SOLAR POWER FOR FUTURE NASA MISSIONS

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ABSTRACT

An overview of NASA missions and technology development efforts are discussed. Future spacecraft will need higher power, higher voltage, and much lower cost solar arrays to enable a variety of missions. One application driving development of these future arrays is solar electric propulsion.

1. INTRODUCTION

In looking to the future NASA seeks to develop technologies that can transform future missions, enable new capabilities, or significantly alter current approaches. Power availability can limit almost all aspects of a space mission from payloads, propulsion and communication systems to life support and surface mobility for human space missions. Components in power systems also degrade over time impacting space mission operations. Technical solutions that provide an abundance of power through a robust infrastructure, such as terrestrial power systems, would significantly change the options for human space exploration and enable expansion of the payloads of robotic missions.

Driving metrics for assessing power generation technologies are watts per kilogram and dollars per watt. A enabling factor for large power systems would be the utilization of space photovoltaics as a terrestrial power source. Current space power systems are focused on the watts per kilogram. Basic research in photovoltaics is focused on material identification, characterization, interfaces and degradation mechanisms while latter-stage development seeks to improve efficiency, reduce cost, and increase life expectancy. With continued incremental development via new materials and manufacturing techniques, solar cells may become relatively inexpensive, light, and versatile enough to be integrated into all structures, fabric, vehicles, sensors, and other exploration systems - serving a multifunctional purpose of providing primary power as well as other possible applications. Space faring nations are looking at applications such as a multifunctional solar sail and cells, and inflatable structures to provide solar power for microsatellites

2. NASA MISSIONS AND TECHNOLOGY DEVELOPEMENT

2.1 The Asteroid Redirect Mission

The Asteroid Redirect Mission (ARM) mission is a concept under study by NASA that would - for the first time - capture and relocate a 7-10 meter diameter, ~500,000-kg Near Earth Asteroid (NEA) to high lunar orbit. The capture, transportation, examination and dissection of an entire NEA would provide valuable information for planetary defense and a unique, meaningful and affordable destination for future robotic and human exploration.

The feasibility of ARM is enabled by three key developments: the ability to discover and characterize an adequate number of sufficiently small near-Earth asteroids for capture and return; the ability to implement sufficiently powerful solar electric propulsion systems to enable transportation of the captured NEA; and the proposed human presence in cis-lunar space in the 2020s enabling exploration and exploitation of the returned NEA. [1] An illustration of the proposed mission concept can be seen in Fig. 1.

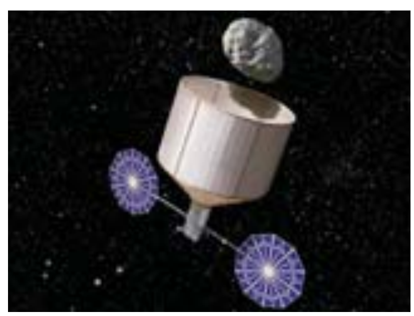

Fig. 1 An artist's concept of the proposed Asteroid Retrieval Mission.

2.2 Missions Involving Extreme Environments

NASA operates photovoltaic arrays in extreme environments of temperature, radiation, and high or low intensity. Current NASA missions using solar arrays in missions to the near-Sun environment includes the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission [2], which was launched in 2004, and has been successfully operating in Mercury orbit [3] for over three years. Missions to the low-temperature, low intensity environment (LILT) farther from the sun include the DAWN mission, launched in 2007 to the asteroids Ceres and Vesta. This spacecraft has two 18-m^2 solar arrays, which produce 10.3 kW at Earth orbit, 1 Astronomical Unit (AU) from the sun, and 1.3kW at their end of life, in orbit around the asteroid Ceres orbit at 3 AU from the sun [4]. Another mission currently in progress is the Juno mission, launched in 2011. It is currently about 4.5 AU from the sun, and is expected to reach orbit around Jupiter (at 5.2 AU from the sun) in 2016. At that point, it will break the record set by the Rosetta spacecraft as the greatest distance from the sun achieved by any spacecraft operating on solar power. In order to operate at Jupiter, the solar cells were screened for LILT operation [5]. The Juno spacecraft uses three solar arrays symmetrically arranged around the spacecraft. With a total area of 60 square meters, these will the largest arrays ever used on a NASA mission other than the Space Station. The arrays can produce over 12 kW at 1 AU, and 486 W at arrival at Jupiter, decreasing to 420 W at end of life.

Meanwhile, the Mars Exploration Rovers mission continues to operate a solar powered rover, Opportunity, in its eleventh year, demonstrating long-duration operation of photovoltaic arrays in the low-temperature, dusty environment on the surface of Mars [6].

