Report of the DOD-DOE Workshop on Fuel Cells in Aviation

DOD-DOE MOU Workshop Summary and Action Plan

FUEL CELL TECHNOLOGIES PROGRAM

DOE Office of Energy Efficiency and Renewable Energy

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Executive Summary

The U.S. Department of Defense (DOD) is highly dependent on liquid fossil fuels, which represent 76% of its total energy consumption. This dependence comes at a high price: the 131 million barrels that DOD consumes each year cost $10.5 billion dollars, plus an additional $450 million in transport expenses.[1] With 60% of this fuel being sourced from foreign suppliers,[2] this dependence also hinders DOD's energy security, making DOD vulnerable to price spikes and supply disruptions that could potentially strain fuel-intensive tactical operations. DOD's high fuel consumption also generates high levels of greenhouse gas emissions.

One of DOD's top priorities is to reduce its use of liquid fossil fuels in order to improve energy security, reduce energy costs, and reduce emissions. Meeting this goal will require fundamental shifts in energy use to provide comprehensive energy solutions that are both effective and economical.

> The commercial and defense aviation sectors are both strategically important. The civil aviation sector alone provides 11 million jobs and more than one trillion dollars of economic activity—about 10% of U.S. gross domestic product.

On July 22, 2010, the DOD and the U.S. Department of Energy (DOE) entered into a Memorandum of Understanding (MOU) for the purpose of coordinating efforts to enhance national energy security and demonstrate federal government leadership in transitioning to a low-carbon economy. A key focus area of the MOU is DOD-DOE collaboration on a broad range of innovative, technology-driven solutions to reduce petroleum use, among other objectives.[3] As a large developer and end user of technology, DOD will aim to speed the movement of innovative energy technologies and technical expertise from DOE's research laboratories to military end users, using military installations as test beds and early markets.

One of the solutions being explored under the MOU is the use of hydrogen and fuel cell applications to curb the use of logistics fuel across several DOD agencies. DOD and DOE have jointly identified three areas of opportunity: developing and installing fuel cells for auxiliary power in ground support equipment (GSE) at airports and on board DOD aircraft; developing and using fuel cells for auxiliary power on surface warfare ships; and leveraging biowaste as feedstock for fuel cell applications in fixed and deployed military operations. Appendix A provides more details about each opportunity, including the estimated total energy savings and emissions reduction for each, and next steps for DOD-DOE collaboration in each area.

This paper discusses the results of a September 30, 2010, workshop focusing on the first of these three opportunities: the development and installation of fuel cells for auxiliary power on board DOD aircraft.

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[1] Defense Logistics Agency, 2009 *Defense Energy Support Center Fact Book* (Fort Belvoir, VA: Defense Logistics Agency, 2009), http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf.
[2] Ibid.
[3] U.S. Department of Energy (DOE) and U.S. Department of Defense (DOD), *Memorandum of Understanding between U.S. Department of Energy and U.S. Department of Defense* (Washington, DC: July 22, 2010, U.S. DOE and DOD), http://www.energy.gov/news/documents/Enhance-Energy-Security-MOU.pdf.

Drivers for Leaner, Cleaner Energy Use in Aviation

In recent years, several trends have started driving the aviation industry to transition to less fuel-intensive, more efficient technologies that generate fewer greenhouse gas emissions.

The most notable driver for change is the need to reduce the cost burden of high fuel use. Aviation is a particularly energy-intensive industry: the commercial airline industry and DOD collectively require more than 1.5 million barrels of jet fuel per day.[4] In the military, jet fuel accounts for 52% of DOD's total energy consumption,[5] with the United States Air Force and its assets consuming more energy (fuel) than any other agency in DOD. The cost of this fuel is a major expense for the aviation sector. In commercial aviation, fuel costs can easily represent 30%–40% of total expenses—more than labor costs.[6] In military aviation, fuel costs have a direct impact on operational costs:

> For every $10 increase in the price of a barrel of oil, DOD's operating costs increase by approximately $1.3 billion. DOD budgets for fuel a year or more in advance of its purchase, therefore an[y] sudden large increases in fuel costs must be paid for with emergency funds or by shifting funds from other programs. The Air Force, which operates most of DOD's fixed-wing aircraft, spends the largest share of DOD's fuel budget. Every $10 increase in a barrel of oil increases the Air Forces' already sizable annual fuel costs by $600 million.[7]

Another major driver for change is the need to enhance energy security. As stated previously, 60% of DOD's liquid fossil fuel is imported. This can potentially make military and commercial operations vulnerable to price spikes and supply disruptions. The uncertainty of future oil supplies (from which traditional aviation fuels are derived) is another factor in energy security. Several analyses have suggested that world crude oil production has reached its peak and may decline in future years. However, growing demand for air transportation will contribute to an expected 3% annual increase in demand for jet fuel.[8]

Increasingly stringent federal and state air quality regulations have emerged as another major driver of change in the aviation industry, especially the commercial aviation sector. U.S. Environmental Protection Agency and California Air Resources Board regulations pertaining to non-road engines have pushed the commercial aviation industry to begin adopting alternative energy technologies for GSE. Appendix B provides additional information about the shift to low-emission GSE in commercial aviation operations.

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[4] Kelly Widener, "DOD, Airline Officials Sign Alternative Fuels Pact," U.S. Air Force, March 23, 1010, http://www.af.mil/news/story.asp?id=123196191.
[5] Defense Logistics Agency, 2009 *Defense Energy Support Center Fact Book* (Fort Belvoir, VA: Defense Logistics Agency, 2009), http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf.
[6] Zubin Jelveh, "Flying on Empty: How U.S. Airlines Can Survive the Spike in Jet Fuel Prices," *Portfolio.com*, June 4, 2008, http://www.portfolio.com/news-markets/national-news/portfolio/2008/06/04/Airlines-Struggle-With-Fuel-Costs/.
[7] Kristine E. Blackwell, *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel – Issues for Congress* (Washington, DC: Congressional Research Service, June 15, 2007), www.fas.org/sgp/crs/natsec/RL34062.pdf.
[8] Kjell Aleklett, "Aviation Fuel and Future Oil Production Scenarios – 'Peak Aviation,'" *Post Carbon Institute Energy Bulletin*, May 3, 2009, http://www.energybulletin.net/node/48838.

The Opportunity for Hydrogen and Fuel Cell Technologies in Aviation

These trends are creating near- and long-term opportunities for hydrogen and fuel cell technology applications in aviation. There is an emerging opportunity for hydrogen and fuel cell technology to be used in off-board aviation applications to help increase energy efficiency, reduce dependence on imported fuels, and reduce emissions. Hydrogen and fuel cell technologies can replace gas- and diesel-powered technologies currently in use in ground power applications such as truck auxiliary power units (APUs), ground power units, primary and emergency power, road vehicles, and gate handling equipment such as conveyors, fuel trucks, catering vehicles, water trucks, and mobile lighting.

There is also a potential longer-term opportunity for hydrogen and fuel cell technologies to be applied in onboard energy systems for commercial and military aircraft. In commercial aircraft, hydrogen fuel cell systems can provide onboard electrical power for galley operations, in-flight entertainment, peak power, and other applications. In military aircraft, hydrogen fuel cell systems can provide power for functions such as engine restart; on-ground heating, ventilating, and air conditioning; electric and pneumatic power; and cargo door operations. Fuel cells may also represent the best alternative for efficient processing of bioaviation fuels presently under development (ref. "Farm to Fly" partnership).[9]

Commercial aviation industry experience has already shown that applying fuel cells to carry nonessential loads (galleys, in-flight entertainment) can be used to gradually introduce this technology to in-service operation. Applying fuel cells in this way can remove these loads from the power system, decreasing the size of the generating system and engine power extraction.

In anticipation of these opportunities, DOE and DOD research is already exploring the application of fuel cells to meet the primary power and auxiliary power needs for manned and unmanned aircraft, ground support systems, general maintenance equipment, airports, and airport infrastructure electrification. For example, he collaboration with the United States Air Force (USAF) includes a proposal to transition GSE to replacement APUs powered by fuel cells. USAF bases, on average, have 800 GSE units that operate in the power range of 2–20 kilowatts (kW).

[9] Billy M. Glover and John P. Heimlich, "Farm to Fly: Toward a Comprehensive Sustainable Aviation Biofuels Rural Development Plan" (presentation, the Air Transport Association of America and Boeing Commercial), http://www.airlines.org/Energy/AlternativeFuels/Documents/FarmtoFlyPresentation071410.pdf.

Industry Pursues "Farm to Fly" Biofuels Partnership

In its *2008 Environment Report*, Boeing estimates that bioaviation fuels could reduce flight-related greenhouse gas emissions by 60%–80% percent. Recognizing biofuels' potential to achieve these dramatic reductions in emissions while improving energy security, the United States Department of Agriculture (USDA) and the Federal Aviation Administration (FAA) have launched the five-year "Farm to Fly" partnership, which will focus on forest and crop residues as potential feedstocks for jet bioaviation fuel development.

