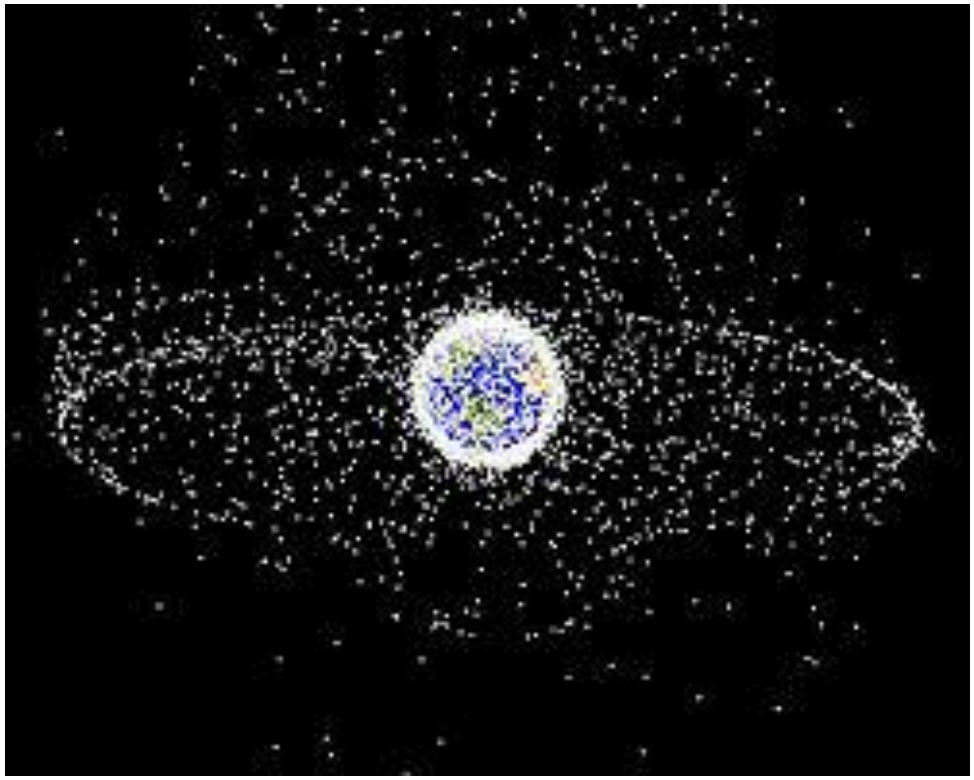
Maintenance Scenario for Solar Power Satellite to Prevent Space Junk

- SPS model Used in this Study
- Mission life of SPS unit (radiation and debris/meteoroid environment)
- Construction and maintenance scenario
- Transportation system required for the scenario

