Draft Technical Description of a Planned Funding Opportunity Announcement: "Research and Development for Hydrogen Storage"

A. *Introduction and Background*

The U.S. Department of Energy's (DOE) Fuel Cell Technologies Office (FCT)[1] within the Office of Energy Efficiency and Renewable Energy (EERE) is requesting applications to fund research and development (R&D) activities for the continued development of advanced hydrogen storage systems and novel hydrogen storage materials supported through the Hydrogen Storage program. The goal is to enable the widespread commercialization of hydrogen and fuel cell technologies and specifically to provide adequate hydrogen storage for onboard vehicle, material handling, and portable power applications that meet the DOE hydrogen storage targets. These activities will support the FCT's goal to: maintain the rapid pace of progress in fuel cells; expand the markets and applications in which hydrogen-powered fuel cells can compete; enable the use of lower-cost hydrogen from diverse and environmentally beneficial sources; enable highly efficient hydrogen production; reduce the cost of hydrogen delivery; reduce the costs of current hydrogen storage technologies; and develop novel, advanced hydrogen storage technologies. FCT is also working to reduce institutional and market barriers that may impede the commercialization of hydrogen fuel cell technologies. To accomplish these goals, the FCT works with partners in state and federal agencies, industry, academia, non-profit institutions, and the national laboratories. DOE intends to provide financial support for this effort under authority of the Energy Policy Act of 2005, Public Law 109-58, Title VIII – Hydrogen.

Full commercialization of fuel cells using hydrogen will require advances in hydrogen storage technologies. Developing systems to enable lightweight, compact, and inexpensive hydrogen storage will help make hydrogen fuel cells competitive in a wide range of portable and stationary applications, and enable longer driving ranges for a wider variety of transportation applications. While hydrogen has the highest energy content per unit weight of any fuel, it has very low energy content per unit volume. This poses a challenge as increasing the energy content per unit volume for gaseous hydrogen storage requires either very high pressures or low temperatures. However, materials that bond to, or adsorb hydrogen enable storage at high density in a compact container. While the energy density challenge exists for all fuel cell installations that use hydrogen, the problem is most acute for light-duty vehicles where the storage systems must operate within stringent size, weight and cost constraints; enable a driving range of more than 300 miles (generally regarded as the minimum for widespread driver acceptance based on the performance of today's gasoline vehicles); and refuel at ambient temperatures fast enough to meet drivers' expectations (normally only a few minutes). Most of the hydrogen that is used today is stored as a compressed gas (with pressures typically ranging from 150 to 700 bar) or a liquid (liquid storage requires cryogenic temperatures at around 20 K). The majority of the fuel cell vehicles in today's demonstration fleets use high-pressure tanks rated at 350 or 700 bar for onboard storage of hydrogen gas. These tanks are more expensive, heavier, and require more volume than conventional fuel tanks. While possibly adequate for some stationary applications and vehicle platforms, they may be too expensive and bulky for many non-stationary applications and may not be able to provide a driving range that meets consumer expectations across the full range of light-duty vehicle platforms. Therefore, to maximize the use of hydrogen as a zero-carbon fuel for fuel cells, advanced storage systems and technologies will be required, especially for automotive applications.

While some hydrogen fuel cell vehicles will soon emerge onto the market which are capable of >300 mile range, this range must be achievable across all light-duty platforms without compromising space and performance and at an acceptable cost in order for hydrogen fuel cell vehicles to be truly competitive with conventionally fueled vehicles and to achieve mass market penetration. Similarly for non-automotive applications, low-cost, compact, and safe hydrogen storage technologies are needed to enable hydrogen fuel cell systems to compete with incumbent technologies, such as batteries and hydrocarbon fueled generators. Therefore, the FCT is focused on the R&D of materials and approaches that will enable widespread commercialization of fuel cell systems for diverse applications across stationary, portable, and transportation sectors. R&D is concentrated on low-pressure, materials-based technologies and low-cost, high pressure tank technologies for hydrogen storage systems to meet performance targets.

Light-duty Vehicle Applications

To meet the objectives for light-duty vehicles, the DOE has developed a comprehensive set of technical targets for onboard hydrogen storage systems in collaboration with automotive manufacturers, such as through the U.S. DRIVE partnership. The full set of technical targets is included in Appendix A and available online at: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf. Interim 2017 targets will allow some light-duty hydrogen fuel cell vehicle platforms to meet customer expectations. To meet all customer expectations across the full range of light-duty hydrogen fuel cell vehicle platforms, the Ultimate Full Fleet targets will be required.

