle life variation [f] • Min delivery pressure from tank; FC= fuel cell, I=ICE • Max delivery pressure [g]	 ºC ºC Cycles % of mean (min) at % confidence Atm (abs) Atm (abs)	 -20/50 (sun) -30/85 500 N/A 8FC / 10ICE 100	 -30/50 (sun) -40/85 1000 90/90 4FC / 35ICE 100	 -40/60 (sun) -40/85 1500 99/90 3FC / 35ICE 100
Charging/discharging Rates • System fill time (for 5 kg) • Minimum full flow rate • Start time to full flow (20 ºC) [h] • Start time to full flow (- 20 ºC) [h] • Transient response 10%-90% and 90% -0%[i]	 min (g/s)/kW s s s	 10 0.02 15 30 1.75	 3 0.02 5 15 0.75	 2.5 0.02 5 15 0.75
Fuel Purity (H_2 from storage)[j]	% H_2	99.99 (dry basis) See Appendix C		
Environmental Health & Safety • Permeation & leakage [k] • Toxicity • Safety	Scc/h - -	Meets or exceeds applicable standards		
• Loss of useable H_2 [l]	(g/h)/kg H_2 stored	**1**	**0.1**	**0.05**

Footnotes to Table 1:

Useful constants: 0.2778kWh/MJ, ~33.3kWh/gal gasoline equivalent.

[a] Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

[b] 2003 US\$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

[c] 2005 US\$; includes off-board costs such as liquefaction, compression, regeneration, etc; based on H_2 production cost of \$2 to \$3/gasoline gallon equivalent untaxed, independent of production pathway. For pathway-dependent

interim targets, refer to the Production Section.

[d] Stated ambient temperature plus full solar load. No allowable performance degradation from -20C to 40C. Allowable degradation outside these limits is TBD.

[e] Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).

[f] All targets must be achieved at end of life.

[g] For delivery to the tank, in the near term, the forecourt should be capable of delivering 10,000 psi compressed hydrogen, liquid hydrogen, or chilled hydrogen (77 K) at 5,000 psi. In the long term, it is anticipated that delivery pressures will be reduced to between 50 and 150 atm for solid state storage systems, based on today's knowledge of sodium alanates.

[h] Flow must initiate within 25% of target time.

[i] At operating temperature.

[j] See Appendix F. The storage system will not provide any purification, but will receive incoming hydrogen at the purity levels required for the fuel cell. Some storage technologies may produce contaminants for which effects are unknown; these will be addressed as more information becomes available.

[k] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

[l] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.