September 2013

SPS End-of Life Requirement to Avoid Space Junk



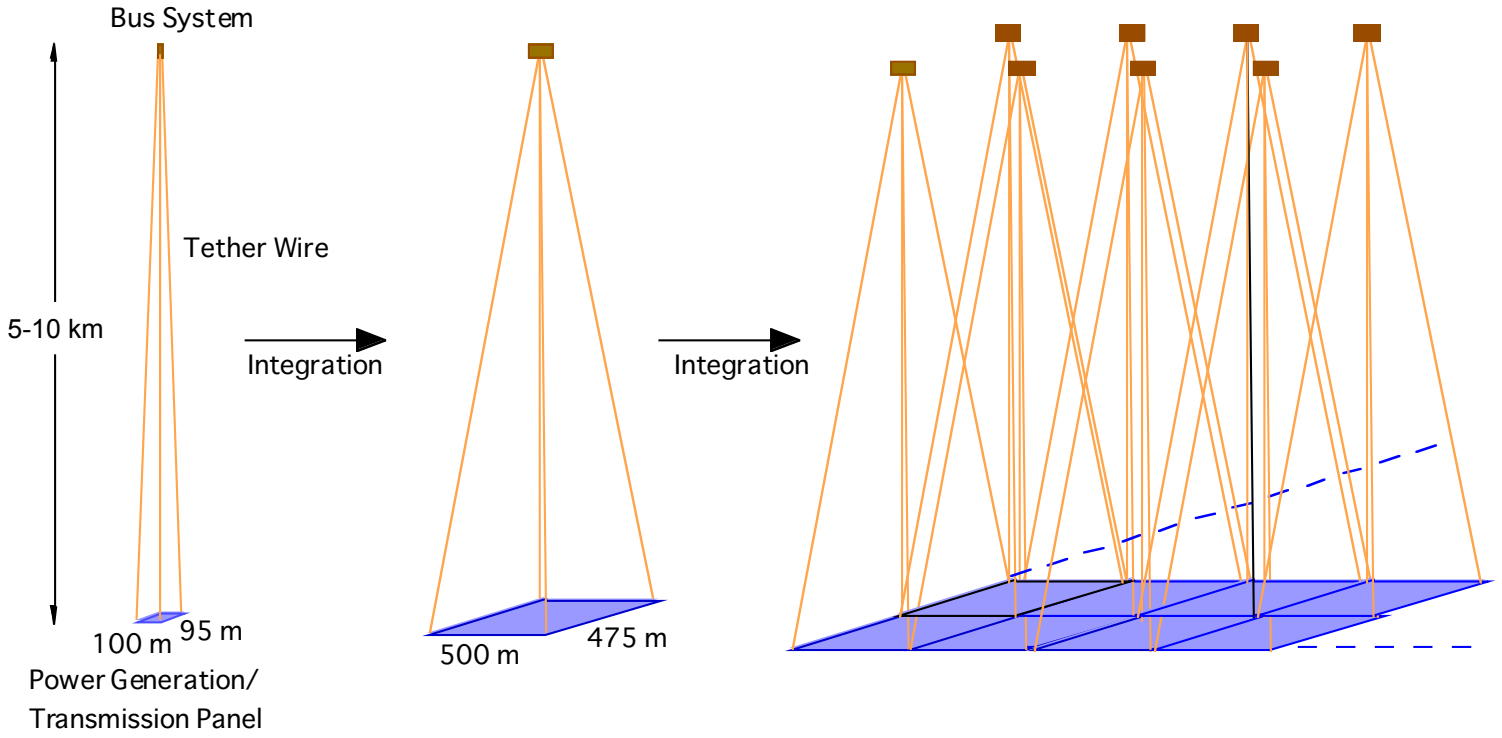
Orbital debris population in the geosynchronous region
http://orbitaldebris.jsc.nasa .govphotogallery/beehives.html

- *The commercial SPS will be placed in the geosynchronous orbit.*
- *There already exist a lot of space debris in the orbit.*
- *The design of the future space systems is strictly requested to prevent the creation of the orbital junk, which is also important to protect the SPS systems themselves.*
- *The regulation requires the end-of-life deorbit, which requires essential constraints in the SPS system design, the SPS system operation, and the space transportation systems for SPS.*

➡ *We have to think of this now!*

SPS Reference Model to Study Maintenance (Replacement) Operation; Tethered-SPS

- *The power generation/transmission panels are suspended by tether wires extended from the upper bus systems.*
- *The attitude of the system is stabilized by the gravity gradient force. A unit of power generation/transmission panel of 100 m x 95 m is suspended by four 5-10 km tether wires extended from a unit bus system.*
- *The power generation/transmission panel is automatically deployed in the orbit and is then connected to each other to form one GW class SPS.*
- *This system can be disassembled into the units by reverse procedures.*

