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Maintenance Scenario for Solar Power Satellite to Prevent Space Junk

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The commercial life of Solar Power Satellite (SPS) is usually considered to be 30-40 years. However the disposal plan after expiration of its life has not been well studied so far. This paper describes the life analysis of SPS by evaluating the radiation and debris (meteoroid) environment, and proposes a replacement scenario at the end of life to prevent generating space junk. The SPS basic model (tethered-SPS) is used for this study. If we set an allowable degradation level at 15-20 % for the commercial life; 5-10 % by radiation degradation, 5 % by hyper-velocity impact loss, and 5% by spontaneous electrical failure, 40 years life is expected in the following assumptions; (1) photovoltaic cells with high radiation-resistance (5-10 % degradation at 2.5 x $10^{15}/cm^2$ (1 MeV electron equivalent fluences)), (2) redundant tether wires (tape tether) of more than 15 mm wide, and (3) modularized structure for the power generation/transmission panel with a module size of 0.5m x 0.5m, beyond that the impact damage does not propagate. In the end of life scenario, new units of SPS are transported to the geostationary orbit from the ground and are exchanged for degraded units, and then the degraded units are transported to the ground for refurbishment. The replacement operation starts near the end of life and is completed in a year in the same way as the initial construction. The replacement operation does not generate any junk in the orbit. This scenario is heavily dependent on the space transportation system between the ground and the orbit, consisting of reusable launch vehicle (RLV) and orbit transfer vehicle (OTV).

1. Introduction

The commercial SPS will be placed in the geosynchronous orbit (GSO). There already exist a lot of space debris in the orbit as shown in Fig.1. 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 as well as operational procedures to avoid contamination of the space environment during the construction and mission operation phase. The operational procedures to minimize debris generation both for the space transportation systems and the orbiters have been already established at a certain level and can be applied to the SPS construction and operation without special difficulty. However, the end-of-life deorbit requires essential constraints in the SPS system design, the SPS system operation, and the space transportation systems for SPS. These constraints have to be well incorporated in the conceptual design phase. The end-of-life procedure to avoid creation of space junk has not been well discussed in any of the past SPS studies. One quick idea is to remove the life-expired SPS from the mission orbit to the other orbit or to the atmosphere for burning, but it is not a practical and economical solution. A realistic solution will be to replace the life-expired units with new units transported from the ground, and to retrieve old units for recycling on the ground. The replacing

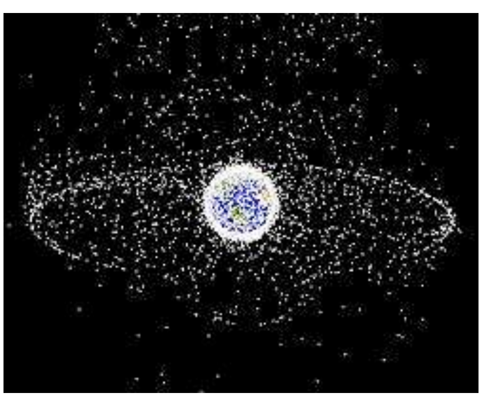

Fig.1 Orbital debris population in the geosynchronous region [1].

Fig.2 Conceptual image of 1 GW class Tethered-SPS.

and retrieving operation is conducted as a maintenance operation when the commercial life of SPS is expired. This solution requires that the SPS system is composed of equivalent units for easy assembling/disassembling and also that the cargo flow between the orbit and the ground is maintained in a high level, typically more than 100 tons/day.

2. Study Model

As a reference model to study the maintenance (replacement) operation, we have selected the Tethered-SPS model in which power generation/transmission panels or so-called sandwich panels are suspended by tether wires extended from the upper bus systems [2]. Figure 2 illustrates a conceptual image of the Tethered-SPS in orbit. The attitude of the system is stabilized by the gravity gradient force between the panels and the bus systems. Figure 3 shows a unit of the Tethered-SPS, in which a power generation/transmission panel of 100 m x 95 m (0.02m thick) is suspended by four 10 km tether wires extended from a unit bus system. The weight of the unit of the Tethered-SPS is 42.5 tons; 40 tons for the panel and 2.5 tons for the unit bus system plus 4 tether wires. The power generation/transmission panel is automatically deployed in the orbit and is then connected to each other. 5x5 units are integrated to a sub-panel (500 m x 475 m) and one integrated bus system composing with 25 unit bus systems. Then, 5 x 5 sub-panels are integrated to form a 1 GW class SPS, leaving each integrated bus system unconnected. Docking assistant robots which are manipulated from the ground control center will be used for the integration work. Each corner of the unit panel except for the outer unit is suspended by 4 redundant tether wires. This system can be disassembled into the units by reverse procedures. Table 1 summarizes the specification of 1 GW class Tethered-SPS. At the completion of integration, the size of the power generation/transmission panel and weight are 2.5 km x 2.375 km and 26,600 tons, respectively. The 1 GW system is composed of 625 units. Each unit panel (2.1 MW output) has 3,800 structural modules of 5 m x 0.5 m size. Each structural module is composed of 10 power generation/transmission modules of 0.5m x 0.5m.

