

---

U.S. Department of Energy  
1000 Independence Avenue, S.W.  
Washington, D.C. 20585-0121

FY 2009  
PROGRESS REPORT FOR THE  
DOE HYDROGEN PROGRAM

November 2009  
DOE/GO-102009-2950

Approved by Sunita Satyapal, Acting Hydrogen Program Manager

---

## NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
Phone: (865) 576-8401  
Fax: (865) 576-5728  
E-mail: [mailto:reports@adonis.osti.gov](mailto:mailto:reports@adonis.osti.gov)

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
Phone: (800) 553-6847  
Fax: (703) 605-6900  
E-mail: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
Online ordering: <http://www.ntis.gov/ordering.htm>



Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

# Table of Contents

I. Introduction .....	1
II. Hydrogen Production .....	17
II.0 Hydrogen Production Sub-Program Overview .....	19
II.A Distributed BDL Production .....	23
II.A.1 H <sub>2</sub> Gen Innovations, Inc.: Low-Cost Hydrogen Distributed Production System Development .....	23
II.A.2 Pacific Northwest National Laboratory: Distributed Hydrogen Production from Biomass Reforming .....	26
II.A.3 Virent Energy Systems, Inc.: Hydrogen Generation from Biomass-Derived Carbohydrates via the Aqueous-Phase Reforming (APR) Process .....	31
II.A.4 Ohio State University: Investigation of Reaction Networks and Active Sites in Bio-Ethanol Steam Reforming over Co-Based Catalysts .....	35
II.A.5 Argonne National Laboratory: Distributed Reforming of Renewable Liquids via Water Splitting Using Oxygen Transport Membrane (OTM) .....	41
II.A.6 National Renewable Energy Laboratory: Distributed Bio-Oil Reforming .....	45
II.A.7 Argonne National Laboratory: Pressurized Steam Reforming of Bio-Derived Liquids for Distributed Hydrogen Production .....	49
II.A.8 Directed Technologies, Inc.: Analysis of Ethanol Reforming System Configurations .....	53
II.B Biomass Gasification .....	58
II.B.1 National Renewable Energy Laboratory: Indirectly Heated Gasification of Biomass to Produce Hydrogen .....	58
II.B.2 United Technologies Research Center: A Novel Slurry-Based Biomass Reforming Process .....	64
II.B.3 Los Alamos National Laboratory: Catalytic Solubilization and Conversion of Lignocellulosic Feedstocks to Hydrogen .....	68
II.C Separations .....	72
II.C.1 Arizona State University: Zeolite Membrane Reactor for Water-Gas Shift Reaction for Hydrogen Production .....	72
II.C.2 Pall Corporation: High Performance Palladium-Based Membrane for Hydrogen Separation and Purification .....	78
II.C.3 Media and Process Technology Inc.: Water-Gas Shift Reaction via a Single Stage Low-Temperature Membrane Reactor .....	83
II.C.4 Oak Ridge National Laboratory: Novel Low-Temperature Proton Transport Membranes .....	87
II.C.5 Sandia National Laboratories: Ultra-Thin Proton Conduction Membranes for H <sub>2</sub> Stream Purification with Protective Getter Coatings .....	92
II.C.6 Savannah River National Laboratory: Membrane Separation–Bulk Amorphous Hydrogen Purification/Separation Membranes .....	95
II.C.7 Linde LLC: Integrated Hydrogen Production, Purification and Compression System .....	99
II.D Hydrogen From Coal .....	102
II.D.1 Worcester Polytechnic Institute: Composite Pd and Pd Alloy Porous Stainless Steel Membranes for Hydrogen Production and Process Intensification .....	102
II.D.2 Eltron Research & Development, Inc.: Scale-Up of Hydrogen Transport Membranes for IGCC and FutureGen Plants .....	106
II.D.3 Southwest Research Institute®: High Permeability Ternary Palladium Alloy Membranes with Improved Sulfur and Halide Tolerance .....	110
II.D.4 United Technologies Research Center: Experimental Demonstration of Advanced Palladium Membrane Separators for Central High-Purity Hydrogen Production .....	114

II.	Hydrogen Production (Continued)	
II.D	Hydrogen From Coal (Continued)	
II.D.5	Western Research Institute: The Integration of a Structural Water-Gas Shift Catalyst with a Vanadium Alloy Hydrogen Transport Device . . . . .	119
II.E	Electrolysis. . . . .	122
II.E.1	Arizona State University: Development of Water Splitting Catalysts Using a Novel Molecular Evolution Approach . . . . .	122
II.E.2	Aváence LLC: High-Capacity, High-Pressure Electrolysis System with Renewable Power Sources . . . . .	128
II.E.3	Giner Electrochemical Systems, LLC: PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane. . . . .	132
II.E.4	National Renewable Energy Laboratory: Renewable Electrolysis Integrated System Development and Testing . . . . .	136
II.F	Hi-Temp Thermochemical. . . . .	140
II.F.1	General Atomics: Solar Cadmium Hydrogen Production Cycle. . . . .	140
II.F.2	Science Applications International, Corporation: Solar High-Temperature Water-Splitting Cycle with Quantum Boost. . . . .	144
II.F.3	University of Colorado at Boulder: Solar-Thermal Hydrogen Production Using a Metal-Oxide Based Thermochemical Water Splitting Cycle. . . . .	152
II.G	Nuclear Hydrogen Initiative . . . . .	155
II.G.1	Argonne National Laboratory: R&D Status for the Cu-Cl Thermochemical Cycle. . . . .	155
II.G.2	Sandia National Laboratories: Sulfur-Iodine Thermochemical Cycle. . . . .	161
II.G.3	Savannah River National Laboratory: Hybrid Sulfur Thermochemical Cycle. . . . .	165
II.G.4	Idaho National Laboratory: Laboratory-Scale High Temperature Electrolysis System. . . . .	170
II.H	Photoelectrochemical. . . . .	175
II.H.1	University of Hawaii at Manoa: Photoelectrochemical Hydrogen Production: DOE PEC Working Group Overview . . . . .	175
II.H.2	Directed Technologies, Inc.: Technoeconomic Boundary Analysis of Photoelectrochemical (PEC) Hydrogen Producing Systems. . . . .	181
II.H.3	University of Nevada, Las Vegas: Characterization of Materials for Photoelectrochemical Hydrogen Production (PEC) . . . . .	184
II.H.4	Stanford University: Nanostructured MoS <sub>2</sub> and WS <sub>2</sub> for the Solar Production of Hydrogen . . . . .	189
II.H.5	University of California, Santa Barbara: Photoelectrochemical Hydrogen Production Using New Combinatorial Chemistry Derived Materials. . . . .	195
II.H.6	National Renewable Energy Laboratory: Semiconductor Materials for Photoelectrolysis . . . . .	202
II.H.7	National Renewable Energy Laboratory: Theory of Oxides for Photo-Electrochemical Hydrogen Production . . . . .	208
II.H.8	MVSystems Incorporated: Photoelectrochemical Hydrogen Production: MVSystems Incorporated. . . . .	212
II.H.9	University of Hawaii at Manoa: Progress in the Study of Amorphous Silicon Carbide (a-SiC) as a Photoelectrode in Photoelectrochemical (PEC) Cells. . . . .	217
II.H.10	University of Hawaii at Manoa: Progress in the Study of Copper Chalcopyrites as Photoelectrodes in Photoelectrochemical Cells. . . . .	221
II.H.11	University of Toledo: Critical Research for Cost-Effective Photoelectrochemical Production of Hydrogen . . . . .	224
II.H.12	University of Arkansas at Little Rock: Photoelectrochemical (PEC) Hydrogen Generation . . . . .	228
II.H.13	University of Nevada, Reno: University of Nevada, Reno Photo-Electrochemical Project . . . . .	232

