Satellite Power System

Photovoltaic – Battery System
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*Photovoltaic – Battery system*

1. Type of solar array and examples
2. Solar cell for space application
3. Design of solar array
4. Battery cells for space application
5. Concept of battery protection
1. Type of solar array

*Photovoltaic – Battery system*

1. Type of solar array and examples
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1. Type of solar array

Previously solar arrays had been bonded on the surface of spacecraft body. This style is called as “Body mount type”.

Because half of solar array can’t generate electrical power in this case, the efficiency of solar arrays are not good. In addition, the area for solar arrays is limited, therefore the generated electrical power from solar arrays is also limited.

To supply much electrical power effectively, recent many satellites use deployable solar array wings.
1. Type of solar array

[Deployable Solar Array Wing]
Solar arrays are bonded on light weight panels or flexible sheet. Wire harness are connected to positive and negative terminal of each solar array circuit to transfer the electrical energy to the spacecraft.

Rigid Solar Array Wing
for ALOS
ALOS (launched in 2006)
8kW Si / One Wing
Wing Size 3.1m x 22.2m

Flexible Solar Array Wing
for ADEOS2
ADEOS2 (launched in 2002)
6.2kW Si / One Wing
Wing Size 2.6m x 25.8m
1. Type of solar array

Examples of Rigid Solar Array Wing

ETS-VIII (launched in 2006)
8kW Si Cell / Two Wings
Wing Size : 2.5m x 18.8m
Panel Size : 2.3m x 3.3m

WINDS (launched in 2008)
5.5kW TJ Cell / Two Wings
Wing Size : 2.3m x 9.8m
Panel Size : 2.2m x 2.0m
1. Type of solar array

Typical Configuration of Rigid Solar Array
1. Type of solar array

- CFRP Substrate
- Solar Array Panel
1. Type of solar array

Cross Section of Solar Array Panel

CFRP : Carbon Fiber Reinforced Plastic
1. Type of solar array

Deployment of Rigid Solar Array

(a) Array is held in place by four hold-down release devices during launch and transfer orbit.

(b) Four hold-down release devices are actuated when final orbit is achieved and yoke begins to unfold.

(c) After center panel is fully unfolded and locked, the outboard panel fully unfolds and locks. Hinge position microswitches send the array-deployed signal.
1. Type of solar array

- Deployment Hinge
- Vibration Test for Solar Array Wing
1. Type of solar array

EED
(Electro Explosive Device)

Blade

Power Cartridge
(Two cartridge can be installed for redundancy)

Tie rod
1. Type of solar array

SADA
(Solar Array Drive Assembly)

Slip Ring Assembly

Note) Photo of slip ring assembly is typical for normal industry. (not for space application)
1. Type of solar array

- Two solar cells, those characteristics are very similar, are bonded in the sensor head at 45 degree from the normal direction. Sensor head are mounted on cell side of solar array wing.
- Small angle can be detected by amplifying the differences of output current between two solar cells.
1. Type of solar array

- Earth observation satellites and/or geosynchronous satellites use SADA to track the Sun, because mission equipment should face to the Earth always.
- In the case of interplanetary mission or astronomy mission, solar array wings don’t need to rotate. Therefore solar arrays are fixed to satellite structure.

HAYABUSA2
(Interplanetary Mission)

ASTRO-E2
(X-ray Telescope)

SOLAR-B
(Sun Observation)
1. Type of solar array

Construction of Flexible Solar Array

- SFU solar arrays
- Launched in 1995
- Generated Power 3kW/2wings
- Retractable solar array
  (for collection by space shuttle)
1. Type of solar array

HST, launched in 1990, had employed roll-up type flexible solar arrays. To reduce the pointing issue in orbit, two solar arrays were replaced to improved solar arrays by Space Shuttle in 1993. In 2002, the solar arrays were exchanged to rigid panels to increase electrical power.
1. Type of solar array