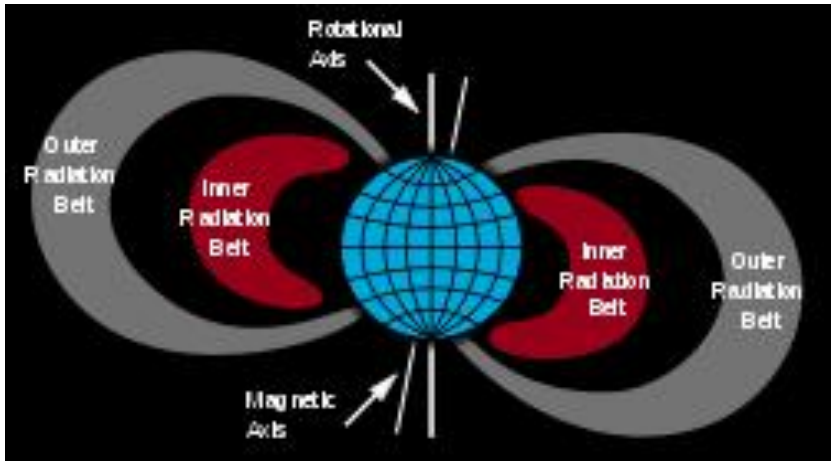


Summary of Tethered-SPS (1GW Constant Output)

Configuration	*Power generation/transmission panel suspended by 100 wires*
Panel size	*2.5 km x 2.375 km x 0.02 m*
Tether wire length	*5-10 km approx.*
Bus separation	*356 m (8°)*
Total weight	*26,600 tons*
Panel weight	*25,200 tons*
Bus weight	*1,400 tons*
Sub-panel	*Power generation/transmission panel suspended by 4 wires (internal 96 redundant wires are slacked)*
Size & weight	*500 m x 475 m x 0.02 m, 1,010 tons*
Unit number/sub-panel	*25 (5x5)*
Tether tension	*54 gw per wire*
Unit panel	*Power generation/transmission panel suspended by 4 wires*
Size & weight	*100 m x 95 m x 0.02m , 40 tons*
Module number/unit panel	*3,800 (20x190)*
Tether tension	*2 gw per wire*
Power transmission	*2.1 MW*
Structural module	*10 power generation/transmission modules (0.5m x 0.5m)*
Module size & weight	*5 m x 0.5 m x 0.02 m, 10.625 kg*
Power generation	*1,181 W*
Power transmission	*555 W constant*
Microwave frequency	*5.8 GHz*
Output power	*1 GW constant (Rectenna site output)*