II.	Hydrogen Production (Continued)	
II.I	Biological	235
II.I.1	Directed Technologies, Inc.: Technoeconomic Boundary Analysis of Photobiological Hydrogen Producing Systems	235
II.I.2	University of California, Berkeley: Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	240
II.I.3	National Renewable Energy Laboratory: Biological Systems for Hydrogen Photoproduction	243
II.I.4	National Renewable Energy Laboratory: Fermentation and Electrohydrogenic Approaches to Hydrogen Production	247
II.I.5	J. Craig Venter Institute: Hydrogen from Water in a Novel Recombinant O <sub>2</sub> -Tolerant Cyanobacterial System	251
II.I.6	Montana State University: Use of Biological Materials and Biologically Inspired Materials for H <sub>2</sub> Catalysis	256
II.J	Cross-Cutting/Production	263
II.J.1	Purdue University: Purdue Hydrogen Systems Laboratory: Hydrogen Production	263
II.J.2	Edison Materials Technology Center: Developing Improved Materials to Support the Hydrogen Economy	266
II.J.3	University of South Florida: Hydrogen Production and Fuel Cell Research	276
III.	Hydrogen Delivery	283
III.0	Hydrogen Delivery Sub-Program Overview	285
III.1	Argonne National Laboratory: Hydrogen Delivery Infrastructure Analysis	289
III.2	National Renewable Energy Laboratory: H2A Delivery Components Model	292
III.3	Concurrent Technologies Corporation: Hydrogen Regional Infrastructure Program in Pennsylvania	296
III.4	Mohawk Innovative Technology, Inc.: Oil-Free Centrifugal Hydrogen Compression Technology Demonstration	301
III.5	Concepts NREC: Development of a Centrifugal Hydrogen Pipeline Gas Compressor	306
III.6	Mohawk Innovative Technology, Inc.: Advanced Sealing Technology for Hydrogen Compression	312
III.7	FuelCell Energy, Inc.: Development of Highly Efficient Solid-State Electrochemical Hydrogen Compressor	317
III.8	Argonne National Laboratory: Hydrogen Pipeline Compressors	319
III.9	Praxair, Inc.: Advanced Hydrogen Liquefaction Process	324
III.10	Prometheus Energy: Active Magnetic Regenerative Liquefier	327
III.11	Gas Equipment Engineering Corp.: Innovative Hydrogen Liquefaction Cycle	331
III.12	Lawrence Livermore National Laboratory: Inexpensive Delivery of Cold Hydrogen in High Performance Glass Fiber Composite Pressure Vessels	336
III.13	Air Products and Chemicals, Inc.: Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen	340
III.14	Pacific Northwest National Laboratory: Design of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels	346
III.15	Lincoln Composites, Inc.: Design and Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery	350
III.16	Oak Ridge National Laboratory: Composite Technology for Hydrogen Pipelines	354
III.17	Savannah River National Laboratory: FY 2009 SRNL Hydrogen Delivery Project—Hydrogen Permeability and Pipeline Integrity/Fiber Reinforced Composite Pipeline	358
III.18	Secat, Inc.: Materials Solutions for Hydrogen Delivery in Pipelines	361
III.19	University of Illinois at Urbana-Champaign: Hydrogen Embrittlement of Pipelines: Fundamentals, Experiments, Modeling	366
III.20	Oak Ridge National Laboratory: Hydrogen Permeability and Integrity of Steel Welds	375