The two agencies will assess the availability of different kinds of feedstocks that could be processed by biorefineries to produce jet fuels and develop a tool to evaluate the status of different components of the bioaviation fuel feedstock supply chain. The partnership supports a larger research plan led by USDA that will include as many U.S. rural areas as possible to maximize the economic benefits of bioaviation fuel production across the country.

Boeing is also involved in other initiatives to develop and commercialize bioaviation fuels. It has established a Sustainable Aviation Fuel Users Research group to accelerate the development and commercialization of bioaviation fuels. The group's research is supported and advised by the World Wildlife Fund and the Natural Resources Defense Council.

Potential Impacts

Carrying the DOD-DOE fuel cell collaboration forward through the entire USAF fleet of aircraft could result in significant energy and emissions reductions. Targeting auxiliary power applications on aircraft during flight, taxiing, and gate operations could represent a savings of 2%–5%[10] of all aircraft fuel per year—an annual savings of 1 million–3 million barrels of oil.[11] These savings are possible because APUs powered by hydrogen fuel cells (such as solid oxide fuel cell APUs) operate at higher efficiencies and use less fuel than APUs powered by gas turbines.

Transitioning all USAF GSE to use replacement APUs powered by hydrogen fuel cells represents even greater potential energy and emissions reductions: a fuel reduction of 7 million–12 million barrels per year.[12, 13, 14]

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[10] R. Braun, M. Gummalla, and J. Yamanis, "System Architectures for Solid Oxide Fuel Cell-Based Auxiliary Power Units in Future Commercial Aircraft Applications," *Journal of Fuel Cell Science and Technology* 6, (August 2009).

[11] Defense Logistics Agency Energy, *Fact Book Fiscal Year* 2010, (Fort Belvoir, VA: Defense Logistics Agency Energy, 2010), http://www.desc.dla.mil/dcm/files/Fact%20Book%20FY10%20Final%20Web.pdf.

[12] Dr. Thomas L. Reitz, Chief Thermal and Electrochemical Propulsion Directorate, Air Force Research Laboratory, "Solid Oxide Fuel Cells (SOFC) as Military APU Replacements" (presentation, DOD-DOE Workshop on Fuel Cells in Aviation, Washington, DC, September 30, 2010).

[13] R. Braun, M. Gummalla, and J. Yamanis, "System Architectures for Solid Oxide Fuel Cell-Based Auxiliary Power Units in Future Commercial Aircraft Applications," *Journal of Fuel Cell Science and Technology* 6, (August 2009).

[14] L.L. Gaines, A. Elgowainy, and M.Q. Wang, *Full Fuel-Cycle Comparison of Forklift Propulsion Systems* (Oak Ridge, TN: U.S. Department of Energy, 2008), https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/forklift_anl_esd.pdf; GSE will use ~ 15,000 Btu/kWh of petroleum energy.

A study by Battelle Memorial Institute also suggests that the transition to GSE powered by hydrogen fuel cells could provide cost savings. The study indicates that airport GSE has the potential to provide significant lifecycle cost savings over lead-acid battery and combustion engine systems under certain types of operation.[15]

Barriers and Challenges

Key challenges must be overcome before the military and commercial aviation industry can realize the full energy- and emissions-reducing potential of hydrogen and fuel cell technology applications. Challenges for hydrogen and fuel cell technology applications in aviation include the following:

- **Technical issues** such as managing waste heat, improving fuel cell durability, improving inverter efficiency, increasing system power densities and system energy densities (including fuel storage), and ensuring reliable power quality. Another significant technical challenge is addressing the differing requirements (packaging, location, and functions) for military and commercial aviation use of APUs. APUs are used for non-propulsion power like cabin pressure, avionics, and gallery power.
- **Fuel issues** such as increasing fuel flexibility and tolerance of high-sulfur fuels. The move toward bioaviation fuels may also pose challenges in terms of tolerance to sulfur and heavy metals.
- **Cost challenges** for hydrogen and fuel cell technology applications in aviation, including the need to reduce fuel cell, hydrogen, and balance of plant costs.
- **Certification** challenges, particularly coordinating certification and approvals for storage of high-pressure hydrogen on aircraft.
- The lack of a **refueling infrastructure** for bases and airports.

Conclusions and Next Steps

The workshop's facilitated discussions explored the barriers and challenges to the successful application of hydrogen and fuel cell technologies in aviation and suggested several potential collaborative activities that could be pursued to overcome them. These included recommendations for identifying the best near-term opportunities for aviation fuel cell applications, beginning with GSE and other off-board applications; conducting additional research, development, and deployment on low-temperature and high-temperature fuel cells; developing a strategic plan for airport and aircraft applications, with a staged implementation process leading to introduction of onboard aircraft APUs; and collaborating with existing efforts to develop bioaviation fuels. Three "big ideas" were proposed as next steps: a two-year multisite mobile fuel cell plasma lighting demonstration, a solid oxide fuel cell (SOFC) battery range extender APU demonstration, and a proton exchange membrane battery range extender APU demonstration.

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[15] K. Mahadevan, *Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, Produced by Battelle, Columbus, OH (Washington, DC: U.S. Department of Energy), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

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1. Introduction to the Aviation Workshop

Background

The U.S. Department of Defense (DOD) and U.S Department of Energy (DOE) entered into a Memorandum of Understanding (MOU) for the purpose of coordinating efforts to enhance national energy security and demonstrate federal government leadership in transitioning to a low-carbon economy. A key focus area of the MOU is DOD-DOE collaboration on a broad range of innovative, technology-driven solutions to petroleum use reduction, among other objectives.[16] As a large developer and end user of technology, DOD will aim to speed the movement of innovative energy technologies and technical expertise from DOE's research laboratories to military end users, using military installations as test beds and early markets. Activities undertaken through this collaboration can also help DOD installations meet the requirements of additional regulations that impact their strategies for energy use. These regulations include the 2005 Energy Policy Act, 2005 Army Energy Strategy, Executive Order 13514, the Energy Independence and Security Act of 2007, the 2007 Army Environmental Requirements and Technology Assessments, and the Defense Science Board recommendations.[17]

To facilitate cooperation in aviation technologies under the MOU, the DOE Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Program (FCT) hosted a workshop on September 30, 2010. The workshop focused on the development and installation of fuel cells for auxiliary power on board DOD aircraft. The DOD-DOE collaboration plans to begin with the United States Air Force (USAF) Air Mobility Command, focusing on those aircraft demanding on average 500 kilowatts (kW) of non-propulsion power during flight. Also proposed in the collaboration with the USAF is transitioning ground support equipment (GSE) to replacements powered by hydrogen fuel cells. USAF bases, on average, have 800 GSE units that operate in the power range of 2–20 kW.[18]

Goals and Objectives

The workshop brought together more than 40 representatives from the Army, Navy, Air Force, DOE national laboratories, and industry; as well as DOD and DOE energy leaders. The workshop's goals included the following:

- To initiate collaborations across DOD and DOE in keeping with the MOU
- To motivate research, development, and demonstration (RD&D) for auxiliary power unit (APU) applications

[16] U.S. Department of Energy (DOE) and U.S. Department of Defense (DOD), *Memorandum of Understanding Between U.S. Department of Energy and U.S. Department of Defense* (Washington, DC: July 22, 2010, U.S. DOE and DOD), http://www.energy.gov/news/documents/Enhance-Energy-Security-MOU.pdf.
[17] Franklin H. Holcomb, René S. Parker, Thomas J. Hartranft, Kurt Preston, Harold R. Sanborn, and Philip J. Darcy, *Proceedings of the 1st Army Installation Waste to Energy Workshop*, ERDC/CERL TR-08-11 (Washington, DC: U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, August 2008), http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA491416.
[18] Dr. Thomas L. Reitz, Chief Thermal and Electrochemical Propulsion Directorate, Air Force Research Laboratory, "Solid Oxide Fuel Cells (SOFC) as Military APU Replacements" (presentation, DOD-DOE Workshop on Fuel Cells in Aviation, Washington, DC, September 30, 2010).

- To identify next steps for the proposed fuel cell working group

Approach

During the morning and afternoon sessions, the workshop featured presentations from DOD and DOE executive staff and six presentations from industry, Air Force Research Laboratory (AFRL), and DOE national laboratory experts, as shown in Figure 1.1. Breakout sessions were convened in the afternoon to reflect on the presentations given, identify key challenges and opportunities, and develop the groundwork for an action plan going forward. Presentations are available online at: http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_aircraft_petrol_use.html.