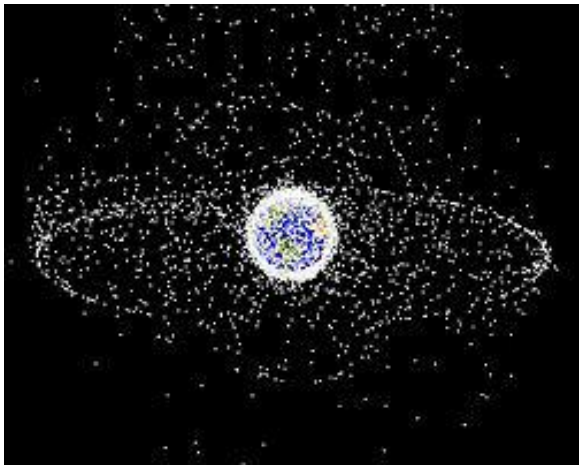
Two Major Factors to Degrade SPS Unit

Radiation Environment



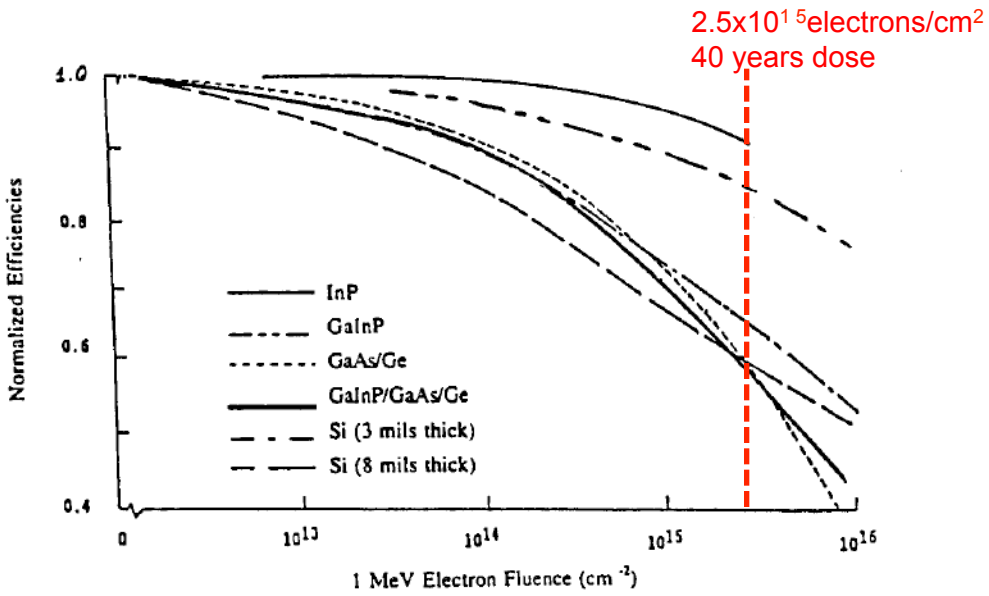
The total radiation dose for 40 years in the GSO is about (2-3)x10^{15} electrons/cm^2 (1 MeV electron equivalent)

Debris(Meteoroid) Environment



100 mm size	*3 x 10^{-10} /km^3*
10 mm size	*1 x 10^{-9} /km^3*
1 mm size	*5 x 10^{-6} /km^3*

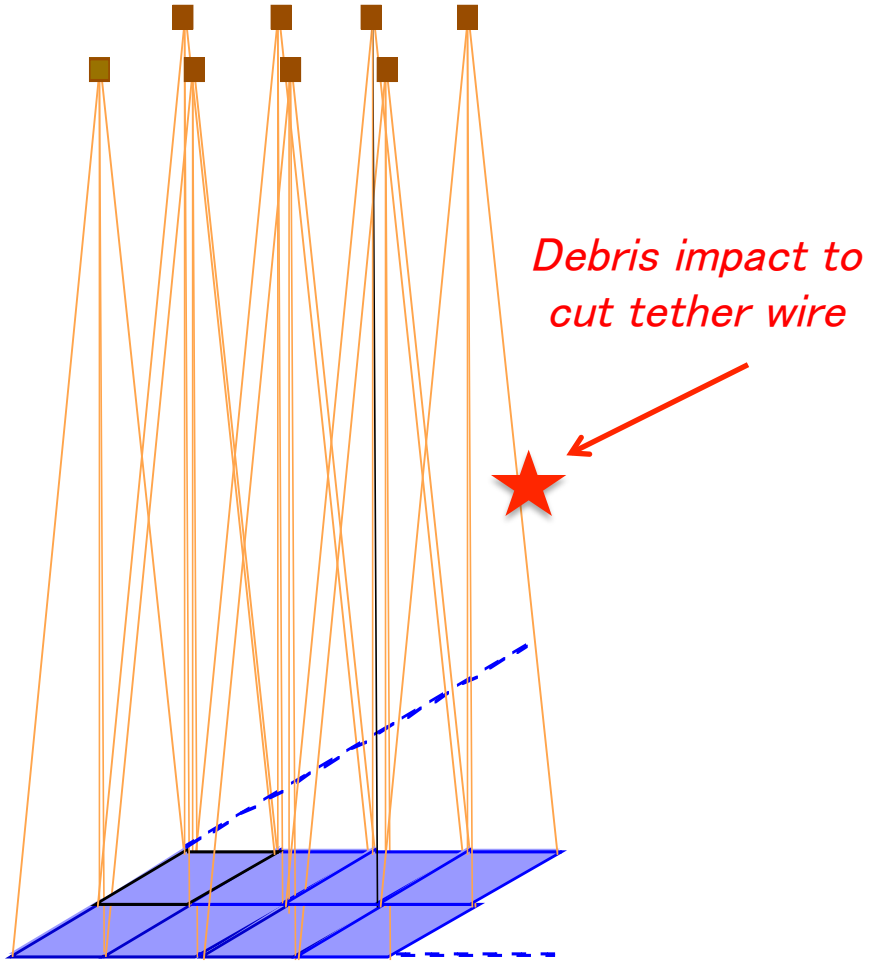
Degradation of Photovoltaic Cell by Radiation