III.	Hydrogen Delivery (Continued)	
III.21	Sandia National Laboratories: Hydrogen Embrittlement of Structural Steels . . . . .	379
III.22	Sandia National Laboratories: Geologic Storage of Hydrogen . . . . .	382
IV.	Hydrogen Storage . . . . .	387
IV.0	Hydrogen Storage Sub-Program Overview . . . . .	389
IV.A	Metal Hydride CoE . . . . .	399
IV.A.1a	Sandia National Laboratories: DOE Metal Hydride Center of Excellence . . . . .	399
IV.A.1b	Stanford University: Thermodynamically Tuned Nanophase Materials for Reversible Hydrogen Storage: Structure and Kinetics of Nanoparticle and Model System Materials . . . . .	403
IV.A.1c	Sandia National Laboratories: Development of Metal Hydrides at Sandia National Laboratories . . . . .	408
IV.A.1d	University of Utah: Chemical Vapor Synthesis and Discovery of H <sub>2</sub> Storage Materials: Li-Al-Mg-N-H System . . . . .	416
IV.A.1e	Brookhaven National Laboratory: Aluminum Hydride Regeneration . . . . .	422
IV.A.1f	Savannah River National Laboratory: Electrochemical Reversible Formation of Alane . . . . .	427
IV.A.1g	University of Hawaii: Fundamental Studies of Advanced High-Capacity, Reversible Metal Hydrides . . . . .	432
IV.A.1h	University of Pittsburgh: First-Principles Modeling of Hydrogen Storage in Metal Hydride Systems. . . . .	439
IV.A.1i	HRL Laboratories, LLC: Thermodynamically Tuned Nanophase Materials for Reversible Hydrogen Storage . . . . .	444
IV.A.1j	United Technologies Research Center: Catalyzed Nano-Framework Stabilized High Density Reversible Hydrogen Storage Systems. . . . .	450
IV.A.1k	National Institute of Standards and Technology: Neutron Characterization and Calphad in Support of the Metal Hydride Center of Excellence . . . . .	455
IV.A.1l	University of Illinois, Urbana-Champaign: Reversible Hydrogen Storage Materials – Structure, Chemistry, and Electronic Structure. . . . .	461
IV.A.1m	Oak Ridge National Laboratory: Preparation and Reactions of Complex Hydrides for Hydrogen Storage: Metal Borohydrides and Aluminum Hydrides. . . . .	467
IV.A.1n	Jet Propulsion Laboratory: Development and Evaluation of Advanced Hydride Systems for Reversible Hydrogen Storage. . . . .	472
IV.A.1o	University of Nevada, Reno: Effect of Gaseous Impurities on Durability of Complex Li-based Hydrides for Hydrogen Storage . . . . .	477
IV.A.1p	Savannah River National Laboratory: Li-Mg-N Hydrogen Storage Materials. . . . .	483
IV.A.1q	California Institute of Technology: Synthesis of Nanophase Materials for Thermodynamically Tuned Reversible Hydrogen Storage. . . . .	487
IV.A.1r	Ohio State University: Lightweight Metal Hydrides for Hydrogen Storage . . . . .	491
IV.A.2	Northwestern University: Design of Novel Multi-Component Metal Hydride-Based Mixtures for Hydrogen Storage . . . . .	496
IV.A.3	Sandia National Laboratories: Tuneable Thermodynamics and Kinetics for Hydrogen Storage: Nanoparticle Synthesis using Ordered Polymer Templates . . . . .	498
IV.A.4	UOP LLC: Discovery of Novel Complex Metal Hydrides for Hydrogen Storage through Molecular Modeling and Combinatorial Methods . . . . .	502
IV.A.5	Delaware State University: Center for Hydrogen Storage Research at Delaware State University . . . . .	504
IV.A.6	University of Connecticut: Effects and Mechanisms of Mechanical Activation on Hydrogen Sorption/Desorption of Nanoscale Lithium Nitrides and Lithium Borohydrides . . . . .	508

IV.	Hydrogen Storage (Continued)	
IV.B	Chemical Hydrogen Storage CoE . . . . .	513
IV.B.1a	Los Alamos National Laboratory: 2009 Overview - DOE Chemical Hydrogen Storage Center of Excellence (CHSCoE) . . . . .	513
IV.B.1b	University of Pennsylvania: Amineborane-Based Chemical Hydrogen Storage . . . . .	518
IV.B.1c	Los Alamos National Laboratory: Chemical Hydrogen Storage R&D at Los Alamos National Laboratory . . . . .	522
IV.B.1d	Pacific Northwest National Laboratory: Chemical Hydrogen Storage Research at PNNL . . . . .	528
IV.B.1e	University of Alabama: Main Group Element and Organic Chemistry for Hydrogen Storage and Activation . . . . .	533
IV.B.1f	Rohm and Haas Company: Low-Cost Precursors to Novel Hydrogen Storage Materials . . . . .	539
IV.B.1g	U.S. Borax Inc.: Ammonia Borane Regeneration and Market Analysis of Hydrogen Storage Materials . . . . .	544
IV.B.1h	University of Oregon: Hydrogen Storage by Novel CBN Heterocycle Materials . . . . .	548
IV.B.1i	University of Washington: Solutions for Chemical Hydrogen Storage: Dehydrogenation of B-N Bonds . . . . .	552
IV.B.1j	University of California, Davis: Chemical Hydrogen Storage using Ultra-High Surface Area Main Group Materials and the Development of Efficient Amine-Borane Regeneration Cycles . . . . .	556
IV.B.1k	Pennsylvania State University: Electrochemical Hydrogen Storage Systems . . . . .	560
IV.B.1l	University of Missouri: Chemical Hydrogen Storage Using Polyhedral Borane Anions and Aluminum-Ammonia-Borane Complexes . . . . .	564
IV.C	Hydrogen Sorption CoE . . . . .	568
IV.C.1a	National Renewable Energy Laboratory: Overview of the DOE Hydrogen Sorption Center of Excellence . . . . .	568
IV.C.1b	Texas A&M University: A Biomimetic Approach to Metal-Organic Frameworks with High H <sub>2</sub> Uptake . . . . .	577
IV.C.1c	University of Michigan: Hydrogen Storage by Spillover . . . . .	582
IV.C.1d	Rice University: Optimization of Nano-Carbon Materials for Hydrogen Sorption . . . . .	586
IV.C.1e	National Renewable Energy Laboratory: NREL Research as Part of the Hydrogen Sorption Center of Excellence . . . . .	591
IV.C.1f	Argonne National Laboratory: Hydrogen Storage Media through Nanostructured Polymeric Materials . . . . .	601
IV.C.1g	Air Products and Chemicals, Inc.: Enabling Discovery of Materials With a Practical Heat of Hydrogen Adsorption . . . . .	605
IV.C.1h	Duke University: Optimizing the Binding Energy of Hydrogen on Nanostructured Carbon Materials through Structure Control and Chemical Doping . . . . .	610
IV.C.1i	Rice University: Nanoengineering the Forces of Attraction in a Metal-Carbon Array for H <sub>2</sub> Uptake at Room Temperature . . . . .	614
IV.C.1j	Lawrence Livermore National Laboratory: Carbon Aerogels for Hydrogen Storage . . . . .	618
IV.C.1k	Oak Ridge National Laboratory: ORNL Progress within the DOE Center of Excellence for Hydrogen Sorption: Synthesis and Processing of Single-Walled Carbon Nanohorns for Hydrogen Storage and Catalyst Supports . . . . .	621
IV.C.1l	California Institute of Technology: Enhanced Hydrogen Dipole Physisorption . . . . .	625
IV.C.1m	University of North Carolina at Chapel Hill: Characterization of Hydrogen Adsorption by NMR . . . . .	630
IV.C.1n	Pennsylvania State University: Advanced Boron and Metal-Loaded High Porosity Carbons . . . . .	635
IV.C.1o	National Institute of Standards and Technology: NIST Center for Neutron Research in Support of the Hydrogen Sorption Center of Excellence (HSCoE) . . . . .	641
IV.C.1p	University of Missouri: Multiply Surface-Functionalized Nanoporous Carbon for Vehicular Hydrogen Storage . . . . .	646