**ROSA (Role Out Solar Array)**

Recently, new flexible solar array called as ROSA was developed and tested in orbit. Solar array blanket is rolled around thick cylinder and deployed by flattening force of carbon tube automatically after release. Because there is no hinges, synchronized cables and thick substrates, it can realize light-weight and cost effective solar array.
1. Type of solar array

Two Dimensional Deploy – SFU 2D Solar Array

This experimental solar array had employed very unique technique in stored configuration that is named Miura-ori. Two extension mast are needed in this solar array in this configuration, so this type solar array has not been used for actual satellites.
1. Type of solar array

Solar Sail – IKAROS

Thin film solar cell, like amorphous Si or CIGS (Cu(IN, Ga)Se₂) solar cells, can be mounted on the solar sail.

IKAROS, launched in 2010, employ α-Si sheet on its sail and demonstrated generation of electrical power.
2. Solar cell for space application

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2. Solar cell for space application
## 2. Solar cell for space application

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Year</th>
<th>Power</th>
<th>Area</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ETS-V</strong></td>
<td>1987</td>
<td>0.8kW</td>
<td>16.6m²</td>
<td>50W/m²</td>
</tr>
<tr>
<td>Conventional Si</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ETS-VI</strong></td>
<td>1994</td>
<td>4.1kW</td>
<td>46m²</td>
<td>90W/m²</td>
</tr>
<tr>
<td>Fine Grid Si (0.05mmt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ETS-VIII</strong></td>
<td>2006</td>
<td>7.5kW</td>
<td>60m²</td>
<td>125W/m²</td>
</tr>
<tr>
<td>High Efficiency Si with texture (0.1mmt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WINDS</strong></td>
<td>2008</td>
<td>5.4kW</td>
<td>24m²</td>
<td>220W/m²</td>
</tr>
<tr>
<td>Triple Junction GaAs (0.15mmt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ETS : Engineering Test Satellite
WINDS : Wideband InterNetworking engineering test & Demonstration Satellites
2. Solar cell for space application

Silicon Solar Cell

Since satellites had used solar cell, Silicon solar cell had been used for a long time as a primary power source.

![Silicon Solar Cell Diagram](image)

ARC; Anti-Reflection Coating

![AM0 Spectrum and response of Si cell](image)
2. Solar cell for space application

The latest Si solar cell can generate about 37mA/cm$^2$ at 0.52V under AM0 (Air Mass Zero) at RT (Room Temperature).

Typical V-I characteristics of Si cell (cell area 28cm$^2$)
2. Solar cell for space application

**Triple Junction GaAs Solar Cell**

Around the end of 1990’s, dual-junction solar cell, growth on Ge substrate, were used for the space application. Following, triple-junction solar cell were available to make p/n junction in Ge substrate. The efficiency become around 30% now.
2. Solar cell for space application

TJ solar cell can generate about 17mA/cm\(^2\) at 2.3～2.4V under AM0 (Air Mass Zero) at RT (Room Temperature).

Typical V-I characteristics of TJ Cell (cell area 28cm\(^2\))
2. Solar cell for space application

### Typical electrical output of Si and TJ cell

<table>
<thead>
<tr>
<th>Factor</th>
<th>Si</th>
<th>TJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}$</td>
<td>1.15A</td>
<td>0.41A</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>0.63V</td>
<td>2.69V</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>0.55W</td>
<td>0.91W</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>1.05A</td>
<td>0.39A</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>0.52V</td>
<td>2.33V</td>
</tr>
<tr>
<td>$\eta$</td>
<td>16~17%</td>
<td>27~29%</td>
</tr>
</tbody>
</table>