Figure 1.1. Workshop Agenda

I. **Introduction**
II. **Workshop Purpose and Format**
III. **Plenary Session Summaries**
   a. *U.S. Department of Energy Perspective*:
      Henry Kelly, U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE)
   b. *Memorandum of Understanding Overview*:
      Richard Kidd, DOE EERE, Federal Energy Management Program
   c. *The Office of the Secretary of Defense*:
      James Short, U.S. Department of Defense, Office of the Secretary of Defense
   d. *U.S. Department of Energy Fuel Cell Technologies Program Overview*:
      Sunita Satyapal, DOE EERE Fuel Cell Technologies Program
   e. *Industry Perspective*:
      Joe Breit, Boeing
   f. *Fuel Cell and Hydrogen Energy Association Aerospace Task Force Overview:*
      Robert Wichert, Fuel Cell and Hydrogen Energy Association Aerospace Task Force
   g. *United States Air Force Perspective*:
      Thomas L. Reitz, United States Air Force Research Laboratory
   h. *Fuel Cell Powered Mobile Light Stand*:
      Lennie Klebanoff, Sandia National Laboratories (SNL)
   i. *Low-Temperature Fuel Cell Perspective*:
      Lennie Klebanoff and J.W. Pratt, SNL
   j. *High-Temperature Fuel Cell Perspective*:
      Larry Chick, Pacific Northwest National Laboratory
IV. **Facilitated Discussion**
   a. Challenges and Barrier Identification
   b. Analytics, Research, Development, and Deployment Needs, with Leadership Responsibilities and Roles Identified for Actions by DOD, DOE, and Industry
V. **Next Steps**
VI. **Conclusion**

2. Workshop Presentation Summaries

The agenda comprised a general overview of the DOD-DOE MOU, with leaders from DOD and DOE providing perspectives on the execution of the MOU relevant to the strategic importance of aircraft petroleum reduction. This was followed by presentations on previous and present aircraft efforts and activities undertaken by industry, the Air Force, and the national laboratories.

The following topics were addressed throughout the workshop:

1. Aircraft petroleum use reduction: the need and opportunity
2. Low-temperature fuel cell technologies and products
3. High-temperature fuel cell technologies and products

The following section summarizes key points from the workshop presentations, which are available online at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_aircraft_petrol_use.html.

U.S. Department of Energy Perspective

PRESENTER**: Dr. Henry Kelly, DOE Office of Energy Efficiency and Renewable Energy (EERE)**

Dr. Kelly, Acting Assistant Secretary and Principal Deputy Assistant Secretary for EERE, welcomed the attendees to the joint workshop, emphasized the importance of DOD-DOE collaboration as well as the need to reduce the use of jet fuel, and outlined three objectives for the meeting: (1) to begin discussing collaboration across DOD and DOE in keeping with the MOU, (2) to motivate RD&D for APU applications, and (3) to identify next steps for the group. He observed that by leveraging the strengths of both organizations, DOD and DOE have the potential to help encourage the full-scale industry use of fuel cell product applications. He emphasized the history of collaboration between the FCT and other government organizations, including DOD.

Memorandum of Understanding Overview

PRESENTER: **Mr. Richard Kidd, DOE EERE, Federal Energy Management Program**

Mr. Kidd provided an overview of the MOU and highlighted federal mandates that are directing strategic actions by DOD, DOE, and other federal agencies. He also discussed the potential joint benefits to DOD and DOE as the result of leveraging unique and distinct DOD and DOE technical resources to fulfill the requirements of the MOU while meeting U.S. energy security goals.

The Office of the Secretary of Defense

PRESENTER: **Mr. James Short, U.S. Department of Defense, Office of the Secretary of Defense**

Mr. Short presented an overview of DOD's approach for meeting its strategic goals in the fuel cell technologies program, the influence of the Defense Science Board studies on DOD energy costs, and the organizational strengths that DOD could leverage to carry out the MOU objectives. He noted that the U.S.

government is a major energy user and that DOD consumes the most energy, with jet fuel accounting for more than half (52%) of its energy needs. He highlighted the recent organizational change at the Pentagon, which created a centralized leadership to steer efforts to implement energy savings. As military services experience the burdens that fuel demands create on their services, many of them have launched their own energy-saving programs. Mr. Short concluded by summarizing the RD&D activities underway at DOD research laboratories, including research involving fuel cells for onboard aircraft and for airport applications, such as GSE.

U.S. Department of Energy Fuel Cell Technologies Program Overview

PRESENTER**: Dr. Sunita Satyapal, DOE EERE Fuel Cell Technologies Program**

Dr. Satyapal presented an overview of DOE's FCT Program and the progress that the United States has made regarding hydrogen and fuel cell RD&D. Dr. Satyapal highlighted the potential for hydrogen and fuel cells to play unique roles in the new clean energy economy. Key points in the presentation included: (1) fuel cells can provide power for many different applications, not just light-duty and on-road vehicle transportation; and (2) fuel cell systems for DOD product applications include stationary power systems, truck APUs, portable electronic equipment, and light-duty and specialty vehicles, such as lift trucks. Dr. Satyapal also discussed other applications that DOE is beginning to assess, including APUs for aircraft. Dr. Satyapal presented preliminary estimates showing that onboard fuel cell APUs could represent an annual fuel savings of 2%–5% per aircraft, which would save 1 million–3 million barrels of oil and avoid 900–2,200 tons of nitrogen oxide (NOx) emissions annually.

Industry Perspective

PRESENTER: **Mr. Joe Breit, Boeing**

Mr. Breit discussed the higher potential efficiency and lower fuel use of solid oxide fuel cell (SOFC) APUs compared to typical APUs. In flight, SOFC APUs offer a specific fuel consumption savings of 0.7%, have the potential to reach 75% efficiency, and use 40% less fuel. SOFC APUs also offer attractive fuel savings when used on the ground. A typical turbine-powered APU is 15% efficient; SOFC APUs have the potential to reach 60% efficiency and use 75% less fuel. By reducing fuel consumption, SOFC APUs will also reduce airplane NOx emissions at airports.

Mr. Breit also discussed efficiency changes to 787s, including composite airframes and efficient no-bleed engines, which are leading a transition to a more electric airplane with an increase in electric power needs of about 1.5 megawatts (MW).

Mr. Breit stated that GSE applications and testing can be used to develop the technology and infrastructure needed to support the use of SOFCs in aircraft. Using SOFCs to power non-essential loads, such as galley operations and in-flight entertainment systems, can gradually introduce this technology to in-service operation. Fuel cells can remove these loads from the power system, decreasing the size of the generating system and engine power extraction, and can also use waste heat and water. Mr. Breit concluded that RD&D specific to this application will help to advance the technology of fuel cells for airplanes.

Fuel Cell and Hydrogen Energy Association Aerospace Task Force Overview

PRESENTER: **Mr. Robert Wichert, Fuel Cell and Hydrogen Energy Association (FCHEA)**

Mr. Wichert gave an overview of the formation of the FCHEA Aerospace Fuel Cell Working Group (WG) to provide a forum for pre-competitive information sharing and interaction among interested industry stakeholders. Members include experts from Boeing, Cessna, Airbus, Bell Helicopter, Sikorsky, the National Aeronautics and Space Administration, and others who are committed to sharing their individual expertise. Similar to SAE International working group structures, there are no formal corporate ties in the WG. Mr. Wichert reported that the WG will explore the primary and auxiliary power needs for all manned and unmanned aircraft, GSE, general maintenance equipment, airports, and airport infrastructure electrification opportunities. In terms of fuel cells, the WG will investigate the state-of-the-art for fuel cells and hydrogen reforming technologies, including reformation and purification of fuels, hydrogen storage, energy and power density, and power electronics. The WG will also evaluate the technology readiness levels of fuel cell technologies; develop methodologies for assessing emission reductions and petroleum usage reductions; evaluate new fuels, including bioaviation fuels; and perform comparisons with other fuel cell technologies or with other competing technologies.

United States Air Force Perspective

PRESENTER: **Mr. Thomas L. Reitz, AFRL**

Mr. Reitz explained that APUs for military aircraft have different requirements than APUs for commercial aircraft. APUs for military use are smaller and are placed in a different location. The primary functions of military APUs include engine restart; heating, ventilation, and air conditioning on the ground; electric and pneumatic power; and cargo door operations. He explained that DOE and many others are working to develop SOFCs, with an emphasis on core technology, system reliability, and affordability. He also stated that AFRL is working on a near-term demonstration of fuel cell systems for ultra-long flights of unmanned aircraft systems and continued RD&D to develop high power densities and tolerance for military logistics fuels with high and variable sulfur content (up to 3,000 parts sulfur per million). Key challenges to SOFC technology include increased power densities (systems greater than 200 watts/kilogram [W/kg]), the ability to use military logistics fuels with high and variable sulfur content, and a high level of performance over an extended lifetime.

Fuel Cell Powered Mobile Light Stand

PRESENTER**: Dr. Lennie Klebanoff, Sandia National Laboratories (SNL)**

Dr. Klebanoff presented on SNL's leadership of a collaborative project to develop a fuel cell powered mobile light tower as an alternative to diesel-powered equipment. The objective of the fuel cell mobile light tower project is to design, build, and field-test a fleet of fuel cell powered mobile light towers in "real world" operating environments, including road construction, airports, and entertainment industry deployments. He highlighted the key stakeholders supporting the project, including DOE, Boeing, and the Caltrans Division of Research and Innovation, which has been assisting in the design and deployment of the system and will be deploying a unit in their District 7 (the Los Angeles Basin). Other project partners include Multiquip Inc., the largest manufacturer of rental construction equipment in the United States; Altergy Systems, a mass manufacturer of fuel cells; Stray Light Optical Technologies; and Luxim Inc., a manufacturer of state-of-the-art plasma lighting. Dr. Klebanoff also commented that Multiquip plans to commercialize a fuel cell powered product, pending successful field-test research and market assessment results.