S.Bailey, G.Landis, and D.Flood, Photovoltaic Space Power, AIAA 98-1053, 36th Aerospace Sciences meeting & Exhibit, Jan.12-15, 1988, Reno, NV

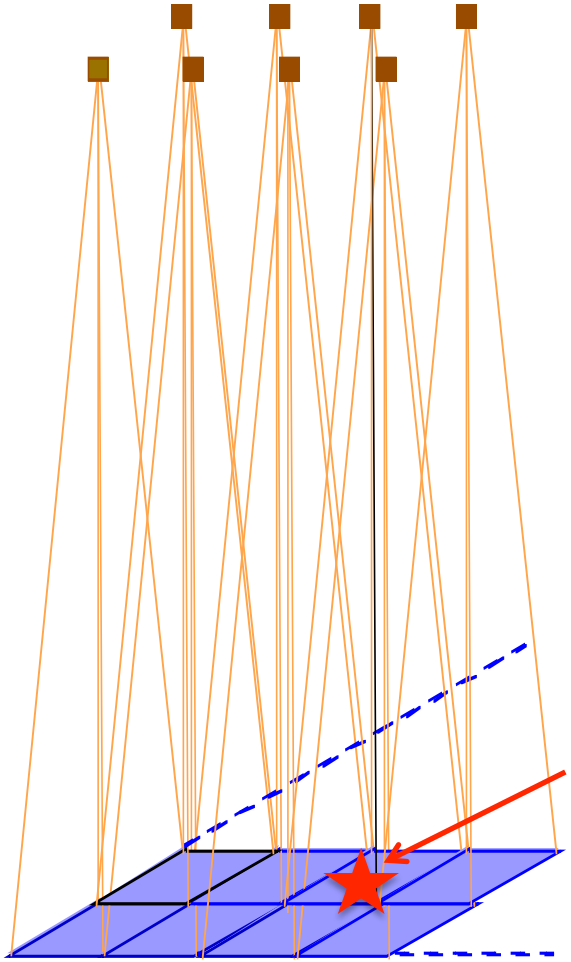
- *At 10^{15} electrons/cm^2 radiation, photovoltaic cells currently used for spacecraft is degraded typically 30 % for Si-type solar cells and by 15 % for three multi-junction solar cells.*
- *Degradation by 5-10 % for 40 years has not been achieved yet, but is a feasible target for SPS application in the future around 2030's.*