IV.	Hydrogen Storage (Continued)	
IV.C	Hydrogen Sorption CoE (Continued)	
IV.C.2	University of Pennsylvania: Carbide-Derived Carbons with Tunable Porosity Optimized for Hydrogen Storage . . . . .	652
IV.C.3	State University of New York: Nanostructured Activated Carbon for Hydrogen Storage. . . . .	657
IV.C.4	University of California, Los Angeles: Hydrogen Storage in Metal-Organic Frameworks . . . . .	662
IV.C.5	University of California, Los Angeles: A Joint Theory and Experimental Project in the High-Throughput Synthesis and Testing of Porous COF and ZIF Materials for On-Board Vehicular Hydrogen Storage. . . . .	666
IV.C.6	Northwestern University: New Carbon-Based Porous Materials with Increased Heats of Adsorption for Hydrogen Storage. . . . .	668
IV.C.7	Pennsylvania State University: Hydrogen Trapping through Designer Hydrogen Spillover Molecules with Reversible Temperature and Pressure-Induced Switching . . . . .	671
IV.D	Hydrogen Storage Engineering CoE . . . . .	675
IV.D.1a	Savannah River National Laboratory: Hydrogen Storage Engineering Center of Excellence (HSECoE) . . . . .	675
IV.D.1b	Savannah River National Laboratory: SRNL Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence: Design and Testing of Metal Hydride and Adsorbent Systems. . . . .	679
IV.D.1c	Pacific Northwest National Laboratory: Systems Engineering of Chemical Hydride, Pressure Vessel, and Balance of Plant for On-Board Hydrogen Storage. . . . .	682
IV.D.1d	United Technologies Research Center: Advancement of Systems Designs and Key Engineering Technologies for Materials Based Hydrogen Storage . . . . .	686
IV.D.1e	Los Alamos National Laboratory: Chemical Hydride Rate Modeling, Validation, and System Demonstration. . . . .	690
IV.D.1f	Jet Propulsion Laboratory: Key Technologies, Thermal Management, and Prototype Testing for Advanced Solid-State Hydrogen Storage Systems . . . . .	693
IV.D.1g	National Renewable Energy Laboratory: System Design, Analysis, Modeling, and Media Engineering Properties for Hydrogen Storage . . . . .	696
IV.D.1h	General Motors: System Design and Media Structuring for On-Board hydrogen Storage Technologies. . . . .	699
IV.D.1i	Ford Motor Company: Ford/BASF Activities in Support of the Hydrogen Storage Engineering Center of Excellence . . . . .	701
IV.D.1j	Oregon State University: Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage . . . . .	703
IV.D.1k	Lincoln Composites, Inc.: Development of Improved Composite Pressure Vessels for Hydrogen Storage. . . . .	706
IV.E	Storage Testing, Safety and Analysis . . . . .	708
IV.E.1	TIAX LLC: Analyses of Hydrogen Storage Materials and On-Board Systems. . . . .	708
IV.E.2	Argonne National Laboratory: System Level Analysis of Hydrogen Storage Options . . . . .	714
IV.E.3	Savannah River National Laboratory: Fundamental Environmental Reactivity Analysis of Hydrogen Storage Materials. . . . .	720
IV.E.4	United Technologies Research Center: Quantifying and Addressing the DOE Material Reactivity Requirements with Analysis and Testing of Hydrogen Storage Materials and Systems. . . . .	724
IV.E.5	Sandia National Laboratories: Chemical and Environmental Reactivity Properties of Hydrogen Storage Materials within the Context of Systems . . . . .	729
IV.E.6	H2 Technology Consulting LLC: Best Practices for Characterizing Hydrogen Storage Properties of Materials . . . . .	735
IV.E.7	Southwest Research Institute®: Standardized Testing Program for Solid-State Hydrogen Storage Technologies . . . . .	739