Cell size 4cm by 6cm, AM0, 1367W/m$^2$, 25degree C

### Temperature coefficient of Si and TJ cell

<table>
<thead>
<tr>
<th>Factor</th>
<th>Si</th>
<th>TJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}$</td>
<td>+0.04 mA/°Ccm$^2$</td>
<td>+0.01 mA/°Ccm$^2$</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>-2mV/°C</td>
<td>-6mV/°C</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>+0.1 mA/°Ccm$^2$</td>
<td>+0.01 mA/°Ccm$^2$</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>-2.1mV/°C</td>
<td>-6mV/°C</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-0.1%/°C</td>
<td>-0.06%/°C</td>
</tr>
</tbody>
</table>
2. Solar cell for space application

Air Mass
In meteorology, an air mass is a volume of air defined by its temperature and water vapor content. Air masses cover many hundreds or thousands of square miles, and adopt the characteristics of the surface below them.

<table>
<thead>
<tr>
<th>Angle Z</th>
<th>Air Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.00</td>
</tr>
<tr>
<td>30°</td>
<td>1.16</td>
</tr>
<tr>
<td>45°</td>
<td>1.41</td>
</tr>
<tr>
<td>60°</td>
<td>2.00</td>
</tr>
<tr>
<td>70°</td>
<td>2.92</td>
</tr>
<tr>
<td>80°</td>
<td>5.76</td>
</tr>
</tbody>
</table>

Angle Z: angle from normal incident.
3. Design of solar array

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3. Design of solar array

**Radiation degradation of solar cell**

Electrical output of solar cell is degraded due to the irradiation of electron and/or proton in orbit. In the case of GEO (Geosynchronous Earth Orbit), about $1E+15$ e/cm$^2$ 1MeV electron is irradiated to the solar cell with 0.1mmt coverglass for 10 years.

![Radiation Factor Graph](image)
3. Design of solar array

- Temperature
  Typical electrical output of solar cell is measured at room temperature (+25 °C). However the temperature of solar cell on orbit around +40～+60°C in GEO and +70～+90°C in LEO (Low Earth Orbit). Therefore V-I characteristics of cell in orbit become lower output from initial curve caused by radiation and temperature.

![Typical TJ Cell V-I in GEO](chart)

- Solar intensity 1367W/m², Normal incidence

**0.73W**

**0.91W**
3. Design of solar array

- **Solar Intensity**
  Distance between Earth and Sun is always changed. Therefore the solar intensity in Earth orbit is varied. Solar constant is 1367 W/m², but it is about 1300 W/m² around summer solstice and increased around 1400 W/m² around 3rd or 4th January. TJ cell output in GEO at EOL is about 0.69 W/cell at summer solstice, not 0.73 W/cell.
3. Design of solar array

- Angle of solar incidence
  In GEO, angle of solar incidence is changed every day.
  On autumnal equinox and Vernal equinox, sunlight incidents to the solar array at normal.
  However on Winter solstice and Summer solstice, sun angle is 23.4 degree from the normal.
  The minimum power of cell in GEO is 0.60W/cell at summer solstice at EOL.
  \[ 0.69W/cell \times \cos 30 \text{ deg.} \]
3. Design of solar array

Example: number of cells for 5kW solar array of GEO satellite

When 5kW is required to solar arrays at summer solstice at EOL, at least 8,400 TJ solar cells are needed. \[ \frac{5000\text{W}}{0.6\text{W/cell}} \]

In the case of 50V bus system, solar array output current is more than 100A. If the harness resistance between solar array and PCU is about 0.03Ω, the voltage drop can be estimated as 3V. Usually isolation diodes will be installed in power hot and their drop is roughly 2V. Therefore **output voltage of solar array should be more than 55V**.