Possibility for Tether Wire to Break by Debris and Meteoroid



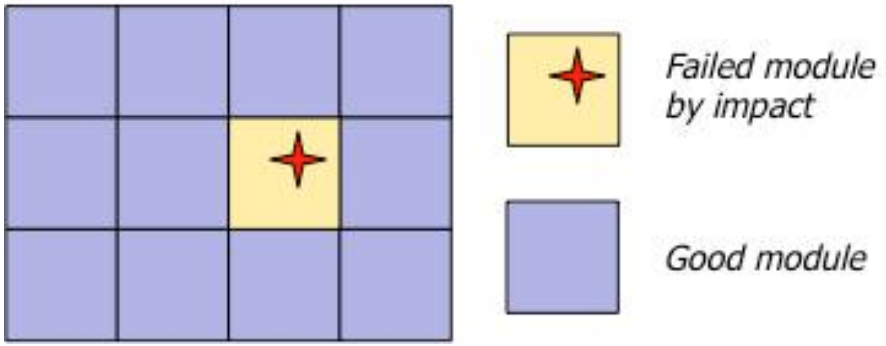
- *Using a tether wire (tape tether) of more than 10 mm wide and 0.5 mm thick, it will not be severed by one hyper-velocity impact of a particulate less than 2.2 mm diameter (Hirayama, 2000).*
- *Fatality rate for 10 km tether, 10 mm wide and 0.5 mm thick, is 0.014 (cut/year) (Hirayama, 2000. 40-years survival rate is calculated as 0.571). Using 5 redundant wires, the survivability is expected to be 0.98.*
- *The fatality rate can be reduced to an acceptable level by using a wider tape or more redundant wires.*

Modular Design for Power Generation/Transmission Panel



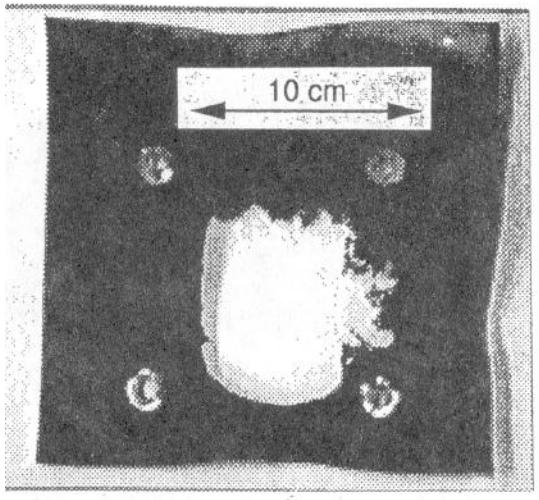
Debris impact to break panel

- Required to design the modules of the panel electrically isolated to each other.
- Designed so as that the failure in one module does not propagate to other modules.

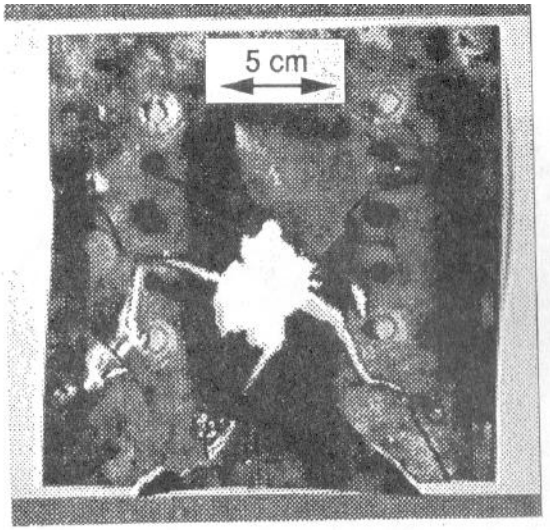


Damage of Power Generation/Transmission Panel by Debris and Meteoroid impact

- *According to the results of hyper-velocity impact experiments, the damage size extends 10 times more than the projectile size in the worst case. In the GSO, the impact probability of the debris and meteoroid larger than 1mm is about 2400 times/ year・km^2.*
- *Supposing that an impact of the debris (meteoroid) larger than 1mm could destroy one module but the failure does not propagate to other modules, the power loss during 40 years is about 5 % in case of the module size of 0.5 m x 0.5 m.*