IV.	Hydrogen Storage (Continued)	
IV.F	New Materials-Independent Projects	745
IV.F.1	University of California, Berkeley: A Synergistic Approach to the Development of New Hydrogen Storage Materials, Part I	745
IV.F.2	Los Alamos National Laboratory: Capacitive Hydrogen Storage Systems: Molecular Design of Structured Dielectrics	752
IV.F.3	University of California: Hydrogen Storage Materials with Binding Intermediate between Physisorption and Chemisorption	758
IV.F.4	Michigan Technological University: Novel Metal Perhydrides for Hydrogen Storage	764
IV.F.5	Gas Technology Institute: Electron Charged Graphite-Based Hydrogen Storage Material	768
IV.G	Tanks	771
IV.G.1	Lawrence Livermore National Laboratory: Compact (L)H <sub>2</sub> Storage with Extended Dormancy in Cryogenic Pressure Vessels	771
IV.G.2	Oak Ridge National Laboratory: Lifecycle Verification of Polymeric Storage Liners	775
IV.G.3	Quantum Fuel System Technologies Worldwide, Inc.: Low-Cost, High-Efficiency, High-Pressure Hydrogen Storage	778
IV.H	Cross-Cutting	782
IV.H.1	Purdue University: Purdue Hydrogen Systems Laboratory: Hydrogen Storage	782
IV.H.2	University of South Florida: Hydrogen Storage Research	786
IV.H.3	SiGNa Chemistry Inc.: NaSi and Na-SG Powder Hydrogen Fuel Cells	792
IV.H.4	University of Arkansas at Little Rock: An Integrated Approach for Hydrogen Production and Storage in Complex Hydrides of Transitional Elements and Carbon-based Nanostructural Materials	796
IV.H.5	The UNLV Research Foundation: Hydrogen Fuel Cells and Storage Technology Project	801
IV.I	Basic Energy Sciences	808
IV.I.1	University of Texas at Dallas: Novel Theoretical and Experimental Approaches for Understanding and Optimizing Hydrogen Interactions in Metal Organic Framework Materials	808
IV.I.2	University of California, Davis: Activation of Hydrogen Under Ambient Conditions by Main Group Molecules	815
IV.I.3	University of South Florida: Design and Synthesis of Novel Porous Metal-Organic Frameworks (MOFs) Toward High Hydrogen Storage Capacity	817
IV.I.4	Carnegie Institution of Washington: Novel Molecular Materials for Hydrogen Storage Applications	820
IV.I.5	SLAC National Accelerator Laboratory & Stanford University: Bonding and Structures of Light Element-Hydrogen Systems under Extreme Conditions	822
IV.I.6	University of Missouri: Networks of Boron-Doped Carbon Nanopores for Low-Pressure Reversible Hydrogen Storage	824
IV.I.7	Savannah River National Laboratory: Elucidation of Hydrogen Interaction Mechanisms with Metal-Doped Carbon Nanostructures	830
IV.I.8	Northwestern University: Kinetics and Thermodynamics of Metal and Complex Hydride Nanoparticles	832
IV.I.9	Brookhaven National Laboratory: Atomistic Transport Mechanisms in Reversible Complex Metal Hydrides	836
IV.I.10	Massachusetts Institute of Technology: Thermodynamics and Kinetics of Phase Transformations in Hydrogen Storage Materials	841
IV.I.11	Pacific Northwest National Laboratory: Control of Hydrogen Release and Uptake in Condensed Phases	846
IV.I.12	Southern Illinois University: First Principles Based Simulation of Hydrogen Interactions in Complex Hydrides	851

IV.	Hydrogen Storage (Continued)	
IV.I	Basic Energy Sciences (Continued)	
IV.I.13	Washington University: NMR of Hydrogen Storage Systems: Ionic Hydrides and Mobile Species	855
IV.I.14	Georgia Institute of Technology: First-Principles Studies of Phase Stability and Reaction Dynamics in Complex Metal Hydrides	859
IV.I.15	Florida International University: Influence of Pressure on Physical Property of Ammonia Borane and its Re-Hydrogenation	861
IV.I.16	Oak Ridge National Laboratory: Atomistic Mechanisms of Metal-Assisted Hydrogen Storage in Nanostructured Carbon	867
IV.I.17	Oak Ridge National Laboratory: Application of Neutron Scattering on Hydrogen Storage	872
IV.I.18	Lawrence Berkeley National Laboratory: A Synergistic Approach to the Development of New Hydrogen Storage Materials, Part II: Nanostructured Materials	875
IV.I.19	Ames Laboratory: Complex Hydride Systems – a New Frontier for Future Energy Applications	879
IV.I.20	Colorado School of Mines: Molecular Hydrogen Storage in Novel Binary Clathrate Hydrates at Near-Ambient Temperatures and Pressures	883
IV.I.21	University of Pennsylvania: Mechanistic Studies of Activated Hydrogen Release from Amine Boranes	886
IV.I.22	University of California, Santa Barbara: Computational Studies of Hydrogen Interactions with Storage Materials	890
IV.I.23	Oak Ridge National Laboratory: Quantum Tuning of Chemical Reactivity for Storage and Generation of Hydrogen	894
IV.I.24	University of Pennsylvania: From Fundamental Understanding to Predicting New Nanomaterials for High-Capacity Hydrogen Storage	897
IV.I.25	University of Georgia: Integrated Nanoscale Metal Hydride – Catalyst Architectures for Hydrogen Storage	903
V.	Fuel Cells	909
V.0	Fuel Cells Sub-Program Overview	911
V.A	Analysis/Characterization	919
V.A.1	Argonne National Laboratory: Fuel Cell Systems Analysis	919
V.A.2	Directed Technologies, Inc.: Mass Production Cost Estimation for Direct H <sub>2</sub> PEM Fuel Cell System for Automotive Applications	925
V.A.3	TIAX LLC: Cost Analyses of Fuel Cell Stacks/Systems	931
V.A.4	Argonne National Laboratory: Fuel Cell Testing at Argonne National Laboratory	937
V.A.5	Los Alamos National Laboratory: Component Benchmarking – Subtask Reported: USFCC Durability Protocol Development and Technical-Assisted Industrial and University Partners	940
V.A.6	Los Alamos National Laboratory: Applied Science for Electrode Cost, Performance, and Durability	942
V.A.7	Oak Ridge National Laboratory: Microstructural Characterization of PEM Fuel Cell MEAs	946
V.A.8	National Institute of Standards and Technology: Neutron Imaging Study of the Water Transport in Operating Fuel Cells	952
V.B	Water Transport Studies	957
V.B.1	Los Alamos National Laboratory: Water Transport Exploratory Studies	957
V.B.2	CFD Research Corporation: Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization	963
V.B.3	Rochester Institute of Technology: Visualization of Fuel Cell Water Transport and Performance Characterization under Freezing Conditions	968