Future NASA missions will extend the operation of photovoltaic arrays into even more extreme environments. A mission currently in development for launch in 2018, Solar Probe Plus, will extend the range of photovoltaic power to the near-Sun environment, operating at a distance of only 9.5 solar radii from the sun [7]. In the opposite extreme, the upcoming Europa Clipper mission [8] is evaluating the use of both radioisotope and photovoltaic power systems for use in Jupiter orbit. Use of high-power solar arrays, at power levels ranging from ~500 KW to several megawatts, has been proposed for a solar-electric propulsion (SEP) demonstration mission, using a photovoltaic array to provide energy to a high-power xenon-fueled engine. One of the proposed applications of the high-power SEP technology is a mission to rendezvous with an asteroid and move it into lunar orbit for human exploration (the Asteroid Retrieval mission). NASA is also exploring options for future power systems for extreme environments, including near-sun environments, solar electric propulsion [9], and operation on the Venus surface [10].

2.3 Solar Electric Propulsion

The Solar Electric Propulsion (SEP) project is dedicated to developing critical technologies to enable trips to further away destinations such as Mars or asteroids. NASA seeks to reduce the cost and complexity of these ambitious exploration missions. High power and high efficiency SEP systems will require much less propellant to meet those requirements. The new system will use xenon propellant energized by electric power from solar arrays and use 10 times less propellant than a chemical propulsion system like the engines on the space shuttle.

Large solar arrays and high power thrusters are being developed for future space launches. Compared with current systems, they will launch one-half the weight with one-quarter of the storage for electricity produced, and will be able to withstand four times the radiation. SEP solar arrays must stow into very small, lightweight packages for launch and then unfurl to cover a very large area to capture enough solar energy to produce high levels of electrical power. They also need to be durable so that they can operate for a long time in places like low Earth orbit (LEO) and the Van Allen radiation belt. SEP also uses electrostatic Hall thrusters instead of a chemical rocket engine. A Hall thruster uses electricity from a solar array to emit electrons from an external cathode.

NASA Glenn Research Center, GRC, currently has several programs to advance near-term photovoltaic array development. One project is to design, build, and test two 20 kW-sized deployable solar arrays, bringing them to technology readiness level (TRL) 5, and through analysis show that they should be extensible to 300 kW-class systems (150 kw per wing). These solar arrays are approximately 1500 m^2 in total area which is about an order-of-magnitude larger than the 160 m^2 solar array blankets on the International Space Station. The project addresses the most-challenging aspects of developing deployable solar array structures, including aspects related to: compact stowage, reliable deployment, high deployed strength and stiffness, robustness to dynamic docking and maneuver loads, modularity, reusability, and ground validation. The performance goals were 1. .1g in all axes; 0.1 Hz; 2. GEO-like thermal design; 3. Photovoltaic blankets to support 160 to 300 VDC power bus and operation near an electric thruster plume. The expectation is that these arrays can go straight to flight qualification or protoflight units and that they can scale to different power levels and mission requirements, e.g. can use triple junction (TJ), inverted metamorphic (IMM), LILT and/or high intensity high temperature (HIHT) solar cells. The NASA project team has verified the structural strength and stiffness of these new arrays while contractors provided ground tests of key aspects of the solar array structural systems developed in this project.

Alliant Technical Systems, ATK, was selected in 2012 by NASA's Space Technology Program under a Game Changing Technology competition for development of a promising lightweight and compact solar array structure. The MegaFlex™ engineering development unit, EDU, was tested at NASA GRC Plumbrook facility this year. See Fig. 2 for the ATK deployment of the demonstration unit.

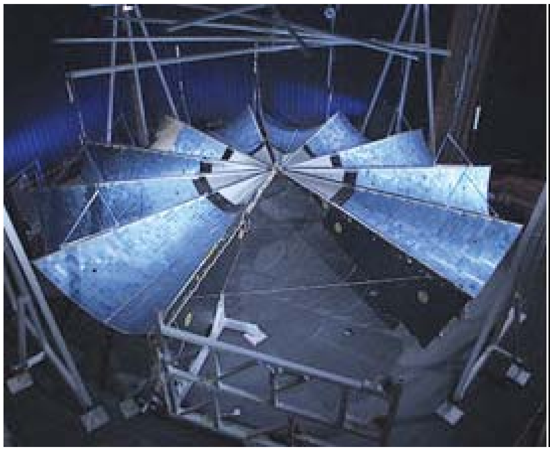

Fig. 2 ATK EDU deployment validation

The unit employs an innovative spar hinge to reduce stowed volume. Deployment is achieved in three stages: release from the spacecraft, unfolding the hinge, and rotating the wing. A single lanyard and motor operates the last two stages. The EDU is 10m in diameter and able to provide ~20kW BOL with TJ cells.