Low-Temperature Fuel Cell Perspective

PRESENTERS**: Dr. Lennie Klebanoff and Dr. J.W. Pratt, SNL**

Dr. Klebanoff and Dr. Pratt explained how their study of polymer electrolyte membrane (PEM) fuel cells applied to specific onboard electrical power needs, including galley power, in-flight entertainment, and peak power. They highlighted the scope, method used, and preliminary findings to date of their ongoing study of onboard fuel cell systems for commercial airplanes. Three components were defined as part of the project's scope: (1) hardware requirements and physical sizing, (2) thermodynamic system analysis, and (3) electrical system design. A total of 11 system options were analyzed based on the handling of waste heat for the thermodynamic system analysis. Drs. Klebanoff and Pratt explained that early results suggest that PEM fuel cells can be used on airplanes with manageable performance impact if heat is rejected properly. Onboard uses may not fully absorb waste heat generated by the fuel cell. They suggested that waste heat could be rejected through the fuel system or through the addition of a cooling system; however, a cooling system would result in a large drag penalty, which would result in additional fuel consumption.

High-Temperature Fuel Cell Perspective

PRESENTER: **Dr. Larry Chick, Pacific Northwest National Laboratory**

Dr. Larry Chick presented on an SOFC system's potential to yield 65% net efficiency for onboard aircraft applications. Benefits of this system include the ability to directly supply hydrogen, carbon, and methane to the anode as fuels, allowing the system to more easily use liquid hydrocarbons and steam reforming supported through high temperatures, which boosts system efficiency. Dr. Chick stated that specific power is the key technical challenge for SOFC to succeed in aircraft applications. The specific power required for an aircraft stack is estimated at 1.0–1.5 kW/kg, which is more than five times better than present technology. The specific power required for an aircraft system is estimated at 0.4–0.5 kW/kg, which is more than 10 times better than present technology. Factors affecting power density include voltage, temperature, fuel concentration, and electrochemical activity (which is improving with new designs and materials). Dr. Chick also described the current Greener Airplane Study to support Boeing.[19] Key elements under review include the 787 load profile, SOFC size and configuration, desulfurization processes, uses for waste heat and water, hydrogen supply for PEM APUs, delivering peak load power needs, optimum system metrics, and assessing technology readiness levels and pathways to deployment.

[19] Larry Chick, Pacific Northwest National Laboratory, "Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft" (presentation, DOE Hydrogen and Fuel Cell Program 2011 Annual Merit Review and Peer Evalutation Meeting, Arlington, VA, May 10, 2011), http://www.hydrogen.energy.gov/pdfs/review11/mt001_chick_2011_o.pdf.

3. Key Points from Facilitated Discussion

The facilitated discussion session worked to identify challenges and barriers to the use of high- and low-temperature fuel cells in onboard and off-board aviation applications, and needs for analysis, research, development, and demonstration to advance fuel cell use in these applications. Figure 3.1 presents a high-level synthesis of the discussion, focusing on the key recommendations for activities that could be pursued under the DOD-DOE MOU. A summary of the key challenges that were identified, and the analysis, research, development, and deployment gaps and needs is provided below. Raw results from the breakout sessions are included in Appendix C.

Challenges and Barriers

- **Cost**. Both fuel (hydrogen[20]) cost and fuel cell cost were identified as barriers. The cost of producing and storing hydrogen must come down, as well as the cost of the fuel cell itself. Hydrogen tanks for onboard storage of fuel are another area where cost is a factor. Fuel cell systems must be cost competitive with other technologies.
- **Refueling infrastructure**. In order to use hydrogen powered fuel cells, new fueling infrastructure is needed. This infrastructure is currently costly to install, particularly when utilization rates are low. Clustering multiple products that use hydrogen together (e.g., material handling equipment, buses, and GSE), and which can use the same refueling station, would help to lower this cost.
- **Weight**. The weight of the fuel cell system (fuel cell, balance of plant, and fuel storage tank) could be an issue, especially for onboard applications.
- **Fuel flexibility**. Military applications benefit from fuel flexibility, and ideal systems would be able to use JP-8, JP-5 and other existing military fuels. Fuel cells need to demonstrate robust performance with multiple fuels.
- **Carbon capture**. For systems that use hydrocarbon fuels, a functional, cost-effective carbon capture and bulk storage system is needed for the system to be carbon-neutral.
- **Retrofit of existing equipment**. Military aircraft (e.g., C-5 and B-52) and GSE have long lifetimes (e.g., approximately 10 years). The challenge is designing cost-effective ways to retrofit these power systems for fuel cell use.
- **Fuel cell power density**. High-temperature fuel cell power density is currently too low to support demands for many applications. During his presentation at the workshop, Dr. Chick reported that power density is currently 0.17 kW/kg, while it needs to be 1.5 kW/kg. System power density (kW/kg) must be higher.
- **Durability**. There is a need to demonstrate required system durability (lifetime) as well as the ability for systems to be reliable and robust as well as sustain required voltage levels at ambient and pressurized environments, including operation with loss of air pressure.

[20] Dr. Sunita Satyapal, DOE EERE Fuel Cell Technologies Program, "Hydrogen and Fuel Cells Program Overview" (presentation, DOE Hydrogen and Fuel Cell Program 2011 Annual Merit Review and Peer Evaluation Meeting, Arlington, VA, May 9, 2011), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/amr11_plenary_satyapal.pdf; $8-$10/kg hydrogen.

- **Ability to handle impurities**. Impurities in petroleum- and biomass-based fuels available in the field (e.g., heavy metals, sulfur) as well as in air feeds (e.g., volcanic ash) could poison the fuel cells.
- **Safety, codes, and standards**. Certification and approvals are needed to store high-pressure hydrogen aboard an aircraft (e.g., Federal Aviation Administration [FAA] certification).

Figure 3.1. Summary of Results of Facilitated Discussions: Recommendations for Collaborative Activities on Use of Fuel Cells in Aviation Applications

Idea	Desired Outcome	Next Steps
 Identify best near-term opportunities for aviation fuel cell applications, beginning with ground support equipment (GSE) and other airport off-board applications	• Meeting notes are shared with broader communities at the U.S. Department of Energy (DOE) and the U.S. Department of Defense (DOD) • Specific DOD sites for near-term demonstration projects are identified by benchmarking current utilization of GSE and other airport off-board applications and benefits are quantified (or determined) • Operating experience for new products and fuels is increased • Business case and air emissions assumptions are validated • Greenhouse gas reduction benefits are measured • More complicated product applications build on succesful near-term demonstrations and deployments	• Complete reporting and documenting results of previous or existing projects involving DOD research laboratories or installations • Prepare Executive Committee Debrief through Information Analysis Centers • Develop multisite mobile fuel cell plasma lighting demonstration • Identify other existing fuel cell products that could be deployed at DOD sites during fiscal year (FY) 2012 or FY 2013 • Analyze life-cycle costs and benefits for fuel cell product applications and, where appropriate, fueling infrastructure • Analyze emissions reduction and petroleum savings
	Responsible Parties • DOD • DOE • Industry	
 Develop strategic plan for airport and aircraft applications, with a staged introduction of on-board aircraft APUs	• Aircraft platforms that are potential targets for retrofits or new APU applications are identified	• Review the long-term (10-year) Product Plan for military aircraft at all services to identify candidates • Develop a strategic plan for GSE and other airport applications
	Responsible Parties • DOD	

Figure 3.1 Summary of Results of Facilitated Discussions: Recommendations for Collaborative Activities on Use of Fuel Cells in Aviation Applications (Continued)

Idea	Desired Outcome	Next Steps	Responsible Parties
Conduct additional research, development, and demonstration (RD&D) on low- and high-temperature fuel cells	• Fuel cell power density performance is improved • Analysis of fuel cell shock/vibration tolerance is completed • Fuel reforming is improved to levels that can support high and variable sulfur levels of existing fuels	• Develop solid oxide fuel cell battery range extender for GSE • Develop polymer electrolyte membrane battery range extender APU demonstration • Conduct testing using logistics fuels to confirm/validate impurity tolerance • Conduct shock/vibration testing • Identify key performance parameters for onboard and off-board APUs • Identify GSE or other airport applications for testing fuel cell system prototypes	• DOD • DOE • Pacific Northwest National Laboratory(PNNL) • Sandia National Laboratories (SNL) • Industry
Collaborate with existing efforts to develop bioaviation fuels for specific fuel cells (e.g., reforming activities)	• Airport or aircraft APU applications that will use bioaviation fuels and fuel cells for high efficiency are introduced	• Coordinate with "Farm To Fly" program • Identify opportunities for testing with high- or low-temperature systems • Conduct fuel cell relevant testing or demonstrations to assess value propositions and air quality benefits	• DOD • DOE • U.S. Department of Agriculture • Federal Aviation Administration • PNNL • SNL • Industry

Analysis and Research, Development, and Deployment Needs

The discussion moved on to consider key gaps and areas where collaboration among DOE, DOD and industry could help to overcome the gaps. A number of potential activity areas were identified (as summarized in Figure 3.1 and briefly described below), with several "big ideas" fleshed out in more detail to identify specific suggestions for the project approach and next steps.