Three overarching performance targets for onboard hydrogen storage systems noted in Appendix A are: gravimetric capacity (kWh/kg or wt.% H_2); volumetric capacity (kWh/L or g H_2/L); and system cost ($/kWh or $/kg $H_{2\ \mathrm{stored}}$). For 2017, the targets are 1.8 kWh/kg (5.5 wt.%), 1.3 kWh/L (40 g H_2/L) and $12/kWh ($400/kg $H_{2\ \mathrm{stored}}$) and the Ultimate Full Fleet targets are 2.5 kWh/kg (7.5 wt.%), 2.3 kWh/L (70 g H_2/L) and $8/kWh ($267/kg $H_{2\ \mathrm{stored}}$). As an example of the challenges these system targets represent, hydrogen gas alone (not including the tank and balance-of-plant) at 700 bar pressure and ambient temperature has a density of approximately 40 g/L, and thus is theoretically not able to meet the 2017 system level volumetric target. Additionally, liquid hydrogen alone at its normal boiling point of 20 K has a density of 71 g/L, and consequently is theoretically not able to meet the Ultimate Full Fleet volumetric target for the full system. For these reasons, the program has previously focused on the development of advanced materials-based storage technologies which have the theoretical potential to meet all onboard storage system targets simultaneously. The materials discovery efforts have been carried out primarily on three classes of hydrogen storage materials: reversible metal hydrides; hydrogen adsorbents; and chemical hydrogen storage materials. These previous efforts included three material-based “Centers of Excellence,” which operated from 2005 through 2010, each focusing on a specific material class.[2,3,4] The program continues to continues to advance the state-of-the-art of hydrogen storage systems, primarily through the Hydrogen Storage Engineering Center of

Excellence (HSECoE).[5] These efforts continue to provide a solid foundation for defining the minimum BOP requirements for material-based storage systems, identifying current performance gaps of each type of system, and developing and refining models that enable the hydrogen storage community to determine the basic material properties required for hydrogen storage materials to meet all of the DOE onboard targets simultaneously. Therefore, applied R&D projects that will further develop advanced materials with the necessary thermodynamic, kinetic, and capacity properties are sought to address these requirements.

Although not optimum, compressed hydrogen offers a near-term pathway for the initial commercialization of hydrogen fuel cell vehicles. While ambient temperature, compressed hydrogen is theoretically not able to meet all system performance targets, it is the most mature hydrogen storage technology and automobile manufacturers have demonstrated that they are able to package sufficient hydrogen onboard some light-duty vehicle platforms to provide acceptable driving ranges. However, a major challenge for this technology is reducing the cost of compressed hydrogen systems to meet the $8-12/kWh target required for the technology to achieve widespread use in light-duty vehicles. The technology currently being pursued for initial introduction of hydrogen fuel cell vehicles is Type IV composite overwrapped pressure vessels (COPV) rated for 350 or 700 bar nominal working pressure. These COPVs consist of polymeric liners fully overwrapped by a filament wound composite layer to provide the strength to withstand high gas pressure. High strength (i.e., typically 700 ksi or higher tensile strength) carbon fiber is most commonly used in the composite structure and cost projections have shown that the carbon fiber composite can account for more than 75% of the total cost for these systems.[6,7] In addition, the rigid cylindrical shape of high-pressure systems limits convenient packaging onboard vehicles. As a result, conformable tanks or tanks with geometries more conducive to packaging onboard vehicles, which do not significantly increase costs or compromise performance, would be beneficial.

Non-automotive Applications

Hydrogen fuel cell technologies are also being developed for applications other than light-duty vehicles through the DOE FCT. These include power for portable, stationary, back-up, and material handling equipment applications. For example, fuel cell systems are poised to supplant battery systems for “man-portable” power as a soldier can reduce his energy burden by a factor of 3 by such a transition. Portable applications like this will require hydrogen storage technologies that are safe, compact, easy to use, and low-cost (i.e., cost competitive with incumbent battery technologies). While rechargeable systems are preferred, it is anticipated, especially during the early stages of commercialization, that both single-use and rechargeable systems will be used. Another example where fuel cell systems are demonstrating performance and economic advantages over incumbent technologies is in material handling equipment. Food handling and storage warehouses require non-polluting service vehicles that operate for a minimum of 8-hour shifts with little down time. Presently hydrogen fuel cells that rely on 350 bar pressure vessels but are finding market acceptance for powering lift trucks and are demonstrating economic and performance benefits over battery electric lift trucks. The benefits of these lift trucks include fast refills (i.e., minutes rather than hours), constant power over the full runtime, and longer runtimes (i.e., 8 to 12 hour shifts) and are documented in analyses by the

National Renewable Energy Laboratory.[8] These analyses, carried out for an average fleet of about 60 lift trucks, also highlighted a disadvantage that current hydrogen fuel cell powered lift trucks display when compared to battery electric lift trucks - the cost of the 350 bar high pressure refueling infrastructure ($3,700/ hydrogen refueling infrastructure versus $1,400 for the battery recharging infrastructure). Therefore, advanced hydrogen storage technologies that can reduce the infrastructure costs while maintaining the advantages of hydrogen fuel cells have the potential to expand the market for hydrogen fuel cell powered lift trucks. As a result of stakeholder input to DOE through workshops and requests for information, hydrogen storage performance targets were developed in these two application areas and are provided in Appendix A.