Because Vmp of TJ cell at EOL is about 2V, more than **28 cells should be connected in series** in one string and **300 strings are connected in parallel** to supply 5kW at 55V.
3. Design of solar array

Example: Solar Array power of GEO satellite

Solar intensity is normalized by 1367 W/m². In summer solstice (22nd June), solar power is about 1320 W/m² and sun angle is 23.4 degree, so sun intensity is about 0.886.

\[ \frac{1320}{1367} \times \cos(23.4 \text{ deg.}) \]

Predicted power of solar array for ETS-VIII (7kW class GEO Satellite)

Nominal curve (red line) is decreased caused by mainly radiation. Minimum case is considered followings conditions.
- One strings failure
- Predicted temperature is 10 degree higher
- Error od sun tracking
- others
3. Design of solar array

Thermal design of solar array

During eclipse, temperature of solar array is decreased rapidly.
In case of GEO satellite, the longest eclipse is 72 minutes and the temperature of solar array is reached at -160 degree C.
3. Design of solar array

Thermal design of solar array

In case of GEO satellite, there are 88 days eclipse per year (44 days / shadow season) and solar array experience very low temperature 88 times per year. When design life of the GEO satellite is 18 years, solar array must survive more than 1584 thermal cycles those temperature range is between +95 degree C and less than -160 degree C. This mean, solar array should be design to survive wide temperate and a few thousands cycles of thermal cycles.

On the other hand, LEO (Low Earth Orbit) satellite experience about 15 rotations per day. Generally eclipse in LEO is between 30 minutes and 40 minutes, so the lowest temperature of solar array in eclipse is around -100 degree C. However, the number of eclipse is about 15 per day, so about 30,000 thermal cycles for five year should be considered for solar array.

These wide temperature and many thermal cycles will affect solder joint of wire, welding between solar cell and interconnector, various bonding on solar array, and so on, in the light of the fatigue. In selecting of materials of solar array, we had to pay attention to the temperature coefficient (CTE) of each material and make effort to reduce CTE mismatch.
3. Design of solar array

Other environmental factors for solar array design

- **UV (Ultra Violet)**
  Discoloration of coverglass and/or coverglass adhesive
  Ce\(^+\) doped coverglass is selected

- **AO (Atomic Oxygen)**
  In LEO, erosion caused by AO should be considered
  AO reaction of Silver (Ag) and Kapton is larger than other material
  Change of transparency of antireflection coating of coverglass
  (In case of MgF\(_2\), single layer coating)

- **Debris and/or micrometeoroids**
  Damage solar cell, wire harness, insulation of solar array, etc.
  Redundant wire connection
  Isolation of strings by diode
  Shield to debris / micrometeoroids
  Moderate margin
4. Battery cells for space application

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4. Battery cells for space application

Ni-Cd battery

Typical output voltage is 1.1～1.2V.

Nickel-cadmium batteries have been used in the majority of space applications since the mid 1970s.

This system possesses good energy density, operating temperatures, and discharge voltage characteristics. However, this system does not handle overcharging well, and it has a relatively short lifetime.
4. Battery cells for space application

Ni-H$_2$ battery

Typical output voltage is 1.2V.

Nickel-hydrogen batteries have the strong points of Ni-Cd batteries, with improved energy density and cycle lifetime.

These two improvements have led to a dramatic increase in NiH$_2$ battery use. NiH$_2$ batteries, however, use hydrogen gas as a reactant in the oxidation reaction.

During use, high pressures develop in the cell. Therefore, the cell case is a rigid pressure vessel. Research is underway to develop lightweight, inexpensive, reliable materials for use in NiH$^2$ cell cases.
4. Battery cells for space application

Li-Ion battery

Typical output voltage is **3.7V**.

A lithium-ion battery (sometimes Li-ion battery or LIB) is a member of a family of rechargeable battery types in which lithium ions move from the anode to the cathode during discharge and back when charging.

Li-ion batteries use an intercalated lithium compound as the electrode material, compared to the metallic lithium used in non-rechargeable lithium battery.

Li-ion batteries are one of the most popular types of rechargeable battery for space application nowadays, with one of the best energy densities, no memory effect, and only a slow loss of charge when not in use.
4. Battery cells for space application

For example, in the case of 50V bus satellite system with 200Ah batteries, Li-Ion battery can save the mass more than 70kg and it’s volume is about \( \frac{1}{4} \) in comparison with Ni-H2 battery.

