Aerospace Power Technology for Potential Terrestrial Applications

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Abstract—**Aerospace technology that is being developed for space and aeronautical applications has great potential for providing technical advances for terrestrial power systems. Some recent accomplishments arising from activities being pursued at the National Aeronautics and Space Administration (NASA) Centers is described in this paper. Possible terrestrial applications of the new aerospace technology are also discussed.**

Index Terms— Batteries, Energy storage, Flywheels, Fuel cells, Hydrogen storage, Power system simulation, Solar energy, Solar power generation, Space technology, Stirling engines.

I. Introduction

THE National Aeronautics and Space Administration's (NASA) Lewis/Glenn Research Center has a long, impressive history in power generation, energy conversion, energy storage and power management and distribution research and development for aerospace missions. Power is a very critical part of every NASA mission, especially since 20-30 percent of a spacecraft's mass is the power system and it can be 20 percent of the cost. Efforts to reduce the mass and cost of spacecraft power systems have led to many innovations. Many technology benefits from this work have already been incorporated into terrestrial systems, and many more are under development [1].

II. Space Power Technologies

A. Power Generation

Fig. 1. Concentrator solar array preparing for installation on a spacecraft.

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Power generation for space missions is often from solar energy. Much work has been done at NASA to develop highly efficient (currently over 30% efficient) solar cells for missions where solar energy is sufficient for supplying mission power. Concentrator solar arrays which focus the sun's rays onto the active solar cell area enable space missions to use solar power farther from the sun where solar intensity is very weak. While space solar cells are very efficient, but very expensive for terrestrial use, concentrator technology can benefit terrestrial solar power by enabling smaller active areas of solar cells, reducing the size of the expensive portion of the solar power system. A prototype terrestrial concentrator system is being developed in a collaborative project between NASA Glenn and Greenfield Solar of Oberlin, Ohio. NASA engineer, Bernard Sater, invented a high temperature solar cell capable of operating efficiently using highly concentrated sunlight and when combined with a sun-tracking concentrator, produces an inexpensive, clean source of electricity and is now being installed in prototype ground power generation sites [2].

Fig. 2. Greenfield Solar concentrator system using innovative, proprietary high temperature solar cells to generate electricity.

For deep space missions and applications where there is not enough solar energy, NASA uses nuclear power. One nuclear space power system converts heat generated from nuclear fuel to electricity using Advanced Stirling Radioisotope Generators, which are being developed at NASA Glenn Research Center in collaboration with the Department of Energy. Technology to enable space fission reactor systems is also being developed and studied for future application to high power missions.

Power generation technology developed at NASA has not been limited to space systems. In the past, NASA Lewis pioneered the development of wind turbines, producing the first mega-watt class wind turbines that were the foundation for today's large terrestrial wind farms. NASA's solar array technology was also used in the 1970's to power remote villages in 58 countries around the world.

B. Energy Conversion

Space systems produce power by converting heat energy (eg. solar, chemical, or nuclear) into electricity. A recent success story is the development, in collaboration with SunPower of Athens, Ohio, of an Advanced Stirling Radioisotope Generator for use in space power systems, which is a factor of four times more efficient than previous thermal energy conversion systems, enabling a greatly reduced requirement for space nuclear fuel (the rare Plutonium 238) for deep space missions [3], [4].

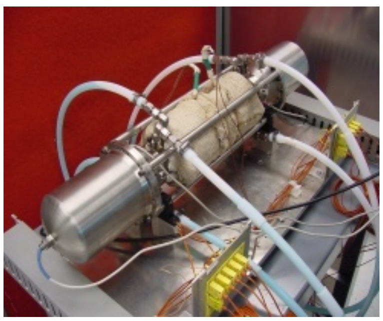

Fig. 3. Two free-piston Stirling convertors on test at the NASA Glenn Research Center.

This technology has great potential for terrestrial applications where a more efficient method for producing electricity from heat sources would have great benefits. One new product is a combined heat and power system which uses heat from a gas furnace to provide heat to a Stirling convertor, which would then produce electricity.

C. Energy Storage

Space power systems rely on many forms of energy storage devices. Batteries are critical to many applications from spacecraft and rovers to astronaut hand tools. While great strides are being made in the terrestrial community to improve energy density by investigating new battery chemistries and improved materials, NASA is working to assure safe and reliable batteries are developed for space missions. NASA is developing High Energy (HE) and Ultra High Energy (UHE) advanced lithium-ion (Li-ion) cells with the goals of attaining specific energies of 180 watt-hours per kilogram (Wh/kg) and 260 Wh/kg, respectively, when measured at C/10 and 0 degrees (°C), in cells that are inherently safe. The HE cell goals are being addressed through the development of advanced cathode components, flame retardant electrolytes, safety devices, and optimized cell designs. The newly developed components will be combined with a commercial graphite anode that can achieve a specific capacity of 330 milliampere-hours per gram (mAh/g) at C/10 and 0°C and a commercial battery-grade separator to comprise the HE cell design. The UHE cell goals will be achieved through the development of advanced anodes and combining them with the cathode, safety device, and separator utilized in the HE cell. A flame retardant electrolyte specially formulated to be compatible with the advanced anode will be used in the UHE cell design. Background information on the cell chemistries, their components, and cell designs are documented in papers by Reid and Bennett and by Reid [5], [6].