B. Scope of Announcement

This FCT Funding Opportunity Announcement (FOA or announcement) seeks to fund applied hydrogen storage R&D projects focused on innovative approaches for pressurized and/or low temperature tank cost reduction and new storage material discovery, development, and characterization efforts to address the critical challenges of hydrogen storage for transportation, material handling, and portable power applications. The goal of this announcement is to foster a dynamic environment of innovation and continuous improvement through results-driven applied research and development. High risk, but technically credible projects with potential for high pay-off are encouraged. The ultimate result of this R&D effort will be the development of hydrogen storage systems that are capable of meeting long-term DOE targets and milestones as reported in the FCT's Multi-Year Research, Development and Demonstration Plan.[9] The requested topic areas of interest are described below. Total project duration will typically be 24 to 36 months and should be proposed with a minimum of two phases. The first phase shall be no longer than 12 months at which time the project will be evaluated against an associated "SMART" (specific, measurable, attainable, relevant, and timely) Go/No-Go milestone. This end of Phase 1 Go/No-Go milestone, with quantitative metrics, must be included in the application and it must not only define success at the end of Phase 1, but also be in line with the DOE targets as presented in Appendix A. Projects that do not meet their Go/No-Go milestone criteria, as determined by DOE, may be ended at the conclusion of Phase 1.

Projects funded through this announcement will be incorporated into FCT's applied hydrogen storage portfolio. Collaborative approaches with teaming across multiple entities including university, industry, and/or national labs with complimentary disciplines and expertise necessary for a holistic approach are highly desirable and encouraged. Informal collaborations will also be encouraged with other FCT hydrogen storage projects and with complementary basic and applied research programs funded by other entities such as the DOE Office of Science, ARPA-E, the National Science Foundation, and Department of Defense. Finally, collaboration through annual DOE hydrogen storage principal investigator meetings will be required.

The technical topics listed below are the only eligible research areas under this announcement; all other technical topics will be considered non-compliant and will not be reviewed. The appropriate topic must be clearly stated on the cover page of the application. <u>Applicants may not submit an application that covers more than one topic</u>, i.e., separate applications must be submitted for separate topics. Applications are sought for R&D projects addressing one of the following three technical topics:

Topic 1 – Reducing the Cost of Compressed Hydrogen Storage Systems

Applications for Topic 1 are sought to develop complete, low-cost, compressed hydrogen storage systems, with an aim to have the potential to achieve the 2017 ($12/kWh) and Ultimate Full Fleet ($8/kWh) cost targets when manufactured at annual rates of 500,000 systems. For instance, a vehicle that achieves a fuel economy of 60 miles per kilogram of hydrogen (i.e., 60 miles per gallon gasoline equivalent), would require a useable hydrogen storage capacity of 5 kilograms or 167 kWh (at a lower heating value of 33.3 kWh per kilogram H_2), which equates to about $2,000 and $1,336 for the complete vehicle fuel tank at the 2017 and Ultimate target levels, respectively.

Novel tank designs and concepts with the potential of reducing costs over current 350 and 700 bar ambient temperature pressure tanks while offering the potential to meet or exceed DOE 2017 performance targets will be considered. This includes, but is not limited to, novel tank designs, cost reduction concepts and processes, carbon fiber reduction or elimination (e.g., through development of composite fillers to significantly enhance composite performance), conformable tank designs, and advanced state-of-the-art compressed tank manufacturing (e.g., fiber placement or liquid composite molding). The application should include a detailed technical analysis which would include a finite element analysis comparing today's tank technology (e.g., 350 and 700 bar Type III and IV high-pressure systems) against the performance (e.g., gravimetric density, volumetric density, conformability, sensitivity to temperature excursions) of the proposed alternatives, along with an economic projection that considers all relevant capital, operations, and maintenance costs involved with tank production and lifecycle costs. The system balance-of-plant should be consistent with existing DOE cost analysis efforts, with appropriate revisions for proposed operational conditions and proposed innovative improvements. The scope of work should also include the development and testing of scalable prototypes, a high-volume manufacturing cost estimate, a balance-of-plant component list, and when appropriate, the construction of one complete tank system for thorough performance testing and validation through an independent party specified by the DOE.

Applications may comprise more than one integrated approach or concept, but should focus on in-depth assessments of tank materials or designs to meet DOE 2017 and Ultimate Full Fleet targets. Experimental results should be reproducible and technical data reported to DOE should include, but not be limited to, mechanical properties of tank and/or fiber materials, cycle life and durability testing, and weight and volume hydrogen capacity testing. DOE may also require material samples (e.g., pressure vessels, NOL rings) resulting from this R&D effort to be submitted for validation through an independent party specified by DOE.