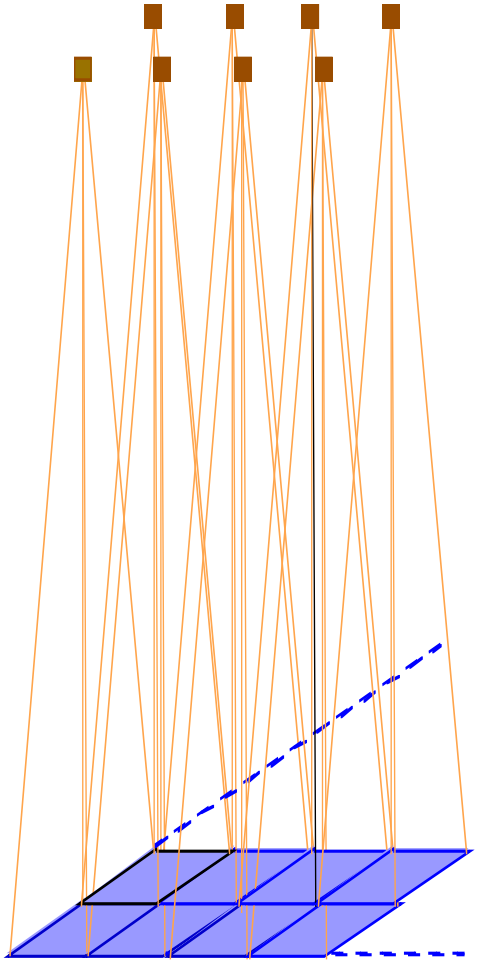
The front polyester sheet



The rear polyester sheet

Typical examples of the hyper-velocity impact damage of a panel structure similar to the thin-film solar cell. The damage extended almost 10 times larger than the projectile scale (10 mm).