- **Analysis needs**. More analysis is needed by DOE to quantify the benefits of using fuel cells in aviation applications, including life-cycle cost/benefit analysis, emission reduction analysis, and petroleum savings analysis.

- **Fuel cell and fuel RD&D**. Research and development is needed to develop improved fuel reforming technology for impurities removal. Demonstrations of fuel cell use with logistics fuels are needed to validate tolerance to existing impurities. Further analysis of bioaviation fuels is also needed, including demonstrations. RD&D is also needed to improve, develop, test, and demonstrate fuel cell performance for use in real-world military operating conditions, including tolerance to shock and vibration, high-pressure ambient environments, loss of air pressure, and power density requirements, among others.
- **Testing and analysis capabilities**. To support the testing and analysis of fuel cells for aviation applications, DOD should develop the capability for flight testing of onboard APUs, and identify key performance parameters.
- **Identification and demonstration of near-term fuel cell applications**. DOD and DOE should work together to identify and demonstrate the best opportunities for near-term applications of fuel cells for GSE and aviation applications. These successful near-term demonstrations will form the basis for fuel cell applications in more complicated applications.

"Big Idea" Next Steps

The following three next steps were identified as "big ideas" that could be immediately pursued to demonstrate the use of fuel cells in military aviation applications:

1) Demonstration of mobile fuel cell plasma lighting systems at several military bases
2) Develop SOFC APUs to extend the battery range of GSE
3) Develop PEM APUs to extend the battery range of GSE

More information on each of these "big ideas" is presented below.

Multisite Mobile Fuel Cell Plasma Lighting Demonstration

Participating Organizations: U.S. Army Engineer Research and Development Center Construction Engineering Research Laboratory, DOE, SNL, and DOD host sites—airstrips would have top priority for deployments

Project Description:

- Two-year demonstration project to deploy multiple fuel cell mobile light systems at various DOD locations in "real-world" operating conditions.
- The fuel cell mobile lighting units consist of a 5 kW Altergy fuel cell, fueled by four 5,000 pounds per square inch (psi) hydrogen tanks containing approximately 8 kilograms (kg) of hydrogen integrated into the system.
- These units may be demonstrated alongside conventional diesel generator light units for performance comparisons.
- Data will be collected on performance, reliability, and operational costs and compared to the existing SNL data.
- These units will be the first fielded in DOD, and this test will assess if the units help meet mission requirements while reducing greenhouse gases and the consumption of diesel fuel.
- The project will look for a community-scale renewable energy project at bases where hydrogen is generated to fuel deployed fuel cell systems.

Operating Specifications:[21]

- The hydrogen-field PEM fuel cell uses pure hydrogen from storage system and oxygen obtained from ambient air.
- The unit has a 43% electrical efficiency compared to the 27% efficiency of a diesel lighting equivalent. Utilizing this system will help reduce diesel consumption inside DOD facilities. This unit produces no carbon dioxide, NOx, or particulates and will help DOD move toward its greenhouse gas emission goals.
- The hydrogen storage can provide approximately 65 hours of lighting with an area of illumination of 50 yards by 75 yards. The units have a fully rotatable light tower that is 30 feet tall and operates with a 43 decibel noise level at 23 feet.
- The plasma lighting provides high efficiency (120 lumens/W) with a 50,000-hour lifetime. The lights have a 30-second turn-on time with rapid re-strike and have no audible noise or flicker. The lights are programmable and are safe for indoor or outdoor use.

[21] Lennie Klebanoff, SNL, "Fuel Cell Mobile Lighting" (presentation, DOE Hydrogen and Fuel Cell Program 2011Annual Merit Review and Peer Evaluation Meeting, Arlington, VA, May 10, 2011) http://www.hydrogen.energy.gov/pdfs/review11/mt010_klebanoff_2011_p.pdf.

SOFC Battery Range Extender Auxiliary Power Unit

Participating Organizations: AFRL, DOE, Defense Logistics Agency (DLA), FAA, U.S. Department of Agriculture (USDA)

Project Description:

- APU platform features will include four primary components: a fuel processing module, which will enable the capability to convert several liquid fuels into a hydrogen syngas; an SOFC module, which will convert the hydrogen into electrical energy; a power conditioning, storage, and management system for the APU; and the balance of plant.

- Thermal management will heat up the reformer and fuel cell initially, but once the system is running, the overall system will recapture this heat to generate steam for the reformer and hot air for the SOFC.
- The initial phase of the program will install the APU on GSE for testing and demonstrations under "real-world" conditions at sites to be identified later.[22]
- The actual specifications of the proposed APU system will be determined as the result of additional GSE application analysis.
- DOE and other key stakeholders will seek to collaborate with the principal "Farm to Fly" stakeholders, including the FAA, USDA, and fuel providers supporting the "Farm to Fly" program and other related activities, for bioaviation fuel and fueling infrastructure testing and validation.
- The battery range extender APU effort envisions that the bioaviation fuels will be physically comparable to other diesel or jet fuels, and would be stored and dispensed in a similar manner, complying with regulations such as FAA Advisory Circular 150/5230-4A, "Aircraft Fuel Storage, Handling, and Dispensing on Airports," which references the National Fire Prevention Association 407 code "Standard for Aircraft Fuel Servicing" and the National Air Transportation Association publication "Refueling and Quality Control Procedures for Airport Service and Support Operations." Other regulations include the Air Transport Association Specification 103, "Standard for Jet Fuel Quality Control at Airports."

Operating Specifications:

- A bank of ultracapacitors will be able to provide immediate power for 5–10 seconds at 10 kW upon the start of a power outage. This power will be necessary to engage the emergency loads that are initiated by the power outage.
- A bank of rechargeable batteries will be able to provide 5 kW of power for up to 15 minutes. In this configuration, the batteries can sustain the emergency loads for short-term power outages. They can also provide sufficient power for intermittent emergency power equipment such as doors and gates.

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[22] Defense Logistics Agency, 2009 *Defense Energy Support Center Fact Book* (Fort Belvoir, VA: Defense Energy Support Center, 2009), http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf.

- The fuel cell system will be used to provide a base load of 2 kW to power constantly operating emergency systems such as lighting. The fuel cell system can also recharge the batteries and ultracapacitors when it is not operating at its full output load, or once power has been restored to the system.
- The system will have the fuel capacity to run the APU for 10 hours.

PEM Fuel Cell Battery Range Extender Auxiliary Power Unit

Participating Organizations: AFRL; U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC); or DLA (lead); and DOE

Project Description:

- Similar to the SOFC APU project, except a PEM APU with a biofuel reformer application will be selected.

Operating Specifications:

- Similar to the SOFC APU project, except a PEM APU with a biofuel reformer application will be selected.

Appendix A. DOD Energy Reduction Using Fuel Cells

Energy security and environmental impact awareness are now at the forefront of the U.S. Department of Defense (DOD) mission. According to a 2008 study by the Defense Science Board Task Force on DOD energy strategy, 76% of DOD's total energy consumption is made up of liquid fossil fuels, including jet fuel (52%), marine diesel (12%), auto diesel (8%), fuel oil (3%), and auto gas (1%). As reported by the Defense Energy Support Center's (DESC) 2009 Fact Book,[23] DOD consumes more than 131 million barrels of fossil fuel per year, at a cost of more than $10.5 billion dollars. DOD purchases the following petroleum-derived fuels: distillates and diesel, JP-4, JAB, JAA&JA1, JP-5, JP-8, jet propellant thermally stable, and motor gasoline. Sixty percent of this fuel is purchased from foreign suppliers and costs DOD more than $450 million to transport each year.

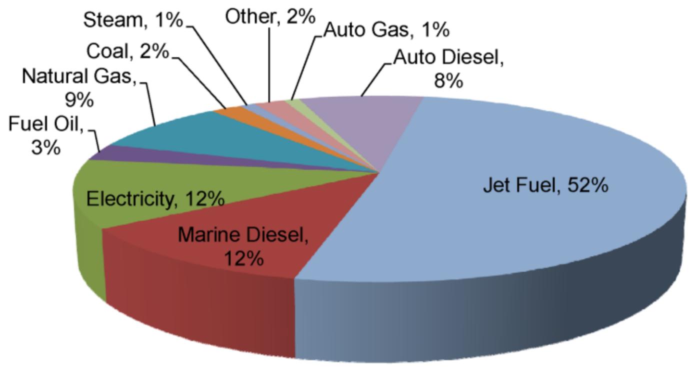

Figure A.1. DOD Energy Consumption by Type of Fuel

In an effort to reduce the amount of oil DOD consumes, as well as associated costs and environmental impacts, DESC (the prime supplier of energy resources to DOD and all of its agencies) has enacted several programs, such as the development of HRJ-5 and HRJ-8 (a biofuel drop-in replacement for JP-5 and JP-8) to curb petroleum-derived fuel use and reduce costs. However, no significant changes have been made to impact aircraft or marine petroleum-derived fuel consumption. Fundamental shifts in energy use must be made in order to meet energy independence and environmental impact reduction goals and maintain DESC's mission of providing "comprehensive energy solutions in the most effective and economical manner possible." To this end, DOD has entered into a Memorandum of Understanding (MOU) with the U.S. Department of Energy (DOE) to collaborate on a broad range of innovative, technology-driven solutions to reduce petroleum use.[24]

DOD and DOE have jointly identified three hydrogen and fuel cell applications to curb the use of logistics fuel across several DOD agencies. These include developing and installing fuel cells for auxiliary power on board DOD aircraft and surface warfare ships and leveraging biowaste as feedstock for combined heat and power applications domestically and abroad. Following are specific opportunities for DOD-DOE collaboration on these fuel cell applications.