<table>
<thead>
<tr>
<th>Type of Cell</th>
<th>100 Ah Ni-H2 cell</th>
<th>100Ah Li-Ion cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series / Parallel</td>
<td>31s × 2p (62 cells)</td>
<td>11s × 2p (22 cells)</td>
</tr>
<tr>
<td>Cell weight</td>
<td>2.2kg</td>
<td>2.9kg</td>
</tr>
<tr>
<td>Total Weight</td>
<td>136.4kg</td>
<td>63.8kg</td>
</tr>
<tr>
<td>Cell Volume</td>
<td>1.8 lit</td>
<td>1.4 lit</td>
</tr>
<tr>
<td>Total Volume</td>
<td>111.6 lit</td>
<td>30.8 lit</td>
</tr>
</tbody>
</table>
4. Battery cells for space application

Trend of energy density of typical battery (industrial)
The performance of Li-Ion battery cell are still improved now.

- Li-Ion battery
- Ni-H2 battery
- Ni-Cd battery

Energy density, Wh/l

Year


Energy Density, Wh/l

100Ah Li-B for space
4. Battery cells for space application

Performance degradation of Li-Ion battery: Cycle Loss

Capacity and output voltage of Li-Ion battery cell degrades caused by charge/discharge cycles.

Example; 100Ah Li-Ion Battery
4. Battery cells for space application

Performance degradation of Li-Ion battery: Calendar Loss

Capacity of Li-Ion battery cell degrades during storage. Degradation is fast in higher temperature and/or higher SOC.

Example; 100Ah Li-Ion Battery
4. Battery cells for space application

Typical characteristics of Ni-H₂ battery and Li-Ion battery

<table>
<thead>
<tr>
<th>Battery</th>
<th>Ni-H₂</th>
<th>Li-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantage</td>
<td>• Long life</td>
<td>• Higher energy density</td>
</tr>
<tr>
<td></td>
<td>• Strong for over charge and over discharge</td>
<td>• Efficiency in charge/discharge is quite high</td>
</tr>
<tr>
<td></td>
<td>• Available for rapid charge</td>
<td>• Self-discharge is very low</td>
</tr>
<tr>
<td></td>
<td>• Wide temperature range</td>
<td>• Long life</td>
</tr>
<tr>
<td></td>
<td>• Higher theoretical energy density</td>
<td>• Available for rapid charge</td>
</tr>
<tr>
<td></td>
<td>• Higher energy efficiency</td>
<td></td>
</tr>
<tr>
<td>Notice</td>
<td>• Self-discharge is slightly higher</td>
<td>• Care about safety for organic electrolyte solution</td>
</tr>
<tr>
<td></td>
<td>• Generation of heat in full charge is high</td>
<td>• Weak for over charge and over discharge</td>
</tr>
<tr>
<td></td>
<td>• Vessel is a limitation for larger capacity</td>
<td>• Degradation in higher SOC</td>
</tr>
<tr>
<td></td>
<td>• In case of Ni-MH, cost of hydrogen absorbing alloy is expensive</td>
<td>• Degradation in higher temperature</td>
</tr>
</tbody>
</table>
5. Concept of battery protection

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5. Concept of battery protection

In case of Li-Ion battery cell, to prevent over-charge, CC-CV charge method is required generally.

(CC : Constant Current, CV : Constant Voltage)

Example of discharge and charge characteristics of Li-Ion Battery cell for space application
5. Concept of battery protection

Following functions are equipped in BCCU or BMU (Battery Management Unit) to use Li-Ion Battery for a long time in orbit.

- UVC (Under Voltage Control) signal
  The voltage of BAT or each cell become under the specific voltage, BCCU or BMU indicate spacecraft processor to reduce the consumption of electrical power to avoid over-discharge of battery cell.