Topic 2 – Lower Cost Carbon Fiber Composites and Balance of Plant Components for Hydrogen Storage Tanks

Inexpensive storage vessels for compressed hydrogen gas are critical to the widespread commercialization of hydrogen fuel cells in non-automotive and light-duty vehicle applications. Currently, high-pressure (i.e., 350 to 700 bar) storage vessels are constructed using expensive high-strength carbon fiber, such as Toray T700S, in a composite matrix as an overwrap to contain the stress. Cost analyses have shown that 75% of the cost can be due to the carbon fiber composite overwrap. Strategies to lower the cost of high-pressure COPVs for hydrogen must include reduction of the cost of the carbon fiber composite through reduction of the cost of carbon fiber, substitution of the high-cost carbon fiber with lower cost alternatives and or reduction in the amount of carbon fiber composite required. Approximately 50% of the cost of carbon fiber production is due to the precursor fiber with the other 50% due to the conversion processing. The overall performance of carbon fiber composites may be improved through the use of fillers added to the composite that, for instance, improves the load sharing between the fiber and the resin matrix, thus reducing the amount of carbon fiber required to produce a composite of specified strength. Low-cost carbon fiber precursors, low-cost carbon fiber manufacture processes, and/or alternative structural materials such as glass or other inexpensive fibers are all potential solutions to reducing the overall system tank costs to meet the DOE 2017 performance and cost targets for onboard vehicle hydrogen storage.[10] Another leading contributor to the cost of high-pressure hydrogen storage systems is the required balance-of-plant components which are currently specialty components built in low-volumes. Innovative concepts that reduce the cost, weight and volume of balance-of-plant are also sought. Thus, proposals under Topic 2 should address the barriers to lowering the cost of composites or BOP for hydrogen storage vessels at the component level through efforts that focus on the areas discussed in Approaches 1 or 2. Each proposal should include Go/No-Go criteria for the initial phase that demonstrates a measureable improvement (e.g., 10% reduction in cost) from the current baseline component status.

<u>Approach 1</u>:

Approach 1 solicits the development of low-cost, high-strength fibers and composite components. Proposed approaches may include use of less expensive precursors, using low-cost carbon fiber manufacturing processes (including associated pre-treatments, stabilization (cross-linking), oxidation, carbonization, graphitization, post-treatments, and packaging) or developing alternative materials to carbon such as glass or polymers. The goal is to significantly lower current high-strength fiber (i.e., fiber with ultimate tensile strength greater than 650 ksi) costs by at least 50% from \$13/lb to approximately \$6/lb. Proposals addressing Approach 1 should include a detailed technical analysis and cost projection of proposed synthesis methods and fiber production methods to yield the desired high-strength fibers required to meet low, medium and high manufactured volumes of COPVs (e.g., 500, 4000 and 25,000 metric tons of carbon fiber per year). If proposing alternative fibers or significantly different strength carbon fibers, the proposals should also include consideration of how their use will impact the overall system performance, e.g., changes in the projected gravimetric capacity due to modifications in the mass of the pressure vessel. The work scope should include fabrication of fibers from the most promising low-cost precursor materials identified and characterization of the mechanical properties and durability of these resultant fibers for use in high-pressure compressed gas cylinder applications. Development of improved resins and resin additives that result in high performing composites that can potentially reduce the amount of carbon fiber required to achieve the strength needed in 350 and 700 bar pressure vessels will also be considered.

Approach 2:
Approach 2 solicits the development of improved, lower-cost materials for balance-of-plant components. For 350 and 700 bar systems, at annual manufacturing volumes of 10,000 systems per year, the balance-of-plant components are projected to account for 57% of the total system cost. Even at volumes of 500,000 systems per year, the balance-of-plant can constitute 30% of the total system costs. For single tank configurations, the BOP is estimated to contribute 15-20% of the total system mass. A schematic that includes balance-of-plant for compressed hydrogen systems can be found in [11]. The balance-of-plant materials must be suitable for operation over the range of pressure and temperature regimes envisioned in SAE J2601 refueling protocols for fast refueling of 700 bar systems with precooling of hydrogen to -40 °C. All seals and other wetted components must therefore be compatible for hydrogen service over the minimum temperature range of -40 to 85 °C and pressures up to 875 bar (i.e., refueling pressure of 1.25 times the nominal working pressure of 700 bar). Also to reduce weight and costs, lightweight, low-cost metallic and non-metallic balance-of-plant components would be preferable when possible, such as for materials of construction and for low-pressure components. Proposals are sought for identification and characterization for materials that can be used to reduce the cost and mass of BOP components for compressed hydrogen systems, especially seals and non-metallic materials. Evaluation should include consideration of the full range of operating conditions, including temperature, pressure and cycling, that the BOP will be exposed to, as well as suitability for hydrogen service. Proposals are not sought for the design and construction of complete BOP components

Topic 3 – New Materials Discovery

Material-based hydrogen storage remains a long-term pathway to meeting customer expectations of driving range, performance, and refueling times and gaining mass market penetration with fuel cell vehicles and other types of hydrogen and fuel cell applications. While numerous candidates (i.e., metal and complex hydrides, high-surface area adsorbents, and chemical hydrogen storage materials) have been proposed and investigated as hydrogen storage media in recent years, none are currently able to satisfy all the performance targets shown in Appendix A required for the full range of light-duty vehicles to be powered by hydrogen fuel cells and meet consumer performance expectations.