Similarly, Deployable Space System, DSS, developed a roll-out array, ROSA, EDU that employs an innovative stored strain energy deployment to reduce the number of mechanisms and parts. The elastic structure maintains stiffness throughout deployment for partially deployed power generation. The rectangular design can be configured in many ways by either lengthening the booms, adjusting the length and width, or attaching several winglets onto a deployable backbone. Lengthening and/or shortening the booms provides power scaling without changing any of the subsystems or stowed configuration. See Fig. 3 for a fully deployed ROSA array.

Fig. 3 Fully deployed ROSA array

2.4 NASA Small Business Innovative Research (SBIR) Awards

In the quest for reducing costs of solar arrays NASA has supported multiple efforts via SBIRs. Several projects have addressed the concern of using high efficiency, space-qualified solar cells that are costly, ~$225/W, plus the cost associated with the large number of piece-parts and labor needed to assemble the cells into the photovoltaic, PV, blanket. One approach was to utilize a thin film technology, such as copper indium gallium selenide, CIGS, in combination with a flexible cover glass replacement [11].

Other programs focus on advanced modular photovoltaic systems. Ideally there would be high efficiency cells to deploy on a modular array at a low cost. There are multiple ways to approach this goal. Recent advances in manufacturing of Inverted Metamorphic Multi-junction (IMM) solar cells have opened new opportunities to improve device performance. By virtue of removal of the epitaxial substrate, IMMs display significant increases in specific power and the resulting product has improved power conversion efficiency and lowered overall stowed weight compared to traditional multi-junction cells. Furthermore, efficient removal and reuse of the substrate during high specific power, multi-junction solar cell manufacturing can lead to significant savings [12]. The potential to utilize such cells in flexible arrays has opened up many array configuration opportunities including the arrays discussed for SEP. Additionally if the automation of the semiconductor industry could be employed then there would be substantial cost reductions.

Some of the same problems face these high specific power arrays independent of cell type. There must be a robust system to provide electrical integration, lamination, and encapsulation. The ability to reduce costs requires economical automated array integration processes that have environmental durability. The semiconductor manufacturing industry offers many high throughput processes that have been in use for decades and can perform wire bonding, fluid dispensing, solder reflow, visual recognition and component placement. The difference between the photovoltaic world and the normal semiconductor processing world is related to size. One could envision however that many of the automated semiconductor processing steps could be adapted to photovoltaic arrays and to some extent these processes have been used in terrestrial solar panel manufacturing. The extra requirement for space arrays has to do with the durability in the space environment.

One place where the semiconductor market can provide significant assistance is the idea of integrating a power management and distribution, PMAD, system within the array itself. With higher power and larger area space solar arrays the ability to control voltages and current flows to protect the net power collection efficiency becomes important. These “smart” arrays would be able to cope with damage from micrometeoroids or environmental degradation including temperature swings in orbit and eclipses.

Cell material and device structure options for these future arrays have grown significantly in the past decade. Part of this is due to an ever increasing number of methods to release III-V epitaxial layers from their substrates. Wafer scale "peel off" processing has been demonstrated by a number of industry and academic research groups; others include "dissolvable" or "dry" methods. It would also be possible to either stack or bond a III-V multi-junction cell with a thin film cell for a higher efficiency combination. Again this is an area where the semiconductor industry excels. Indeed, we even find ourselves exploring a path to 40% efficient silicon single junction cells [13]. A variety of nano-structured cells and coatings could be envisioned. The potential low costs and reproducibly high-precision of Si-based nanostructured cells would allow for plug-and-play array solutions to be developed.

The models and tools for simulation and analysis has also been the target for NASA SBIRs. The capability to determine the technical feasibility of proposed new concepts will certainly be an asset for evaluating new technologies. This would be particularly true for improving the Si solar cell radiation tolerance for space use. Recent theory has predicted that the Yablonovitch limit does not hold in very thin absorbing layers [14]. This improved light-trapping permits development of radiation hardness-enhanced ultra-thin silicon solar cells.

3. THE FUTURE

There is a great deal more to consider in looking at longer term projections for space solar cells. Nano-structured designs including light trapping and plasmonic coatings, as well as new materials. It is difficult to predict the ultimate efficiencies for hybrid organic/inorganic and perovskite cells, for example. We also find ourselves re-examining old materials in new ways and combining materials in new ways. Breathtaking new materials processing and device design options have re-invigorated space photovoltaics for future space exploration.

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