V.	Fuel Cells (Continued)	
V.C	Impurities	974
V.C.1	Los Alamos National Laboratory: Effects of Fuel and Air Impurities on PEM Fuel Cell Performance	974
V.C.2	Clemson University: Fundamental Effects of Impurities on Fuel Cell Performance and Durability	978
V.C.3	University of Connecticut: Effects of Impurities on Fuel Cell Performance and Durability	983
V.D	Membranes	989
V.D.1	University of Central Florida: Lead Research and Development Activity for DOE's High Temperature, Low Relative Humidity Membrane Program	989
V.D.2	Giner Electrochemical Systems, LLC: Dimensionally Stable High Performance Membrane	993
V.D.3	Pennsylvania State University: New Proton Conductive Composite Materials with Co-Continuous Phases Using Functionalized and Crosslinkable VDF/CTFE Fluoropolymers	997
V.D.4	University of Tennessee: Poly(cyclohexadiene)-Base Polymer Electrolyte Membranes for Fuel Cell Applications	1001
V.D.5	Virginia Polytechnic Institute and State University: High Temperature, Low Relative Humidity, Polymer-type Membranes Based on Disulfonated Poly(arylene ether) Block and Random Copolymers Optionally Incorporating Protonic Conducting Layered Water Insoluble Zirconium Fillers	1008
V.D.6	Arizona State University: Protic Salt Polymer Membranes: High-Temperature Water-Free Proton-Conducting Membranes	1012
V.D.7	Clemson University: Fluoroalkylphosphonic-Acid-Based Proton Conductors	1016
V.D.8	Case Western Reserve University: Poly(p-Phenylene Sulfonic Acids): PEMs with Frozen-In Free Volume	1021
V.D.9	Vanderbilt University: NanoCapillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells	1026
V.D.10	FuelCell Energy, Inc.: High Temperature Membrane with Humidification-Independent Cluster Structure	1031
V.D.11	Colorado School of Mines: Novel Approaches to Immobilized Heteropoly Acid (HPA) Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes	1034
V.D.12	Arkema Inc.: Improved, Low-Cost, Durable Fuel Cell Membranes	1039
V.D.13	3M Company: Membranes and MEAs for Dry, Hot Operating Conditions	1042
V.D.14	Lawrence Berkeley National Laboratory: New Polyelectrolyte Materials for High Temperature Fuel Cells	1048
V.D.15	Kettering University: Development of Novel PEM Membrane and Multi-Phase CFD Modeling of PEM Fuel Cell	1055
V.D.16	University of Southern Mississippi: Alternate Fuel Cell Membranes for Energy Independence	1061
V.E	Catalysts/Supports	1065
V.E.1	3M Company: Advanced Cathode Catalysts and Supports for PEM Fuel Cells	1065
V.E.2	UTC Power Corporation: Highly Dispersed Alloy Catalyst for Durability	1075
V.E.3	Pacific Northwest National Laboratory: Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells	1081
V.E.4	Argonne National Laboratory: Non-Platinum Bimetallic Cathode Electrocatalysts	1087
V.E.5	Los Alamos National Laboratory: Advanced Cathode Catalysts	1092
V.F	Recycling	1100
V.F.1	BASF Catalysts LLC: Platinum Group Metal Recycling Technology Development	1100

V.	Fuel Cells (Continued)	
V.G	Bipolar Plates/Seals	1104
V.G.1	Oak Ridge National Laboratory: Nitrided Metallic Bipolar Plates	1104
V.G.2	GrafTech International Ltd.: Next Generation Bipolar Plates for Automotive PEM Fuel Cells	1108
V.G.3	UTC Power: Low Cost Durable Seals for PEMFCs	1113
V.H	Water Management	1117
V.H.1	Nuvera Fuel Cells, Inc.: CIRRUS: Cell Ice Regulation & Removal Upon Start-up	1117
V.H.2	Honeywell Aerospace: Development of Thermal and Water Management Systems for PEM Fuel Cells	1121
V.I	Distributed Energy	1124
V.I.1	Intelligent Energy Inc.: Development and Demonstration of a New-Generation High Efficiency 1-10 kW Stationary Fuel Cell System	1124
V.I.2	UTC Power: PEM Fuel Cell Powerplant Development and Verification	1128
V.I.3	Plug Power Inc.: Intergovernmental Stationary Fuel Cell System Demonstration	1132
V.I.4	Plug Power Inc.: FC40 International Stationary Fuel Cell Demonstration	1136
V.I.5	Acumentrics Corporation: Development of a Low Cost 3-10 kW Tubular SOFC Power System	1141
V.I.6	Colorado School of Mines: Renewable and Logistics Fuels for Fuel Cells at the Colorado School of Mines	1144
V.I.7	Bloom Energy, Inc.: Low-Cost Co-Production of Hydrogen and Electricity	1151
V.I.8	Materials and Systems Research, Inc.: Development of a Novel Efficient Solid-Oxide Hybrid for Co-Generation of Hydrogen and Electricity Using Nearby Resources for Local Application	1155
V.I.9	NanoDynamics Energy Inc.: Biogas-Fueled Solid Oxide Fuel Cell Stack	1159
V.I.10	University of Akron: Development of kW Scale Coal-Based Solid Oxide Fuel Cell Technology	1163
V.I.11	Rolls-Royce Fuel Cell Systems (U.S.) Inc.: Extended Durability Testing of an External Fuel Processor for SOFC	1167
V.J	Auxiliary/Off-Road/Portable	1169
V.J.1	Cummins Power Generation: Diesel-Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power	1169
V.J.2	Delphi Corporation: Solid Oxide Fuel Cell Development for Auxiliary Power in Heavy Duty Vehicle Applications	1173
V.J.3	Superprotonic, Inc.: Solid Acid Fuel Cell Stack for APU Applications	1177
V.J.4	IdaTech, LLC: Research & Development for Off-Road Fuel Cell Applications	1183
V.J.5	MTI Micro Fuel Cells: Direct Methanol Fuel Cell Prototype Demonstration for Consumer Electronics Applications	1186
V.J.6	Lilliputian Systems, Inc.: Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics	1190
V.J.7	Nanosys, Inc.: Engineered Nanostructured MEA Technology for Low Temperature Fuel Cells	1194
V.K	Cross-Cutting	1198
V.K.1	Case Western Reserve University: Light-Weight, Low-Cost PEM Fuel Cell Stacks	1198
V.K.2	University of South Carolina: Fuel Cell Research at the University of South Carolina	1201
V.K.3	Michigan Technological University: Center for Fundamental and Applied Research in Nanostructured and Lightweight Materials	1206
V.K.4	Microcell Corporation; Martin County Hydrogen Fuel Cell Development	1212
V.K.5	Stark State College of Technology: Fuel Cell Balance of Plant Reliability Testbed	1214
V.K.6	University of South Carolina: Hydrogen Fuel Cell Development in Columbia (SC)	1218