FCT remains committed to the discovery, development, and characterization of advanced hydrogen storage materials. Through advanced modeling of complete materials-based hydrogen storage systems, a better understanding of the material-level performance properties necessary to meet the DOE 2017 system level targets for onboard vehicle storage is being achieved.[12,13,14] While the DOE targets are for full systems, these analyses provide a way to determine the full set of material thermodynamic, kinetic, gravimetric, and volumetric properties that will be needed for a material to be incorporated into a system that meets the performance targets. For instance, analyses has shown that a reversible metal hydride with an enthalpy of hydrogen release of around 27 kJ/mol of H_2 and sufficient release kinetics (so that waste heat from the fuel cell (i.e., 80 °C or less) can be used to provide the heat and temperature of desorption), must have a useable material gravimetric capacity of at least 11 wt.%. If either the hydrogen release thermodynamics is greater, or the kinetics are slower (such that additional heat or temperature must be provided, thus requiring consuming some of the stored hydrogen), then even higher gravimetric capacities are required.[12] At a minimum, any material discovery proposal for automotive applications must include targeted material property metrics for volumetric and gravimetric capacity, kinetics, and thermodynamics in addition to other key performance targets, regardless of material type.

Furthermore, to stress the importance of reliable material property measurement techniques to facilitate the development of hydrogen storage materials, researchers are referred to DOE's "Recommended Best Practices for the Characterization of Storage Properties of Hydrogen Storage Materials".[15] This document provides an introduction and overview of the recommended best practices in making measurements of hydrogen storage material properties and is suggested reading prior to initiating hydrogen storage materials development activities.

Approach 1:
Approach 1 solicits applications for the discovery of novel, advanced hydrogen storage materials for onboard vehicle storage of hydrogen that have the potential to meet the DOE 2017 and Ultimate Full Fleet targets specified in Appendix A. While the performance targets are for the complete system, recent complete system modeling efforts provide an understanding of the "acceptable" material properties, such as thermodynamic, kinetic, and volumetric and gravimetric capacities. Applications under this approach must specify quantitative metrics for a range of material properties that need to be met for the material to operate.

The first phase of the project must include synthesis and characterization of material with the results for at least two properties, e.g., desorption kinetics and desorption thermodynamics, that meet specified metrics and demonstrate the potential to meet the overall set of material property metrics. DOE may require that materials developed under Approach 1 be sent to an independent party as specified by DOE for independent material evaluation and testing.

Neither hydrolysis of sodium borohydride[16] nor pure, undoped single-walled carbon nanotubes[17] as onboard storage media, are being solicited in order to be consistent with the FCT's no-go decisions previously made in these areas. Applications in these areas will be deemed non-compliant and will not be reviewed. Systems that were discontinued for investigation by the three DOE Hydrogen Storage Material Centers of Excellence (as referenced in Section A) are also not solicited as onboard storage media unless a new approach has been developed that addresses the reasons why the subject material was discontinued for R&D.

Approach 2:
Approach 2 solicits applications for the development of materials-based advanced hydrogen storage technologies for material handling equipment or portable power systems that have the potential to meet the DOE 2015 and 2020 performance targets (see Appendix A). Under Approach 2, applications must either incorporate the proposed material into a complete prototype hydrogen storage system or address identified material issues, such as low-cost material synthesis or regeneration, for existing prototype systems. Applications should describe the specific application being addressed, as related to either material handling or portable power, and provide sufficient information for evaluation on how the proposed work will result in a system

meeting the performance targets listed in Appendix A. Experimental results should be reproducible and technical data that is reported to DOE should include, but not be limited to, all properties of the material including sorption thermodynamics, kinetics, gravimetric and volumetric capacities, and system level performance evaluated against appropriate targets. Applicants under Approach 2 must include a letter of support from at least one industrial partner interested in commercializing hydrogen fuel cell products in the application area. The commercialization partner can either formally or informally participate in the project. The scope of work for system development should include development and testing of scalable prototypes, high-volume manufacturing cost estimate, balance-of-plant component list, and when appropriate, the construction of one complete tank system for thorough performance testing by an independent party specified by the DOE. The scope of work for proposals addressing material issues should also include production of sufficient quantity of material for thorough characterization and evaluation for analysis of the material performance and testing by an independent party specified by the DOE.

C. Additional Information

Applicants will be required to submit an initial "Concept Paper" that briefly describes the proposed project. DOE will then review each Concept Paper and provide feedback to encourage or discourage each applicant from applying to the full application based on DOE's view of the merit of the proposed concept and the likelihood the proposed concept would be favorably viewed during the full application stage. This saves the applicant from having to complete a full application if the brief concept description is not well received by DOE.