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[23] Defense Logistics Agency, 2009 *Defense Energy Support Center Fact Book* (Fort Belvoir, VA: Defense Logistics Agency, 2009), http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf.
[24] U.S. Department of Energy (DOE) and U.S. Department of Defense (DOD), *Memorandum of Understanding Between U.S. Department of Energy and U.S. Department of Defense* (Washington, DC: July 22, 2010, U.S. DOE and DOD), http://www.energy.gov/news/documents/Enhance-Energy-Security-MOU.pdf.

Air Force Energy Reduction Opportunity

The United States Air Force (USAF) and its assets consume more energy (fuel) than any other agency in DOD. In an effort to reduce energy use by military aircraft, the DOE Hydrogen and Fuel Cell Technologies Program is proposing collaboration focused on developing and implementing fuel cells to meet auxiliary power needs in a range of military aircraft. Beginning with the Air Mobility Command (AMC), which oversees more than 900 launches per day worldwide,[25] this collaboration would focus on those aircraft that demand (on average) 500 kilowatts (kW) of non-propulsion power during flight.[26] The majority of aircraft in the current AMC fleet already use gas turbine auxiliary power units (APUs). The early stages of this collaboration will focus on designing and developing fuel cell APUs to replace these gas turbine systems.[27] Carrying the collaboration forward to include fuel cell replacement throughout the entire fleet of USAF aircraft could result in significant energy reductions. Targeting auxiliary power application on aircraft during flight, taxiing, and gate operations could save 2%–5% of aircraft fuel per year. In 2009, the USAF consumed 57.7 million barrels of jet fuel. Replacing APUs with fuel cells would therefore result in a reduction of 1 million–3 million barrels of jet fuel per year.[28] Other non-aircraft opportunities also exist within the scope of USAF equipment.

Also proposed in the collaboration with the USAF is transitioning ground support equipment (GSE) to replacements powered by fuel cells. On average, USAF bases have 800 GSE units that operate in the power range of 2–20 kW.[29] Replacing these units with fuel-cell-powered GSE would reduce fuel consumption by 7 million–12 million barrels per year across the entire USAF fleet.[30]

Early stage activities are underway to analyze and prepare for prototype testing of APUs in aircraft beginning in 2013. To support this timeline, the DOE Hydrogen and Fuel Cell Technologies Program has initiated fuel cell systems integration analysis through both Sandia National Laboratories and Pacific Northwest National Laboratory. This analysis will build on work performed by the National Aeronautics and Space Administration as outlined in its 2006 feasibility study concerning SOFC APUs for long-range commercial aircraft.[31] The results of this analysis results will also support the formation of a joint DOD-DOE solicitation that will drive collaboration with industry to meet goals of prototype testing by 2013.

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[25] Don Erbschloe PhD, Air Mobility Command, USAF.

[26] Joe Breit, Boeing Commercial, "BCA Perspective on Fuel Cell APUs" (presentation, U.S. Department of Energy and U.S. Department of Defense Workshop: Aircraft Petroleum Use Reduction: Can Fuel Cells be a Game Changer?, Washington, DC, September 30, 2010).

[27] Hans-Jürgen Heinrich, Airbus,"Fuel Cell Integrated Power Systems," (presentation, U.S. Department of Energy private meeting, Washington, DC, March 10, 2010).

[28] Defense Logistics Agency, 2009 *Defense Energy Support Center Fact Book* (Fort Belvoir, VA: Defense Logistics Agency, 2009), http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf.

[29] Dr. Thomas L. Reitz, Chief Thermal and Electrochemical Propulsion Directorate, Air Force Research Laboratory, "Solid Oxide Fuel Cells (SOFC) as Military APU Replacements" (presentation, DOD-DOE Workshop on Fuel Cells in Aviation, Washington, DC, September 30, 2010).

[30] L.L. Gaines, A. Elgowainy, and M.Q. Wang, *Full Fuel-Cycle Comparison of Forklift Propulsion Systems* (Oak Ridge, TN: U.S. Department of Energy, 2008), https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/forklift_anl_esd.pdf; GSE will use ~ 15,000 Btu/kWh of petroleum energy.

[31] Hari Srinivasan, *Solid Oxide Fuel Cell APU Feasibility Study for a Long Range Commercial Aircraft Using UTC ITAPS Approach*, NASA CR-2006-214458/VOL1, Produced by United Technologies Research Center, East Hartford, CT (Hanover, MD: NASA, December, 2006), http://gltrs.grc.nasa.gov/reports/2006/CR-2006-214458-VOL1.pdf.

Navy Energy Reduction Opportunity

DOE, in collaboration with the Office of Naval Research (ONR), has identified several near-term opportunities on board various surface ship platforms that could result in significant energy reduction. Based on an analysis of the guided missile destroyer (DDG) 1000 ship class under development, installing auxiliary power fuel cells with power output between 4 MW and 10 MW, at an energy use efficiency of 38%, would result in a fuel reduction of 12%–18%.[32] On a ship requiring 91,000 barrels of fuel per year, this amounts to a reduction of 10,900–16,000 barrels of fuel per year. Further analysis conducted by ONR has shown the ability to achieve 48% efficiencies at 10 watts per liter for a molten carbonate ship fuel cell operating on reformed JP-5, and achieving a 36 watts per liter power density with improved reforming operating on low-sulfur F76, JP-5, and JP-8.

Continued research and development efforts are underway to improve operations to meet performance and cost requirements. Retrofitting existing surface ship platforms such as the DDG 51 ship class could produce even higher fuel use reductions. For this platform, a fuel cell producing 3–6 MW through an electric drive system would result in 20% fuel savings per year, equivalent to 16,000 barrels of fuel. Assuming that only 35 ships install mechanical drives or hybrid electric drives using fuel cells in a fleet consuming 11 million barrels per year, this represents a 4%–5% fuel savings per year over the entire maritime fleet.[33]

Further opportunities exist in the use of biofuel on board surface ships. ONR, in an initiative to achieve the U.S. Secretary of the Navy's energy goal to sail the "Great Green Fleet" by 2016, is completing an analysis of the use of biofuel in conjunction with fuel cells to increase power density and performance. DOE will conduct a workshop with DOD to further analyze these opportunities and prepare for a joint collaboration between DOE and DOD (ONR) proposed to address key research, development, and demonstration challenges and demonstrate fuel cell prototypes running on reformed biofuel by 2014.[34]

Air National Guard Energy Reduction Opportunity

The DOE Hydrogen and Fuel Cell Technologies Program has identified opportunities to leverage biowaste currently on site at many Air National Guard (ANG) bases as feedstock for combined heat and power fuel cells. DOE is currently scoping projects at both ANG's Joint Forces Training Base (JFTB) and USAF's Eglin Air Force Base. Based on current energy usage data provided by JFTB and efficiency data provided by a Verizon case study[35], JFTB could experience on average 4,000 therms/month (400 million British thermal units [Btus]/month or 117,000 kilowatt-hours [kWh]/month) and 48,000 therms (4.8 billion Btus or 1.4 million kWh) at 80% efficiency using both the heat and power generated by the fuel cell. Looking at aggregate savings across all ANG bases (to date there are 134), the numbers are even more impressive. At the rates mentioned above, assuming a grid efficiency of 30%, savings could reach 188 million kWh or 634 billion Btus annually. Financial feasibility studies have shown waste-to-energy

[32] Bomse, Conner, Douglass, Partos, *Shipboard Fuel Cell (SFC) Thrust*, CME D0008923.A1/Final (Alexandria, VA: CNA, Center for Naval Analyses, September 2003).
[33] Ibid.
[34] Ibid.
[35] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Case Study: Fuel Cells Provide Combined Heat and Power at Verizon's Garden City Central Office" (Washington, DC: U.S. Department of Energy, December 2010), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fccs_verizon10.pdf.

installations can yield internal rates of return up to 12%, with average payback periods of capital investment at less than seven years.[36]

In an effort to kick off this initiative, the DOE Hydrogen and Fuel Cell Technologies Program will host a third workshop with DOD to determine next steps in implementing a plan that would reach a 50% adoption rate across ANG. Further opportunities exist in leveraging biowaste on site at other DOD facilities, which will also be explored in collaboration with DOD.