VI.	Manufacturing R&D .....	1221
VI.0	Manufacturing R&D Sub-Program Overview .....	1223
VI.1	National Renewable Energy Laboratory: Fuel Cell Membrane Electrode Assembly Manufacturing R&D .....	1225
VI.2	Pacific Northwest National Laboratory: Digital Fabrication of Catalyst Coated Membranes .....	1229
VI.3	Ballard Material Products: Reduction in Fabrication Costs of Gas Diffusion Layers ...	1233
VI.4	UltraCell Corporation: Modular, High-Volume Fuel Cell Leak-Test Suite and Process...	1239
VI.5	W. L. Gore & Associates, Inc.: Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning .....	1243
VI.6	Rensselaer Polytechnic Institute: Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacture .....	1249
VI.7	Quantum Fuel System Technologies Worldwide, Inc.: Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels .....	1254
VI.8	Lawrence Livermore National Laboratory: Inexpensive Pressure Vessel Production Through Fast Dry Winding Manufacture .....	1257
VII.	Systems Analysis .....	1261
VII.0	Systems Analysis Sub-Program Overview .....	1263
VII.1	National Renewable Energy Laboratory: HyDRA: Hydrogen Demand and Resource Analysis Tool .....	1267
VII.2	Lawrence Livermore National Laboratory: Water Needs and Constraints for Hydrogen Pathways .....	1271
VII.3	Argonne National Laboratory: Cost Implications of Hydrogen Quality Requirements...	1274
VII.4	National Renewable Energy Laboratory: Macro-System Model .....	1279
VII.5	National Renewable Energy Laboratory: Discrete Choice Analysis of Consumer Preferences for Refueling Availability .....	1283
VII.6	Sandia National Laboratories: Analysis of Energy Infrastructures and Potential Impacts from an Emergent Hydrogen Fueling Infrastructure .....	1287
VII.7	National Renewable Energy Laboratory: Hydrogen Deployment System Modeling Environment (HyDS-ME) .....	1291
VII.8	RCF Economic and Financial Consulting, Inc.: Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System .....	1296
VII.9	National Renewable Energy Laboratory: Adapting the H2A Hydrogen Production Cost Analysis Model to Stationary Applications .....	1300
VII.10	Missouri University of Science and Technology: Hydrogen and Fuel Cell Analysis: Lessons Learned from Stationary Power Generation .....	1303
VII.11	Oak Ridge National Laboratory: Development of HyTrans Model and Integrated Scenario Analysis .....	1307
VII.12	Argonne National Laboratory: Fuel-Cycle Analysis of Hydrogen-Powered Fuel Cell Systems with the GREET Model .....	1312
VII.13	University of Illinois, Urbana-Champaign; Evaluation of the Potential Environmental Impacts from Large-Scale Use and Production of Hydrogen in Energy and Transportation Applications .....	1316
VII.14	Tetra Tech, Inc.: Potential Environmental Impacts of Hydrogen-Based Transportation and Power Systems .....	1321
VII.15	Pacific Northwest National Laboratory: Pathways to Commercial Success: Technologies and Products Supported by the Hydrogen, Fuel Cells & Infrastructure Technologies Program .....	1325
VII.16	National Renewable Energy Laboratory: DOE Hydrogen Program Risk Analysis in Support of EERE's Portfolio Analysis .....	1328
VII.17	Sandia National Laboratories: Thermodynamic, Economic, and Environmental Modeling of Hydrogen (H <sub>2</sub> ) Co-Production Integrated with Stationary Fuel Cell Systems (FCS) .....	1332