The work plan for each application should cover a 24 to 36 month period and must include identification of key milestones (at least 1 per year). Two phases of work should be proposed, separated by a go/no-go decision point / milestone at or before the 12 month point along with the criteria for making the decision. Total amount of funding for this FOA, maximum amount per project and expected number of projects are still to be determined.

Hydrogen Storage technologies vary significantly in their technology readiness level. It is anticipated that Topic 1 applications will be closer to market and Topic 2 and 3 applications will further from market. As a result, cost share will be based on the technology readiness of the proposed concept. Cost share requirements for Topic 1 will be 20% for all applicants. For Topics 2 or 3, projects may be selected with technology readiness levels of 2 or 3. As a result, the FCT plans to request a 0% cost share requirement for education institutions, FFRDCs, and non-profit entities for Topics 2 and 3.

Inclusion of foreign entities to participate will require submittal and approval of a waiver requesting exemption from having all work performed with the United States. A written waiver request must be included in the Full Application. Approval of the waiver request will be at the discretion of the DOE-EERE Contracting Officer.

It is expected that the efforts funded under Topic 1, "Reducing the Cost of Compressed Hydrogen Storage Systems" and Topic 2, "Lower Cost Carbon Fiber Composites and Balance of

Plant Components for Hydrogen Storage Tanks", of this announcement will serve to address the immediate needs of the hydrogen community leading up to the anticipated widespread deployment of hydrogen vehicles starting in 2015. While work funded under Topic 3, "New Materials Discovery", may cover transportation, materials handling, and/or portable applications that address longer term approaches or applications that will serve to build a supply chain for advanced hydrogen storage concepts. It is expected that work under all three topics will complement, but not duplicate, current and previous work funded by the Office. For more information on previous and existing projects within the hydrogen storage portfolio, please review the following links:

- • The Hydrogen Storage sub-program at http://www.eere.energy.gov/hydrogenandfuelcells/storage;
- The DOE Hydrogen and Fuel Cells Program Annual Progress Reports at http://www1.eere.energy.gov/hydrogenandfuelcells/annual_reports.html;
- The DOE Hydrogen and Fuel Cells Program Annual Program Merit Review and Peer Evaluation Reports at http://www1.eere.energy.gov/hydrogenandfuelcells/merit_review.html; http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/;
- The DOE Office of Basic Energy Sciences at http://www.science.doe.gov/bes/BES.html;
- Metal Hydride Center of Excellence Final Report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/metal_hydride_coe_final_report.pdf;
- Chemical Hydrogen Storage Center of Excellence Final Report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/chemical_hydrogen_storage_coe_final_report.pdf;
- Hydrogen Sorption Center Final Report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_sorption_coe_final_report.pdf.

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[1] US DOE EERE Fuel Cell Technologies Office. http://www.eere.energy.gov/hydrogenandfuelcells/.

[2] Metal Hydride Center of Excellence Final Report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/metal_hydride_coe_final_report.pdf.

[3] Chemical Hydrogen Storage Center of Excellence Final Report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/chemical_hydrogen_storage_coe_final_report.pdf.

[4] Final Report for Hydrogen Sorption Center: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_sorption_coe_final_report.pdf.

[5] Hydrogen Storage Engineering Center of Excellence website: http://hsecoe.srs.gov/.

[6] Hua, T. Q., Ahluwalia, R. K., Peng, J. -K., Kromer, M., Lasher, S., McKenney, K., Law, K. and Sinha, J. "Technical assessment of compressed hydrogen storage tank systems for automotive applications," Int. J. Hydrogen Energy, 36 (2011): 3037-3049.

[7] Hua, T. Q., Ahluwalia, R. K., Peng, J. -K., Kromer, M., Lasher, S., McKenney, K., Law, K. and Sinha, J., "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications," [Accessed 23 April 2013] http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf.

[8] Kurtz, J., Sprik, S., Ramsden, T., Saur, G., Ainscough, C., "What We've Learned from 2.5 Years of Early Market Fuel Cell Operation," [Accessed 23 April 2013] http://www.nrel.gov/hydrogen/cfm/pdfs/57759.pdf.

[9] FCT's Hydrogen Storage Multi-Year Research, Development, and Demonstration Plan: http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html.

[10] DOE Targets for On-Board Hydrogen Storage Systems for Light-Duty Vehicles, February 2009, published on DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf.

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[11] James, B.D., Moton, J.M., Colella, W.G., Hydrogen Storage Cost Analysis, 2013 US DOE Hydrogen Program Annual Merit Review Proceedings. Arlington (VA); 2013. Link TBD.

[12] Anton, DA, Motyka, T. Hydrogen Storage Engineering Center of Excellence. 2012 US DOE Hydrogen Program Annual Merit Review Proceedings. Arlington (VA); 2012. http://www.hydrogen.energy.gov/pdfs/review12/st004_anton_2012_o.pdf.