- OV (Overvoltage)
  Overcharged cell has risk of over-heat, explosion, or ignition. To avoid the risk, BCCU quits it’s charge of battery, when the voltage of BAT or each cell reached at the specific voltage.

- OT (Over-temperature cut-off)
  When temperature of the battery become higher than usual or predicted range without abnormal of thermal control, there is a possibility of explosion of battery cell. To avoid the risk of damage of BAT, BCCU quits it’s charge of BAT, when the temperature of the BAT is over the specific temperature.
Secondary batteries, those which are discharged and then recharged numerous times, are principally used for satellite. In space applications, reliability, cost producibility, responsiveness, risks, safety, and maintainability are more important current contents.

Battery types are selected for specific applications based on a number of factors including specific energy and energy density (see Figures 1 and 2), lifetime, number of cycles, discharge rate, charge retention, shelf life, ruggedness, operating temperature, and other factors. Figure 3 presents these factors for various battery types. Figure 3 should be used by the designer as an initial tool for selecting the required battery type. The design of batteries for space flight should be accompanied by battery level electrical, mechanical and thermal analysis.
Supplementation; Selection of battery cell for spacecraft (Reference)

<table>
<thead>
<tr>
<th>CHEMISTRY:</th>
<th>PRIMARY</th>
<th>SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCF</td>
<td>AgZn</td>
<td>NiH2</td>
</tr>
<tr>
<td>LiSOCl₂</td>
<td>AgZn</td>
<td>NiH2</td>
</tr>
</tbody>
</table>

| Lifetime (cycles) | Not Applicable | Not Applicable | 200⁺³ | 45K⁺⁴ | 40K⁺⁴ | ² | ² | 500⁺ |
| Watt-Hours/Kilogram | 130 | 185 | 110 | 100 | 65 | 35 | 55 | 20 |
| Watt-Hours/Liter | 160 | 240 | 200 | 185 | 80 | 85 | 180 | 200 |
| Discharge Rate | Low | Mod | High | High | Mod | High | High | High++ |
| Charge Retention | Not Applicable | Not Applicable | High | Low | Mod | Mod | Mod | Mod |
| Memory | Not Applicable | Not Applicable | No | No | Yes | No | No | No |
| Wet Shelf Life | Long | Short | Short | Mod | Mod | Long | Long | Long |
| Failure Tolerance | Low | High | High | High | Mod | High | Mod | Mod |
| Notes: | Not Sensitive within limits⁹,¹⁰ | Activation req’d at time of use; May have free Electrolyte | Pressure Vessel; Capacity loss concerns after storage | Not Sensitive¹⁰ | Activation req’d at time of use; May have free Electrolyte¹⁰ |
| Operating Temp | ⁰°C - 100°C | ¹⁰°C - 50°C | ⁰°C - 45°C | ⁰°C - 20°C | ⁰°C - 50°C | ⁰°C - 10°C | ² |
| Venting Requirements | Burst vent req’d | Can be sealed | Can be sealed | None | Can be sealed | None | Req’d |
| Cell Voltage (Operating) | 2.95V | 3.1V | 1.5V | 1.5V | 1.3V | 1.25V | 1.32V | 2.1V |
| Experience Level | High | Mod | High | Low | Moderate | High | Low | Low-- |
| Costs | Low | Low | Low | Low | High | Mod | High | High |

1 Based on MSFC applications (EB12)
2 New Technology
3 Approximately 50% depth of discharge
4 Refers to 61 minute sun and 35 minute eclipse low earth orbit cycle with approximately 5500 cycles per year at less than 20% depth of discharge
5 Can be designed for high rate use
6 Significantly improves with lower temperature (⁰°C)
7 Lifetime is limited to 90 - 200 days depending on construction
8 High temperature buildup on "high-rate" overcharge
9 Unstable at very high temperatures and high rate of discharge
10 Environmental concerns with constituent materials

Figure 3. Approximate Battery Comparisons for Space Power Applications in 1992