Fuel cells, which were originally developed for NASA's Project Gemini, can be considered both a power generation device and a method of energy storage (in the form of the chemical energy storage in the fuel cell's "fuel tank"). NASA has continued to support the development of fuel cell technology over many decades, following a defined roadmap that consistently focuses on the requirements most important to aerospace applications. As a means of minimizing the investment required, NASA tries to use technology already developed for commercial applications. However, since the human space flight program offered the first truly economical and very advantageous application of fuel cells, NASA, at the time, found little commercial work upon which to build. However, in the mid-1990's, interest in "Green Energy" and "The Hydrogen Economy" led to an enormous increase in investment in fuel cell development, at a level dwarfing that of NASA by a good two orders of magnitude. As much of this commercial investment is focused on the proton exchange membrane (PEM) or "hydrogen" fuel cell, one might presume that NASA could, certainly after ten years of this massive program, find the power plants we need off the shelf. This is completely untrue. The differences in requirements between the human spaceflight program and almost all commercial applications, including cars, drive fundamental design differences down even to the level of the catalyst lay-up in the membrane electrode assemblies (MEAs) [7]. So, NASA has continued to use and improve fuel cells for their aerospace needs and most recently (2011) won an R&D 100 award for an innovative non-flow-through fuel cell which greatly reduces the size, while tripling the power output, of a proton exchange membrane (PEM) fuel cell system [8]. These improved aerospace fuel cell systems have some features (such as the award-winning patented balance of plant design) that can be advantageous to terrestrial applications [9].

Solid oxide fuel cells, which require high temperature operation, are also of interest in applications where hydrogen and oxygen may not be available, or other fuel choices are the best for the application. Solid oxide fuel cells (SOFC) have potential for a number of industrial and NASA applications, because of their high energy efficiency. NASA applications for SOFCs include auxiliary power units for commercial airlines, power sources for high-altitude drones, and reversible fuel cells to electrolyze water and generate power for lunar satellites and space stations and to electrolyze carbon dioxide to produce oxygen for a Mars mission. A key advantage of SOFCs is that they can be sulfur tolerant, so they can operate on any hydrocarbon fuel, most of which contain some level of sulfur. The higher the temperature, the greater is the efficiency and power output of a fuel cell. SOFCs have the potential to operate at high temperatures, from 600 to 1000 °C. However, the majority of industrial SOFC designs contain a metal interconnect between the ceramic cells that limits the operating temperatures to 600 to 700 °C. Operation at low temperature makes it more difficult for conventional SOFCs to meet the high specific power density (kilowatts per kilogram) requirements of NASA and industry applications. For example, a Boeing study sponsored by the NASA Glenn Research Center determined that a commercial jet auxiliary power unit requires an SOFC specific power density of 1.0 kW/kg. Present state-of-the-art SOFC developers are struggling to attain power densities of 0.1 kW/kg. An order-of-magnitude improvement in performance must be achieved. NASA Glenn has developed a novel fuel cell and fuel cell stack design that is ideally suited to high temperatures and can achieve the high specific power densities required for aeronautics applications. Glenn has developed both a novel cell design and a novel ceramic fabrication technique that has a predicted specific power density of 1.0 kW/kg. This design is called a bielectrode-supported cell (BSC). It has both low volume and low weight. The BSC uses a thin ceramic interconnect rather than a metal interconnect, which makes it ideally suited to operate at high temperatures, in the 800 to 1000 °C range. Higher operating temperatures allow the BSC to take advantage of higher power density and higher efficiency, and thus make it suited for reversibility applications, such as water and carbon dioxide electrolysis, and for sulfur tolerance.

One other aspect of the Glenn design that is critical for many NASA applications is that fully hermetic seals can be fabricated. Because the BSC all-ceramic design allows multiple cells, with seals, to be built into a stack using low temperature assembly techniques, followed by a high-temperature sintering of the ceramic stack and seals, the product is a hermetic stack that can be leak tested prior to its application. No other design has this advantageous feature. Previous SOFC technology that was evaluated for NASA lunar and Mars missions failed because of leaking seals. We believe that Glenn's technology can be developed to deliver a stack with hermetic seals [10].