[36] Josh Rapport, “Modeling the Design and Financial Feasibility of an Anaerobic Digester Producing Energy from Organic Solid Waste” (presentation, The U.S. Composting Council’s 17th Annual Conference and Trade Show, Houston, TX, January 26, 2009).

Appendix B. The Airline Industry's Transition to Low-Emission Ground Support Equipment

Ground support equipment (GSE) includes forklifts, tugs, belt loaders, bobtails, cargo loaders, lifts, air conditioners, service trucks, deicers, fuel delivery trucks, and ground power units. The Battelle Memorial Institute study, "Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets," indicates that airport GSE has the potential to provide significant lifecycle cost savings over lead-acid battery and combustion engine systems under certain types of operation.[37]

Technical Considerations

Generally, there are no technical limitations on the size or type of GSE that can be converted to or replaced with battery-powered equipment. However, a primary issue in evaluating the potential acceptability of battery-powered GSE is the daily usage demand placed on the equipment. Equipment that is in continuous or near-continuous service throughout the day will require quick-turnaround battery replacement facilities, quick recharge capability, or the availability of fully charged backup equipment. Most GSE will require between one and five charging cycles per day.

GSE that can operate for a full day on a single charge are candidates for off-peak charging, but most equipment will require all-hours recharging access, at least with current battery technology. Battery storage advances could increase the fraction of GSE that can operate throughout the day on a single charge, but existing technology can only be extended through an increase in battery pack size (thus imposing additional storage space considerations).

Regulations Drive the Change to Low-Emission GSE

Since the mid-1990s, the airline industry has been investigating the benefits of using electricity or alternative fuels instead of gasoline and diesel fuel in ground support vehicles.[38] U.S. Environmental Protection Agency (EPA) emission standards applicable to non-road diesel engines may further encourage the airline industry to transition away from vehicles powered by internal combustion engines (ICEs). These standards, to be implemented in phases between 2008 and 2014, will require diesel engine manufacturers to outfit new engines with advanced emission control technologies. New ground support vehicles powered by diesel-powered ICEs will be required to meet these standards.[39]

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[37] K. Mahadevan, *Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, Produced by Battelle, Columbus, OH (Washington, DC: U.S. Department of Energy), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

[38] Sandy Webb, "Technical Data to Support FAA's Advisory Circular on Reducing Emissions from Commercial Aviation" (memorandum to Bill Albee, Federal Aviation Administration, and Rich Wilcox, Environmental Protection Agency, 1995), http://www.epa.gov/oms/regs/nonroad/aviation/meta-faa.txt.

[39] Federal Aviation Administration, Office of Environment and Energy, *Aviation and Emissions: A Primer* (Washington, DC: Federal Aviation Administration, 2005), accessed June 2006, http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/AEPRIMER.pdf#search=%22Aviation%20and%20Emissions%20-%20A%20Primer%22.

The California Air Resources Board (CARB) has proposed to adopt more stringent emission standards and test procedures for large (> 25 horsepower/19 kilowatt), spark-ignited engines in various types of equipment, including forklifts, sweepers/scrubbers, industrial tow tractors, and GSE.[40] CARB has proposed the adoption of EPA's 2007 model-year emission standard and a more stringent 2010 model-year emissions standard. CARB also proposed stricter emission standards for fleets in use that requires operators of in-use fleets to reduce their emissions by retrofitting existing equipment or replacing uncontrolled engines with zero- or low-emission engines.

Emissions from ground support vehicles impact not only the air within airport environments but also the air quality of the surrounding community. This could potentially become a concern, particularly in air quality nonattainment areas. FAA and EPA have identified more than 100 U.S. airports in eight-hour nonattainment or maintenance areas, or about one-third of the U.S. commercial service airports.[41] This creates further incentive for regional air quality boards and state agencies to support cleaner GSE technology deployment because they want to avoid being penalized for nonattainment.

Government Programs Support Low-Emission GSE

Federal and state agencies have also begun advancing programs that support low-emission GSE. In April 2000, Congress authorized the Inherently Low-Emissions Airport Vehicle (ILEAV) Pilot Program as part of the Wendell H. Ford Aviation Investment and Reform Act for the 21st Century (AIR-21). AIR-21 authorized 10 ILEAV project grants for up to $2 million each under the FAA Airport Improvement Program (AIP).

FAA and EPA have expanded the initiative to all commercial airports listed in the FAA National Plan of Integrated Airport Systems and located in EPA-designated air quality nonattainment areas through the Voluntary Airport Low Emission (VALE) program. The VALE program allows airport sponsors to use the AIP and passenger facility charges (up to $4.50 for every enplaned passenger) to finance low-emission vehicles, refueling and recharging stations, gate electrification, and other airport air quality improvements.[42] This includes the conversion of airport vehicles and GSE to low-emission technologies, modification of airport infrastructure to support use of alternative fuels, and a pilot program to explore retrofit technology for airport GSE. The VALE program creates opportunities for vehicles powered by fuel cells to enter this market.[43]

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[40] California Environmental Protection Agency, Air Resources Board, *Staff Report: New Emission Standards, Fleet Requirements, And Test Procedures For Forklifts And Other Industrial Equipment* (Sacramento, CA: California Environmental Protection Agency, Air Resources Board, 2006), accessed June 2006, http://www.arb.ca.gov/regact/lore2006/isor.pdf.

[41] Office of Airports, Airport Planning and Programming, *Voluntary Airport Low Emission Program Technical Report*, Version 7, DOT/FAA/AR-04/37 (Washington, DC: Federal Aviation Administration, 2010), http://www.faa.gov/airports/environmental/vale/media/vale_techreport_v7.pdf; Federal Aviation Administration, *List of U.S. Commercial Service Airports and their Nonattainment and Maintenance Status* (Washington, DC: Federal Aviation Administration, 2005), accessed September 2006, http://www.faa.gov/airports_airtraffic/airports/environmental/vale/media/vale_eligible_airports.xls.

[42] Office of Airports, Airport Planning and Programming, *Voluntary Airport Low Emission Program Technical Report*, Version 7, DOT/FAA/AR-04/37 (Washington, DC: Federal Aviation Administration, 2010), http://www.faa.gov/airports/environmental/vale/media/vale_techreport_v7.pdf.

[43] Federal Aviation Administration, Office of Environment and Energy, *Aviation and Emissions: A Primer* (Washington, DC: Federal Aviation Administration, 2005), accessed June 2006, http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/AEPRIMER.pdf#search=%22Aviation%20and%20Emissions%20-%20A%20Primer%22.

The VALE program includes low-emission standards for non-road vehicles with either spark-ignition (SI) or compression-ignition engines. Non-road standards differ from on-road standards in that they are based on the horsepower of the engine rather than the vehicle weight. The only regulatory mechanism that preserves adequate cost-effective emission reductions for large SI non-road engines is EPA's voluntary Blue Sky Engine Program. EPA Tier 4 non-road diesel engine emission standards apply to Vehicle Category 5. These stringent low-emission standards for non-road diesel engines, which began in 2008, are based on the use of ultralow-sulfur diesel fuel and the growing ability of non-road engine manufacturers to incorporate advanced clean engine technologies to meet Tier 4 emission requirements.[44]

Industry Begins the Transition

Many airlines have voluntarily agreed to reduce emissions from their ground support vehicle fleets. For example, major airlines have forged agreements with state agencies in both California and Texas to reduce emissions from ground support vehicles by converting gasoline and diesel equipment to alternative fuels and electricity.[45] Air carriers operating in California's South Coast air basin entered into a Memorandum of Understanding (MOU) with CARB in 2002, committing to reduce hydrocarbon and nitrogen oxide emissions from new and in-use GSE. While the MOU was terminated in late 2005, under CARB's proposed emission requirements those airlines were still required to meet the MOU's zero-emission requirement for existing fleets by 2010.[46]

The airline industry has taken steps to replace ICE-powered tugs with battery-powered models. For example, a major ground support service provider at Miami International Airport committed to replacing most of its gas-fueled baggage tugs in an attempt to improve terminal air quality, which had been degraded by emissions from the ICE-powered vehicles.[47]

[44] Office of Airports, Airport Planning and Programming, *Voluntary Airport Low Emission Program Technical Report*, Version 7, DOT/FAA/AR-04/37 (Washington, DC: Federal Aviation Administration, 2010), http://www.faa.gov/airports/environmental/vale/media/vale_techreport_v7.pdf.

[45] Federal Aviation Administration, Office of Environment and Energy, *Aviation and Emissions: A Primer* (Washington, DC: Federal Aviation Administration, 2005), accessed June 2006, http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/AEPRIMER.pdf#search=%22Aviation%20and%20Emissions%20-%20A%20Primer%22.

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Appendix C. Raw Results of Breakout Sessions

The following tables includes the “raw” output from the facilitated brainstorm discussion session held during the workshop, during which participants recorded written responses to specific questions and posted them to a central “storyboard.