Timing for Maintenance (Replacement) of SPS Units

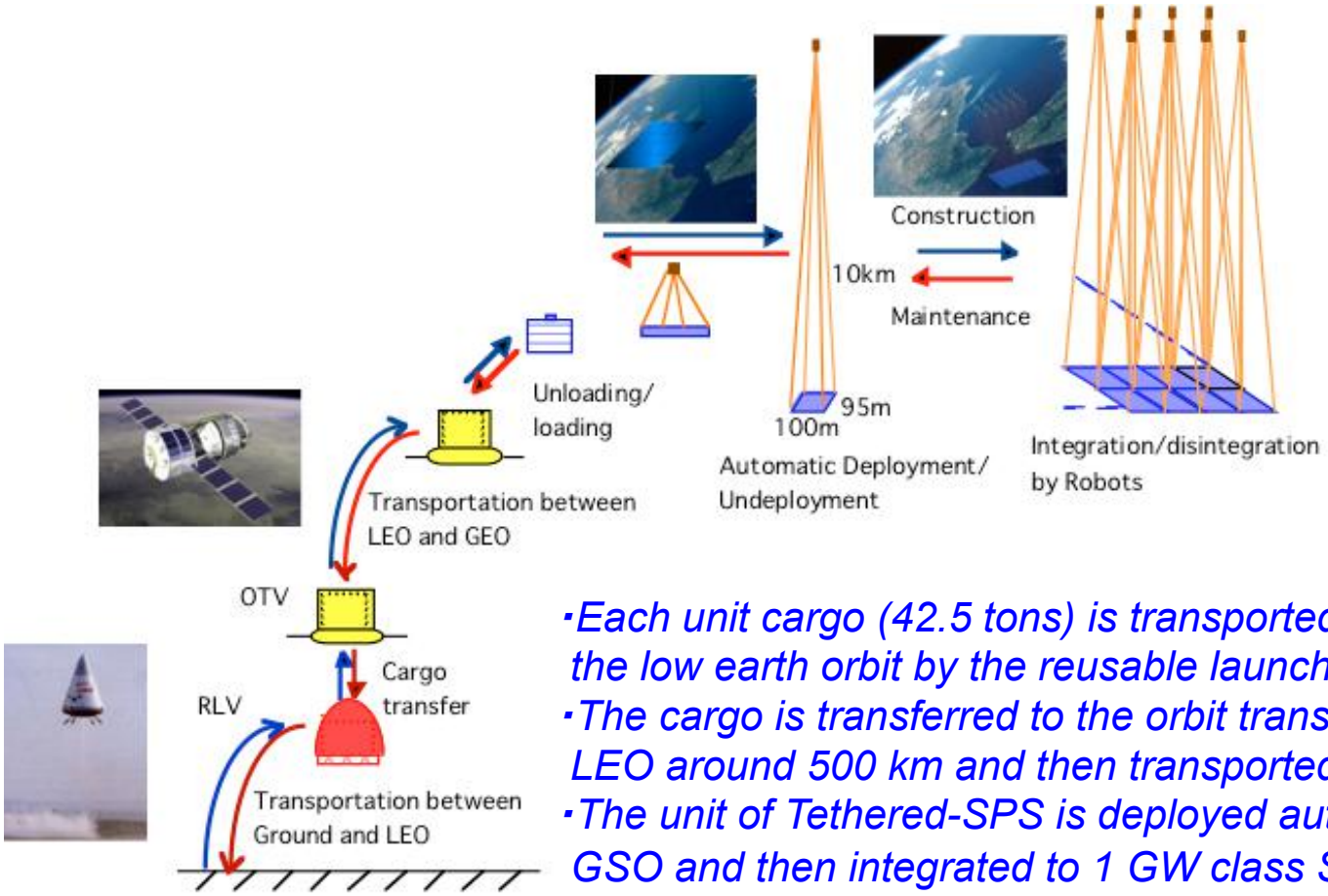


40 years power loss:

Power loss by radiation degradation	*5-10%*
Power loss by debris(micrometeoroid) impact	*5 %*
Spontaneous electrical failure rate of the module	*5 %*
Total power loss	*15-20%*

40 years after construction is a reasonable timing for the maintenance (replacement) of the commercial SPS.

Construction (blue) and Maintenance (red) Scenario.



- *Each unit cargo (42.5 tons) is transported from the ground to the low earth orbit by the reusable launch vehicle.*
- *The cargo is transferred to the orbit transfer vehicle in the LEO around 500 km and then transported to the GSO.*
- *The unit of Tethered-SPS is deployed automatically in the GSO and then integrated to 1 GW class SPS..*

- *At the maintenance (replacement) phase about 40 years after the initial construction, all units are replaced by the new units transported from the ground. The transportation system carries the new unit from the ground to the orbit and the old unit from the orbit to the ground in the round trip operation.*
- *This replacement procedure does not leave any space junk in the orbit and does not waste the SPS materials in the recycling process.*

Transportation System Required for Construction and Replacement Scenario

Operation orbit	*Geosynchronous Orbit*
SPS class	*1GW*
Total weight (Tethered-SPS)	*26,600 tons*
Construction/replacement	*1 year*
Payload mass	*45 tons (1 SPS unit)*
Reusable Launch Vehicle (RLV)	*Ground to LEO (500km)* *50 tons payload capability* *14 RLVs, 73 round trips/year* *2.8 launches/day*
Orbit Transfer Vehicle (OTV)	*LEO (500km) to GSO* *45 tons payload capability* *35 ton fuel /round trip* *6 months round trip* *154 OTVs*

- *For the construction and maintenance scenario, RLV and OTV listed above are required.*
- *The payload capability of the RLV is 50 tons containing the SPS unit (42.5 tons), miscellaneous cargo (2.5 tons), and the fuel (5 tons) for the OTV.*
- *To construct 1 GW class SPS in a year, the RLV needs to be launched every 8 hours (3 times per day).*
- *Totally 154 OTVs are required if we set 6 months for the round trip between the LEO and the GSO.*

Summary and Conclusion

- *Evaluating the space environment, the commercial life of SPS is estimated to be about 40 year.*
- *An end of life operation is proposed, in which new units are transported from the ground to the GSO, the degraded units are replaced by the new ones, and then the old ones are transported to the ground for maintenance and refurbishment.*
- *This procedure guaranties that any space junk is not generated at end of life operation.*
- *This scenario requires well-established space transportation system consisting of advanced RLV and OTV.*