Powering Space Exploration

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On both terrestrial and non-terrestrial planets, and the space between, human technology thrives using a well-known power: solar energy. This executive briefing probes photovoltaic technologies used in space exploration, highlighting advancements like the use of more efficient gallium arsenide in solar cells.

Solar Cells in Space Exploration

Solar electric propulsion (SEP) is a means of creating in-space thrust for spacecrafts using solar cells to create electric power. SEP provides high fuel economy, albeit at a lower thrust, than traditional chemical propulsion (e.g., NASA's Space Shuttle or SpaceX's Dragon capsule). As a result, solar cells provide power for spacecraft with ten times less fuel requirements. Less fuel means less weight, which significantly reduces launch costs or frees up capacity for non-fuel related cargo or equipment.[1] SEP is currently used on unmanned spacecraft as far out into space as Jupiter, a practical restriction caused by solar panels generating less energy as they travel further from the sun (solar energy diffuses over distance).[2]

Figure 1: NASA's Juno Spacecraft

Source: NASA*, Accessed December 30, 2023*

NASA's Juno spacecraft, a probe sent to explore Jupiter, uses 18,698 silicon and gallium arsenide solar cells, organized in three, nine-meter-long solar arrays to provide 500 watts of power at Jupiter (the same solar cells would provide 14kW at Earth due to greater solar energy) (figure 1).[3] Spacecraft, like Juno, typically only need 300W to 2.5kW to power the required systems.[4] Other examples of spacecraft that used or currently use solar cells are the International Space Station, NASA's Magellan probe to Venus, and NASA's James Webb Space Telescope, among many others.

SEP is only one technology that powers electric propulsion for spacecraft. Radioisotope power systems (RPS) use heat generated from the radioactive decay of plutonium-238 to power spacecraft designed for long-term (plutonium-238 has a half-life of 88 years), deep-space (solar cells become less effective past Jupiter) missions that would not be able to use solar cells. However, RPS has several drawbacks compared to solar cells, including limited supply, regulatory concerns, and higher relative cost. In terms of supply, the United States did not produce plutonium-238 between the late 1980s and 2011, and while NASA, in conjunction with the U.S. Department of Energy, is planning to increase production of the isotope to 1.5kg annually by 2026, there still might not be enough fuel for all planned NASA missions.[5] For example, NASA's planned Uranus Orbiter and Probe mission, originally scheduled for an early-2030s launch, may need to be delayed until the mid-2030s due to lack of plutonium-238.[6] Additionally, a Presidential Memorandum

[1] NASA, "Solar Electric Propulsion," accessed December 30, 2023.
[2] NASA, "Onboard Systems," accessed December 30, 2023.
[3] NASA, "NASA's Juno Spacecraft Breaks Solar Power Distance Record," January 13, 2016.
[4] NASA, "Onboard Systems," accessed December 30, 2023.
[5] NASA, "About Plutonium-238," accessed December 30, 2023; Foust, "Plutonium Availability Constrains Plans for Future Planetary Missions," May 3, 2023.
[6] Foust, "Plutonium Availability Constrains Plans for Future Planetary Missions," May 3, 2023.

on Launch of Spacecraft Containing Space Nuclear Systems established a multi-tier review process for missions involving spacecraft using RPS, and depending on the amount of nuclear material, they need approval from the Office of the President.[7] Lastly, plutonium-238 is a relatively costly fuel source. The Juno probe was the first Jupiter spacecraft to use solar cells rather than plutonium-238, in part because it would have required 18kg of the isotope, costing approximately $200 million.[8] Due to these limitations, NASA typically only uses RPS when necessary. NASA's Voyager 1 and 2 spacecrafts to Uranus and Neptune, as well as NASA's New Horizons spacecraft to Pluto, are examples of spacecrafts using RPS.[9]

Gallium Arsenide Solar Cells

Gallium arsenide (GaAs) solar cells are considered to be more durable than more widely utilized silicon-based solar cells.[10] In space applications, GaAs-based solar cells are more efficient than silicon-based solar cells, as they can withstand areas of elevated temperatures (temperatures in space range from hundreds of degrees above freezing to hundreds of degrees below freezing) and radiation damage more effectively.[11] GaAs cells have a wider band gap than silicon-based cells, meaning the material is more semiconductive when radiation levels are higher —one reason they are more commonly used in space applications, as well as for semiconductors.[12] GaAs-based solar cells contain layers of photovoltaic cells called multi-junction or cascade solar cells. Each layer contains a different composition and materials with different band gaps to absorb light in different spectral regions. The top layer absorbs most of the visible spectrum and the bottom layer absorbs infrared light. GaAs-based solar cells are too expensive for common use: an 8-inch diameter silicon wafer costs $5, while an 8-inch diameter GaAs wafer can cost up to $5,000.[13] Therefore, the GaAs-based solar cells have more limited applications, such as the aerospace industry.

Trade in Gallium Arsenide Wafers

Statistical reporting numbers for GaAs wafers are broken into doped and undoped – both of which are used in the fabrication of solar cells.[14] The doping process for GaAs involves adding impurities to GaAs to make the material more electrically conductive.[15] U.S. imports of doped GaAs wafers ($117.7 million) far exceeded undoped GaAs wafers ($724 thousand) in 2023 – with Taiwan leading in exports of doped GaAs wafers to the United States, and Singapore and Taiwan leading in exports of undoped GaAs wafers to the United States. The United States has historically imported more finished solar modules over undoped solar cells. However, imports of undoped GaAs wafers increased by 4,500 percent from 2022 to 2023. Imports of GaAs wafers may have skyrocketed due to the possible presence of unwanted defects that can be caused by impurities in doped wafers. When defects and impurities occur during the doping process, it can be difficult to eliminate them; these defects or impurities can lead to voltage loss.[16]

[7] NASA, "Onboard Systems," accessed December 30, 2023; The White House, Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems, August 20, 2019.
[8] Brakels, "Why NASA Chose Solar Power Over Nuclear For The Juno Space Probe," July 6, 2016.
[9] NASA, "About RPS," accessed December 30, 2023.
[10] Silicon is the most common semiconductor used in solar cells, representing 95 percent of modules sold.
[11] Conway, Walker, and Heinbockel, "GaAs Solar Cells for Space Applications," accessed December 2023.
[12] In solid-state physics, the band gap is the range where no electronic states exist or the distance between the valence band of electrons and the conduction band. The band gap of GaAs is 1.42 eV, and the band gap of silicon is 1.12 eV. Papež et al., "Overview of the Current State of Gallium Arsenide-Based Solar Cells," June 4, 2021.
[13] Abate, "New Stanford manufacturing process could yield better solar cells, faster chips," March 24, 2015.
[14] HTS codes: Undoped GaAs wafers: 2853.90.9010; doped GaAs wafers: 3818.00.0010.
[15] An example of doping silicon for solar cells includes adding atoms with one less negative charge than silicon like boron and gallium to result in electricity conduction. University of Calgary, "Dopant," accessed December 2023.
[16] Papež et al., "Overview of the Current State of Gallium Arsenide-Based Solar Cells," June 4, 2021.