Table C.1. Challenges and Barriers to the Use of Low-Temperature and High-Temperature Fuel Cells for U.S. Department of Defense (DOD) Aircraft (in onboard and off-board applications)

General Technology Issues

- Fuel cost, durability, and robustness to use JP-8 and other existing military fuels
- Hydrogen cost
- Hydrogen storage, in terms of both cost and packaging with aircraft or ground support equipment (GSE)
- Off-board applications, such as GSE: no hydrogen refueling infrastructure at air force bases (AFBs)
- Where hydrogen refueling infrastructure exists, low infrastructure utilization without a cluster of products using the hydrogen
- Lifetimes—mean time between failures
- Time it takes to get to full power
- Management of waste heat
- Weight
- Coking (hydrocarbon fuels)
- Fuel flexibility
- Materials and joining
- Management of coolant water and effluent water
- Carbon dioxide capture (hydrocarbon fuels)
- Availability of commercial products (Technology Readiness Level = 3–4 for solid oxide fuel cells (SOFCs) and 6–8 for polymer electrolyte membrane [PEM] fuel cells)
- Competitiveness against other energy technologies
- Balance of plant (BOP) issues
- Inverter efficiency
- Hybrid systems—two fuel cells (PEM and SOFC)
- Ability of PEM products that are successful in other early markets, such as forklifts, to provide comparable value propositions for aviation applications
- Commercial aircraft applications likely represent different needs and value propositions than military applications—galley/hoteling for commercial versus heating, ventilation, and air conditioning; load-bay door; and lighting for military
- Distributed power versus centralized power
- Aircraft (e.g., C5 and B52) and GSE lifetimes suggest retrofits of power systems may be desirable; however, ability to do retrofits presents many challenges
- Power quality
- Alternative direct current bus design needs
- Fixed wing versus rotary aircraft expertise required

Fuel Types

- Need to use existing logistical fuels such as JP-5, JP-8
- Off-board applications need to be placed strategically in order to cost-effectively use hydrogen
- Bioaviation fuels for future onboard applications

Fuel Cell Power Density Needs

- System power density—high-temperature fuel cell power density is too low to support demands for many applications

- System energy density (kilowatt-hours per kilogram) is also important

Fuel Cell Durability Issues

- Graceful degradation by design so can sustain required voltage levels
- Need to be able to support a variable quality of military fuels

Capital Cost Constraints

- Develop low-cost fuel cell manufacturing methods
- Capital costs of fuel cell versus petroleum reduction savings
- Cost: Stack materials, membrane, and electrolyte cost
- BOP cost

Air Feed Issues

- Need to perform under ambient or pressurized environments, including operation at loss of air pressure (air feed issue)
- Volcanic ash

PEM Storage Issues

- High-density hydrogen storage for high-power applications (50–100 kilowatts) (GSE)
- Need to store hydrogen at an energy density greater than liquid energy density
- Need to leverage hydrogen infrastructure off-board costs with other applications (e.g., airport shuttle buses)
- Heat release problem if metal hydride used for hydrogen storage

Safety, Codes, and Standards Needs

- Export markets (e.g., Korea and Japan)
- Determine certification and approvals needed to have high-pressure hydrogen on an aircraft
- Power quality MIL-704F
- Federal Aviation Administration certification

Feedstock Purity Issues

- Heavy metals (e.g., lead) tolerance
- Sulfur tolerance
- Do not assume biofuels are “clean”

Table C.2. Analysis, Research, Development, and Deployment Needs *[and leadership responsibility: DOD, U.S. Department of Energy (DOE), and/or Industry]*

Key Gaps	Actions Needed
• Need life-cycle cost/benefit analysis, emissions reduction analysis, and petroleum savings analysis for fuel cell product applications and, where appropriate, fueling infrastructure for auxiliary power units (APUs) and ground support equipment (GSE) for Air Force base (AFB) applications *[DOE]* • Improve fuel reforming tolerance of fuels to levels that can support high sulfur levels and conduct demonstrations using logistics fuels to confirm/validate tolerance *[DOD, DOE, Industry]* • Complete further analysis of bioaviation fuels, including demonstrations *[DOD, DOE, Industry]* • Develop capability for flight testing for onboard APUs *[DOD]* • Identify key performance parameters for onboard APUs *[DOD]*	• Identify best opportunities for aviation fuel cell applications, beginning with GSE and other airport off-board applications and move to more complicated product applications via staged implementation process that is built on successful demonstrations or deployments *[DOD, DOE, Industry]* • Assess potential for Tyndall AFB and McChord AFB to be early-stage sites by benchmarking air base ground power current utilization *[DOD]* • Perform additional research on high-temperature fuel cell APUs to better identify requirements for improvements to power density and other key performance requirements *[DOD, DOE]* • Perform laboratory-scale testing of low-temperature and high-temperature fuel cell APU systems [DOD, DOE] • Review the long-term (10-year) Product Plan for military aircraft at all services to identify aircraft platforms to be candidates for target onboard applications, including retrofit opportunities [DOD] • Ensure results of previous Air Force Research Laboratory, TACOM, and Construction Engineering Research Laboratory APU projects are well-documented, evaluated, analyzed, etc. *[DOD]* • Complete further analysis of fuel cell shock/vibration tolerance *[DOD]*

Appendix D. Acronyms and Abbreviations

AFB	Air Force base
AFRL	Air Force Research Laboratory
AIP	Federal Aviation Administration Airport Improvement Program
AIR-21	Wendell H. Ford Aviation Investment and Reform Act for the 21st Century
AMC	Air Mobility Command
ANG	Air National Guard
APU	auxiliary power unit
BOP	balance of plant
Btu	British thermal unit
CARB	California Air Resources Board
DDG	guided missile destroyer
DESC	Defense Energy Support Center
DLA	Defense Logistics Agency
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	U.S. Department of Energy, Office of Energy Efficiency and Electricity Reliability
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FCHEA	Fuel Cell and Hydrogen Energy Association
FCT	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program
FY	fiscal year
GSE	ground support equipment
ICE	internal combustion engine
ILEAV	inherently low-emissions airport vehicle
JFTB	Joint Forces Training Base
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
MOU	Memorandum of Understanding
MW	megawatts
NASA	National Aeronautics and Space Administration
NOx	nitrogen oxide
ONR	Office of Naval Research
PEM	polymer electrolyte membrane
psi	pounds per square inch
RD&D	research, development, and deployment
SNL	Sandia National Laboratories
SOFC	solid oxide fuel cell
TARDEC	U.S. Army Tank Automotive Research, Development, and Engineering Center
USAF	U.S. Air Force

USDA	U.S. Department of Agriculture
VALE	Voluntary Airport Low Emission
W	watt
WG	working group

Appendix E. List of Participants

Name	Organization
Mike Aimone	Battelle
Paul Bakke	U.S. Department of Energy (DOE), Office of Commercialization and Project Management
Joe Breit	Boeing
Valarie Browning	Defense Advanced Research Projects Agency (DARPA)
Richard Carlin	Office of Naval Research
John Christensen	National Renewable Energy Laboratory (NREL)
Ruth Cox	Fuel Cell and Hydrogen Energy Association (FCHEA)
Pete Devlin	DOE, Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Program (FCT)
Maj. Michelle Ewy	U.S. Air Force (USAF)
Rick Farmer	DOE/EERE/FCT
Stu Funk	LMI Government Consulting
John Garbak	DOE/EERE/FCT
Nancy Garland	DOE/EERE/FCT
Leo Grasilli	Navy consultant
Thomas J. Gross	LMI Government Consulting
Bill Haris	Army Tank Automotive Research, Development and Engineering Center (TARDEC)
William E. Harrison	Air Force Research Laboratory (AFRL)
Fred Joseck	DOE/EERE/FCT
Henry Kelly	DOE/EERE, Office of the Assistant Secretary (Acting Assistant Secretary)
Richard Kidd	DOE, Federal Energy Management Program
Hyun Kim	National Aeronautics and Space Administration (NASA)
Lennie Klebanoff	Sandia National Laboratories (SNL)
Jaime Link	DOE/EERE, Office of the Assistant Secretary
Jason Marcinkoski	DOE/EERE/FCT
Srini Mirmira	DOE, Advanced Research Projects Agency-Energy (ARPA-E)
Greg Moreland	SRA International
Jonathan Morris	Office of the Secretary of Defense
Bryan Pai	SRA International
Dimitrios Papageorgopoulos	DOE/EERE/FCT
Donald Phelps	Office of the Secretary of Defense

Name	Organization
J.W. Pratt	SNL
Peter Protopappas	SRA International
Carole Read	DOE/EERE/FCT
Thomas L. Reitz	AFRL
Michael Resner	Office of Naval Research
Mike Rinker	Pacific Northwest National Laboratory
Sunita Satyapal	DOE/EERE/FCT
James Short	Office of the Secretary of Defense
Dan Shumaker	SRA International
Marcus Smith	AFRL
Sam Tam	DOE, Office of Fossil Energy
Robert Wichert	FCHEA
Joseph Wong	DOE, Office of Fossil Energy