[13] Anton, DA, Motyka, T. Hydrogen Storage Engineering Center of Excellence. 2013 US DOE Hydrogen Program Annual Merit Review Proceedings. Arlington (VA); 2013. Link TBD.

[14] Ahluwalia, R.K., Hua, T.Q., Peng, J-K., Roh, H.S., System Level analysis of Hydrogen Storage Options, 2013 US DOE Hydrogen Program Annual Merit Review Proceedings. Arlington (VA); 2013. Link TBD.

[15] DOE's "Recommended Best Practices for the Characterization of Storage Properties of Hydrogen Storage Materials," http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/best_practices_hydrogen_storage.pdf.

[16] Go/No-Go Recommendation for Sodium Borohydride for Onboard Vehicular Hydrogen Storage: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/42220.pdf.

[17] Go/No-Go Decision: Pure, Undoped Single Wall carbon nanotubes for Vehicular Hydrogen Storage. http://www.hydrogen.energy.gov/pdfs/go_no_go_nanotubes.pdf.

Appendix A: Hydrogen Storage Technical System Targets

Table 1.0: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles [a]

Storage Parameter	Units	2017	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg (kg H_2/kg system)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost:	$/kWh net	12	8
	($/kg H_2 stored)	400	266
- Fuel cost [c]	$/gge at pump	2-4	2-4
Durability/Operability:			
- Operating ambient temperature [d]	ºC	-40/60 (sun)	-40/60 (sun)
- Min/max delivery temperature	ºC	-40/85	-40/85
- Operational cycle life (1/4 tank to full)	Cycles	1500	1500
- Min delivery pressure from storage system	bar (abs)	5	3
- Max delivery pressure from storage system	bar (abs)	12	12
- Onboard Efficiency [e]	%	90	90
- "Well" to Powerplant Efficiency [e]	%	60	60
Charging / Discharging Rates:			
- System fill time (5 kg)	min	3.3	2.5
	(kg H_2/min)	(1.5)	(2.0)
- Minimum full flow rate	(g/s)/kW	0.02	0.02
- Start time to full flow (20 °C)	s	5	5
- Start time to full flow (-20 °C)	s	15	15
- Transient response at operating temperature 10%-90% and 90%-0%	s	0.75	0.75
Fuel Quality (H_2 from storage) [f]:	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety:			
- Permeation & leakage [g]	-	Meets or exceeds applicable standards, for example SAE J2579	
- Toxicity	-		
- Safety	-		
- Loss of usable H_2 [h]	(g/h)/kg H_2 stored	0.05	0.05

[a] Targets are based on the lower heating value of hydrogen, 33.3 kWh/kg H_2. Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant. All targets must be met at the end of service life (approximately 1500 cycles or 5000 operation hours, equivalent of 150,000 miles).

[b] Capacities are defined as the usable quantity of hydrogen deliverable to the powerplant divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants (e.g., water for hydrolysis-based systems), and system components. Tank designs that are conformable and have the ability to be

efficiently package onboard vehicles may be beneficial even if they do not meet the full volumetric capacity targets. Capacities must be met at end of service life.

[c] Hydrogen threshold cost is independent of pathway and is defined as the untaxed cost of hydrogen produced, delivered and dispensed to the vehicle. [http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf] For material-based storage technologies, the impact of the technology on the hydrogen threshold cost, e.g., off-board cooling, off-board regeneration of chemical hydrogen storage materials, etc., must be taken into account.

[d] Stated ambient temperature plus full solar load (i.e., full exposure to direct sunlight). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Onboard efficiency is the energy efficiency for delivering hydrogen from the storage system to the fuel cell powerplant, i.e., accounting for any energy required for operating pumps, blowers, compressors, heating, etc. required for hydrogen release. Well-to-powerplant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. H2A and HDSAM analyses should be used for projecting off-board efficiencies.

[f] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards for fuel cell vehicles (see SAE J2719 and ISO/PDTS 14687-2). Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case-by-case basis as more information becomes available.

[g] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with applicable standards for vehicular tanks including but not limited to SAE J2579 and the United Nations Global Technical Regulation. This includes any coating or enclosure that incorporates the envelope of the storage system.