Another promising energy storage technology is flywheels. Researchers at NASA's Glenn Research Center in Cleveland -- in collaboration with several other organizations, including Northrup Grumman Space Technologies, University of Texas Center for Electromechanisms, Texas A&M University, University of Toledo and Lockheed Martin -- have developed flywheel energy storage systems using composite rotors that operate at 60,000 revolutions per minute, which works out to nearly 2.5 times the speed of sound. Glenn Research Center has specialized in magnetically suspended flywheels which do not have mechanical friction or wear mechanisms. The combination of high strength composite wheels with magnetic suspension enables high specific energy with long life and low sensitivity to environmental temperature variation. These features make them an ideal candidate for replacing rechargeable chemical batteries on future spacecraft. Flywheels are especially beneficial for spacecraft since they provide not only energy storage, but also spacecraft attitude control – replacing the momentum wheel system and saving mass. Flywheel specific energy is limited by the strength/density ratio of the rotor material de-rated for safety and life. The effective system specific energy is reduced by the mass of the motor/generator, power electronics and other supporting components. Flywheel specific energy and specific power improve as the system gets larger. Small flywheel systems (1-2 kW-hr) using carbon fiber materials usually have a system (all components required to provide a regulated DC power output) specific energy in the range of 35-75 W-hr/kg. New rotor materials are being developed incorporating nanotubes to improve the baseline strength and fatigue strength. Carbon nanotubes can have strengths as high as 200 GPa, compared to presently used carbon fiber which has a strength of up to 6 GPa. Currently nanotube fibers a few inches long with these mechanical properties have been produced, so we are many years away from realizing these strengths at the production levels required to build a flywheel rotor and developing the supporting components to work with such a high energy flywheel. The potential specific energy for highly advanced flywheels using carbon nanotube fibers being developed is beyond 1000 W/hr/kg.

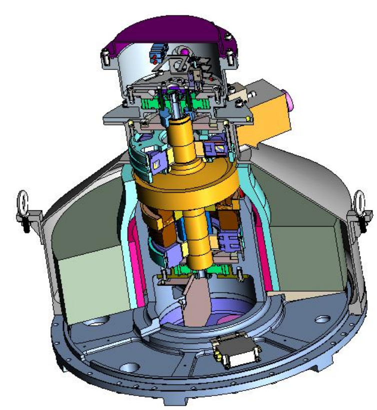

Fig.4. Cross section of a flywheel which uses an advanced composite rotor and magnetic bearings to safely achieve high rotation speeds (50,000 rpm) for high energy density storage capability.

D. Power System Architecture and Engineering

NASA is currently designing power systems for the next generation of spacecraft, rovers, launch systems and other space applications. System integration, power quality specification development, performance modeling and test bed development for a 120-volt system architecture is underway. Currently, electrical power on spacecraft is distributed by direct current (DC) at fixed voltages ranging from 28V DC to 120V DC. The International Space Station (ISS) is unique with its 120V DC distribution architecture [11].

Fig. 5. International Space Station solar arrays all together are nearly the size of a football field, powering the largest space power system ever flown in space.

As NASA's science and human exploration missions of the future are examined, the need for significant increases in electrical power on spacecraft becomes clear. With these higher power levels, an extrapolation of the current technologies for power management and distribution (PMAD) would result in unacceptably high mass and complexity. PMAD on a space system uses copper cables and connectors. As higher power systems are developed, higher voltage distribution will be required to avoid very heavy wire bundles. This can be done with either DC or alternating current (AC) architectures. Paschen's law limits high-voltage DC systems to a maximum of about 270 V DC. Therefore, high power levels will require more attention to AC systems, probably at relatively high frequencies. The demand for lower mass will challenge the traditional copper materials for the bus, and the need to operate at higher temperatures (to increase the efficiency of the thermal management systems as well as electronics efficiencies) will conflict with the need to reduce ohmic losses in transmission lines. With DC currents, to reduce the mass penalty of larger cables, alternate materials such as superconductors or nano-material conductors may need to be developed, along with lighter space-qualified insulating materials capable of protecting systems at high voltage. With AC power systems, advancing beyond the 116 V AC system in the space shuttle may require very high operating frequencies; for example, NASA funded development of a 440 volt, 20 kHz AC power system for Space Station Freedom until it was reconfigured to use a DC power system [12]. Technical needs include keeping transmission losses to a minimum, reducing transformer masses, incorporating fault protection and smart telemetry into power distribution architectures, and developing new connectors.