VII. Systems Analysis (Continued)	
VII.18 National Renewable Energy Laboratory: Stranded Biogas Decision Tool for Fuel Cell Co-Production	1342
VIII. Technology Validation	1345
VIII.0 Technology Validation Sub-Program Overview	1347
VIII.1 National Renewable Energy Laboratory: Controlled Hydrogen Fleet and Infrastructure Analysis	1351
VIII.2 Chevron Technology Ventures LLC: Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project	1359
VIII.3 Ford Motor Company: Hydrogen Fuel Cell Vehicle & Infrastructure Demonstration Program Review	1362
VIII.4 Chrysler Group LLC: Hydrogen to the Highways	1365
VIII.5 General Motors: Hydrogen Vehicle and Infrastructure Demonstration and Validation	1370
VIII.6 Air Products and Chemicals, Inc.: Validation of an Integrated Hydrogen Energy Station	1374
VIII.7 Air Products and Chemicals, Inc.: California Hydrogen Infrastructure Project	1378
VIII.8 National Renewable Energy Laboratory: Technology Validation: Fuel Cell Bus Evaluations	1382
VIII.9 University of Hawaii at Manoa: Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems	1387
VIII.10 Southeast Michigan Council of Governments: Detroit Commuter Hydrogen Project	1389
VIII.11 Tanadgusix Foundation: TDX Foundation Hydrogen Project	1392
VIII.12 Texas H2 Coalition: Texas Hydrogen Highway - Fuel Cell Hybrid Bus and Fueling Infrastructure Technology Showcase	1394
VIII.13 Florida Hydrogen Initiative, Inc.: Florida Hydrogen Initiative	1397
IX. Safety, Codes & Standards	1407
IX.0 Safety, Codes & Standards Sub-Program Overview	1409
IX.1 National Renewable Energy Laboratory: Hydrogen Codes and Standards	1413
IX.2 National Renewable Energy Laboratory: Hydrogen Safety Sensors	1416
IX.3 Sandia National Laboratories: Materials Compatibility	1420
IX.4 Pacific Northwest National Laboratory: Hydrogen Safety Knowledge Tools	1424
IX.5 Los Alamos National Laboratory: Hydrogen Fuel Quality	1427
IX.6 Sandia National Laboratories: Hydrogen Release Behavior	1431
IX.7 Pacific Northwest National Laboratory: Hydrogen Safety Panel	1436
IX.8 Regulatory Logic LLC: Codes & Standards for the Hydrogen Economy	1440
IX.9 Intelligent Optical Systems, Inc.: Hydrogen Optical Fiber Sensors	1443
X. Education	1447
X.0 Education Sub-Program Overview	1449
X.1 Pacific Northwest National Laboratory: Hydrogen Safety: First Responder Education	1453
X.2 National Renewable Energy Laboratory: Hydrogen Education for Code Officials	1457
X.3 California State University, Los Angeles: Hydrogen and Fuel Cell Education at California State University, Los Angeles	1460
X.4 Humboldt State University: Hydrogen Energy in Engineering Education (H <sub>2</sub> E <sup>3</sup> )	1464
X.5 Michigan Technological University: Hydrogen Education Curriculum Path at Michigan Technological University	1468
X.6 University of Central Florida: Bachelor of Science Engineering Technology Hydrogen and Fuel Cell Education Program Concentration	1472
X.7 University of North Dakota: Development of a Renewable Hydrogen Production and Fuel Cell Education Program	1475

X.	Education (Continued)	
X.8	Carolina Tractor & Equipment Co. Inc.: Dedicated To The Continued Education, Training and Demonstration of PEM Fuel Cell Powered Lift Trucks In Real-World Applications . . . . .	1479
X.9	Houston Advanced Research Center: Hydrogen Education in Texas. . . . .	1483
X.10	South Carolina Hydrogen and Fuel Cell Alliance: Development of Hydrogen Education Programs for Government Officials . . . . .	1486
X.11	Virginia Clean Cities: VA-MD-DC Hydrogen Education for Decision Makers. . . . .	1489
X.12	Connecticut Center for Advanced Technology, Inc.: State and Local Partnership Building. . . . .	1494
X.13	Ohio Fuel Cell Coalition: Raising H <sub>2</sub> and Fuel Cell Awareness in Ohio . . . . .	1497
X.14	Hydrogen Education Foundation: H <sub>2</sub> and You: A Public Education Initiative by the Hydrogen Education Foundation . . . . .	1499
X.15	Clean Energy States Alliance: Hydrogen Education State Partnership Project . . . . .	1502
X.16	University of California, Berkeley: Hydrogen Technology and Energy Curriculum (HyTEC). . . . .	1506
X.17	Oak Ridge National Laboratory: Hydrogen Knowledge and Opinions Assessment. . . . .	1510
X.18	NEED Project: H <sub>2</sub> Educate – Middle School Hydrogen Education Program . . . . .	1514
XI.	Small Business Innovation Research . . . . .	1517
XI.0	Small Business Innovation Research (SBIR) Hydrogen Program New Projects Awarded in FY 2009 . . . . .	1519
	Phase I Projects . . . . .	1520
XI.1	InnovaTek, Inc.: Integrated Membrane Water Gas Shift Reactor for Hydrogen Production . . . . .	1520
XI.2	Materials and Systems Research, Inc.: Development of a “4-in-1” Device for Cost Effective and Efficient Production of Hydrogen. . . . .	1520
XI.3	ElectroChem, Inc.: Advanced PEM Based Hydrogen Home Refueling Appliance. . . . .	1520
XI.4	Giner Electrochemical Systems, LLC: Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5000 psi . . . . .	1520
XI.5	Lynntech, Inc.: Design, Optimization and Fabrication of a Home Hydrogen Fueling System . . . . .	1521
XI.6	STTR Project: Development of a Hydrogen Home Fueling System . . . . .	1521
XI.7	Proton Energy Systems: Hydrogen by Wire-Home Fueling System . . . . .	1521
XI.8	Reactive Innovations, LLC: On-Line Measurement of PEM Electrolyzer Stacks. . . . .	1521
XI.9	TIAX, LLC: Modeling of Hydrogen Dispensing Options for Advanced Storage . . . . .	1522
	Phase II Projects . . . . .	1522
XI.10	Directed Technologies, Inc.: Aqueous Phase Base-Facilitated-Reforming (BFR) of Renewable Fuels . . . . .	1522
XI.11	Faraday Technology, Inc.: Faradayic ElectroEtching of Stainless Steel Bipolar Plates . . . . .	1522
XI.12	Giner Electrochemical Systems, LLC: Anode Concepts for SO <sub>2</sub> Crossover Reduction in the HyS Electrolyzer. . . . .	1522
XI.13	InnovaTek, Inc.: Power Generation from an Integrated Biofuel Reformer and Solid Oxide Fuel Cell . . . . .	1522
XII.	Acronyms, Abbreviations and Definitions. . . . .	1523
XIII.	Primary Contacts Index . . . . .	1543
XIV.	Hydrogen Program Contacts. . . . .	1547
XV.	Project Listings by State. . . . .	1551
XVI.	Project Listings by Organization . . . . .	1573