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

Table 2.0 Onboard Hydrogen Storage Systems for Material Handling Equipment[a]

Storage Parameter	Units	2015	2020
Hydrogen Capacity	kg	2	2
System Volumetric Capacity			
• Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.0 (0.03)	1.7 (0.05)
Storage System Cost	$/kWh net ($/kg $H_{2\ \text{stored}}$)	20 (667)	15 (500)
Durability/Operability			
• External operating temperature range [c]	ºC	-40/60	-40/60
• Min/max delivery temperature [d]	ºC	-40/85	-40/85
• Operational cycle life (1/10 tank to full)	Cycles	5000(5 yr)	10,000(10 yr)
• Min delivery pressure from storage system	bar (abs)	3	3
• Max delivery pressure from storage system	bar (abs)	12	12
Shock & Vibration			
• Shock	g	40	40
• Vibration	g	5@10Hz – 0.75@200Hz	10@10Hz – 1@200Hz
Charging / Discharging Rates			
• System fill time (2 kg)	min (kg H_2/min)	4.0 (0.5)	2.8 (0.7)
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20 °C)	s	5	5
• Start time to full flow (-20 °C)	s	15	15
• Transient response 10%-90% and 90%-0%	s	0.75	0.75
Fuel Purity (H_2 from storage) [e]	% H_2	SAE J2719 & ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety			
• Permeation & Leakage [f]	-	Meets or exceeds applicable standards, for example CSA HPIT 1	
• Toxicity	-		
• Safety	-		
• Loss of useable H_2 [g]	(g/h)/kg $H_{2\ \text{stored}}$	0.1	0.05

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life. Since most applications of material handling equipment (MHE) require extra mass as a counterbalance, the system gravimetric capacity is not specified as it can vary widely among types of MHE. However, system gravimetric capacity should be considered when developing hydrogen storage systems for MHE applications. All targets must be met at the end of service life.

[b] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell power plant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[c] Stated ambient temperature. No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[d] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[e] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as: CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[f] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, for example CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. This includes any coating or enclosure that incorporates the envelope of the storage system.

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

Table 3.1 Hydrogen Storage Systems for Low Power (≤2.5W) Portable Equipment[a]

Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	≤1			
System Gravimetric Capacity [b] - Usable, specific-energy from H_2 (net useful energy/max system mass) [c]	kWh/kg (kg H_2/kg system)	0.7 (0.02)	0.5 (0.015)	1.3 (0.04)	1.0 (0.03)
System Volumetric Capacity - Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	1.0 (0.03)	0.7 (0.02)	1.7 (0.05)	1.3 (0.04)
Storage System Cost	$/Wh net ($/g $H_{2\ \text{stored}}$)	0.09 (3.0)	0.75 (25)	0.03 (1.0)	0.4 (13)

Table 3.2 Hydrogen Storage Systems for Medium Power (>2.5W-150W) Portable Equipment[a]

Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	>1 - 50			
System Gravimetric Capacity [b] - Usable, specific-energy from H_2 (net useful energy/max system mass) [c]	kWh/kg (kg H_2/kg system)	0.7 (0.02)	0.5 (0.015)	1.3 (0.04)	1.0 (0.03)
System Volumetric Capacity - Usable energy density from H2 (net useful energy/max system volume) [c]	kWh/L (kg H_2/L system)	1.0 (0.03)	0.7 (0.02)	1.7 (0.05)	1.3 (0.04)
Storage System Cost	$/Wh net ($/g $H_{2\ \text{stored}}$)	0.2 (6.7)	1.0 (33)	0.1 (3.3)	0.5 (17)

Table 3.3 Portable Power Durability & Operational Targets [a]

Storage Parameter	Units	2015	2020
		Single-Use & Rechargeable	Single-Use & Rechargeable
Durability/Operability			
- External operating temperature range [d]	°C	-40/60	-40/60
- Min/max delivery temperature [e]	°C	10/85	10/85
- Min delivery pressure from storage system;	bar (abs)	1.5	1.5
- Max delivery pressure from storage system	bar (abs)	3	3
- External temperature [f]	ºC	≤40	≤40
Discharging Rates			
- Minimum full flow rate	(g/s)/kW	0.02	0.02
- Start time to full flow (20 °C)	s	5	5
- Start time to full flow (-20 °C)	s	10	10
- Transient response 10%-90% and 90%-0%	s	5	2
Fuel Purity (H_2 from storage) [g]	% H_2	Meets applicable standards	
Environmental Health & Safety - Toxicity - Safety - Loss of usable H_2 [h]		Meets ISO-16111:2008; IEC 62282 Part 6; or other applicable standards as appropriate or required for the application and targeted usage	

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life.

[b] Generally the 'full' mass (including hydrogen) is used; for systems that gain weight on hydrogen release, the highest mass during discharge is used (e.g., hydrogen release through hydrolysis reaction resulting in the formation of oxides/hydroxides). All capacities are net usable capacity able to be delivered to the fuel cell power plant. Capacities must be met at end of service life.

[c] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell powerplant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[d] Stated ambient temperature plus full solar load (i.e., if exposed to direct sunlight or stored within a container exposed to direct sunlight for extended periods of time). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[f] The external device temperature is the maximum temperature generated at the external surface of the hydrogen storage container during operation.

[g] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as: ISO-16111:2008 and IEC 62282 Part 6. Note that some storage technologies may produce contaminants for which

effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[h] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, such as ISO-16111:2008 and IEC 62282 Part 6. This includes any coating or enclosure that incorporates the envelope of the storage system.