The nature of future missions will dictate the architecture and technologies used for vehicle power systems, and that, in turn will define the requirements for the PMAD system. For example, the electrical power from a nuclear reactor-turboalternator system will likely be high-voltage AC, while power from photovoltaics is always generated as a D.C. voltage. If electric thrusters are needed for the mission, very-high-voltage DC power (kilovolts) will be required, perhaps from a nuclear prime-power source.

The voltage and current of electrical power available on any particular spacecraft will be dictated by the power source and the power management and distribution architecture. Various payloads will then most likely require the power in a different form, such as higher voltage for electric propulsion. The purpose of electrical power conversion and regulation is therefore to provide the necessary bridge between the power source and payloads, and to regulate this power to within the tolerances required by the payloads. In order to take advantage of recent advances in non-aerospace power technology, NASA will need to (1) space qualify existing terrestrial high-voltage components and (2) replace space qualified components that currently lag significantly behind the commercial state of the art. Important parameters for improving power conversion and regulation devices include increasing conversion efficiency, operating temperature range, and radiation tolerance. The need for high-voltage regulation is also associated with some electric propulsion technologies that require high voltages (kilovolts) to function. Development of high-voltage regulation capabilities would require a major project that includes the development of many new technologies and facilities. An example of advanced conversion and regulation technology is a higher band gap material such as silicon-carbide or gallium-nitride that would replace the traditional silicon materials in switching components, thereby increasing device operating temperature and efficiency while decreasing mass and volume. Another example is advanced magnetics for improved conversion and regulation devices. NASA is currently developing power convertors, switchgear, and modular hardware systems for fully autonomous power management and distribution systems. Some goals include producing 300-400 W/kg power converters at 1 kW power levels; solid state and hybrid switchgear capable of operating up to 600 volts; reconfigurable modular hardware and "smart" electronics [12]. The development of these technologies could also enable more efficient future terrestrial smart grid power systems.

E. "Green" Technologies

A power system demonstration is being studied which would provide a test bed for advanced power technologies at NASA Glenn. A "smart grid" demonstration would include solar arrays, fuel cells, wind turbines, flywheel and battery energy storage systems, and Stirling convertors connected with innovative power management and distribution technology. This system could be used to study technology advances for use in both space and terrestrial power systems.

The heart of the smart grid demonstration is a GreenLab Research Facility [13] which is envisioned to be a self-sustainable renewable energy ecosystem focusing on global food, fuel, water, and energy shortages and solutions [14]. Researchers at NASA Glenn are studying halophytes (salt-loving plants) to determine their growth characteristics in various environments that vary in local water salt-content. The facility has salt-water tanks that simulate the Floridian coast, for example, and experiments are performed to determine the capability for halophytic plants to flourish in that environment. These plants can be used for food, bio-fuel, or land protection to prevent soil run-off and erosion problems [15]. The facility itself has grow-lights partially powered by wind turbines and will soon be connected to a field of solar panels nearby (panels previously used in the 1970's to develop the solar power system for the International Space Station). In the past few years, NASA had a project to study the halophytes as a feedstock to make prototype bio-fuels since they have high lipid content and are good candidates for producing high quality aviation fuels [16].

Fig. 6. Salt-water tanks with varying degrees of salinity provide simulated environments to grow halophytes for research purposes in NASA Glenn's renewably-powered GreenLab Facility.

NASA is working with some industry partners to produce a home power unit fueled by natural gas to produce electricity and use the excess heat for domestic hot water and home heating. The NASA GRC will provide the expertise for developing the Stirling power convertor which is the centerpiece of the unit. The design is based on a Stirling Duplex concept that was developed to provide power and cooling on the surface of Venus. The new patent-pending technology has no moving parts and is predicted to provide high efficiency.

Another green energy project which NASA is currently supporting is the installation of Ohio's first electrolysis-based hydrogen fueling station. Previous financial support came from the Cleveland Foundation for this project which seeks to establish a fueling station at a Cleveland Regional Transit Authority site which will be used to fuel a fuel-cell powered bus to be used in a revenue-generating route in 2012 [17].

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IV. Biography

Valerie Lyons (AIAA Associate Fellow) graduated from Rensselaer Polytechnic Institute, Troy, New York, with a BS in Aeronautical Engineering, MS Aerospace Engineering from the University of Michigan and a Ph.D. in Mechanical Engineering from the University of California- Berkeley.

She has worked at NASA's Lewis/Glenn Research Center for over 35 years. She is currently the Chief of the Power and In-Space Propulsion Division where she leads the research and development of advanced space power and propulsion systems. Her past research in combustion science and laser diagnostics led to the reduction of gas turbine combustor emissions for aircraft. Dr. Lyons has been selected as a Cleveland Crain's Business "Woman of Note" and has been inducted into the Ohio Women's Hall of Fame for her contributions to NASA and the community.