3. Maintenance Scenario

3.1 Mission Life of SPS Unit

There are two major factors to degrade the SPS unit, radiation environment for the photovoltaic cells and debris (meteoroid) impacts onto the power generation/transmission panel. The total radiation dose for 5 years in the GSO is about

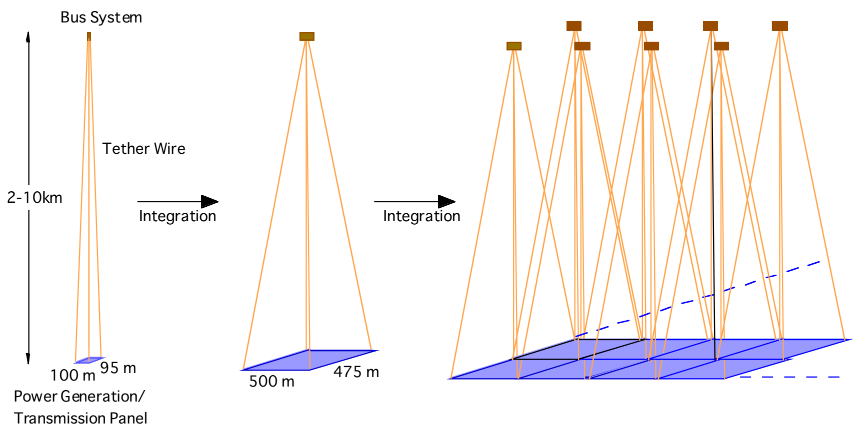

Fig.3 Unit of the Tethered-SPS and its integration process to a large-scale SPS.

Table 1 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)

$3x10^{14}$ electrons/cm^2 (1 MeV electron equivalent dose) [3]. If we consider 40 years commercial life, the equivalent total dose amounts to (2-3) $x10^{15}$ electrons/cm^2. When exposed to 10^{15} electrons/cm^2, the degradation of the photovoltaic cells currently used for spacecraft is typically 30 % for Si-type solar cells and 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.

Concerning the structural damage of the SPS unit, we have to consider the possibility for the tether wire to break by the impact of debris and meteoroid. Using the tether wires (tape tether) of more than 10 mm wide and 0.5 mm thick, it will not severed by one hyper-velocity impact of a particulate less than 2.2 mm diameter. The fatality rate for the 10 km tether, 10 mm wide and 0.5 mm thick, is 0.014 (cut/year) [4]. 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 the acceptable level by using a wider tape and more redundant wires.

For the debris (meteoroid) impact damage to the power generation/transmission panel, it is very important to design the modules of the panel electrically isolated to each other. In another word, the panel needs to be designed so as that the failure in one module does not propagate to other modules as is illustrated in Fig.4. According to the results of hyper-velocity impact experiments, the size of the impact damage in a panel structure is not always the same as the size of the projectile (debris or meteoroid). A typical example of the damage is shown in Fig.5. The damage size

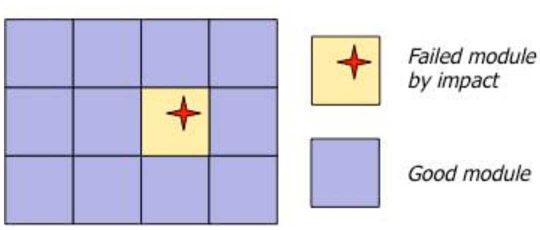

Fig 4 Modules are electrically isolated to each other so as that a failure in a module does not propagate to the other modules.

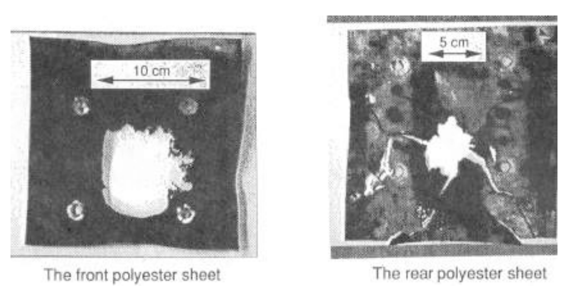

Fig 5 Typical examples of the hyper-velocity impact damage of a panel structure similar to the thin-film solar cell. The damage extended almost 10 times larger than the projectile scale (10 mm).

extends 10 times more than the projectile size in the worst case [5]. In the GSO, the impact probability of the debris and meteoroid larger than 1mm is about 2400 times/year $\cdot$ 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.

If we assume the spontaneous electrical failure rate of the module during 40 years is 5 %, the total power loss is estimated to be 15-20 % for 40 years. Thus 40 years after construction is a reasonable timing for the maintenance (replacement) of the SPS units.

3.2 Construction and Maintenance

The over all construction and maintenance scenario is illustrated in Fig.6. Each unit cargo (10m x 5m x 3.8m, 42.5MT) is transported from the ground to the low earth orbit (LEO) by the RLV (reusable launch vehicle). The cargo is transferred to the OTV (orbit transfer vehicle) in the LEO around 500 km and then transported to the GSO. Delta-V required for the transportation from the LEO to the GSO is 4,500 m/s. To reduce the degradation effect of the solar cells by the trapped energetic particles in the radiation belt, the cargo will be contained in a radiation shield vessel. If we use a 200 tons OTV equipped with an electric propulsion of 80 N thrust, the 45 tons cargo is transferred to the GSO rapidly in 3 months. The unit of Tethered-SPS is deployed automatically in the GSO. Totally 625 units are required for the 1 GW class SPS, but some extra units are also transported and stored near the SPS main body. During the operation phase after construction, any unit in trouble can be unconnected and removed from the SPS main body for maintenance, and a new unit in the storage area can be installed for that.

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.

4. Space Transportation System

In order to support the construction and

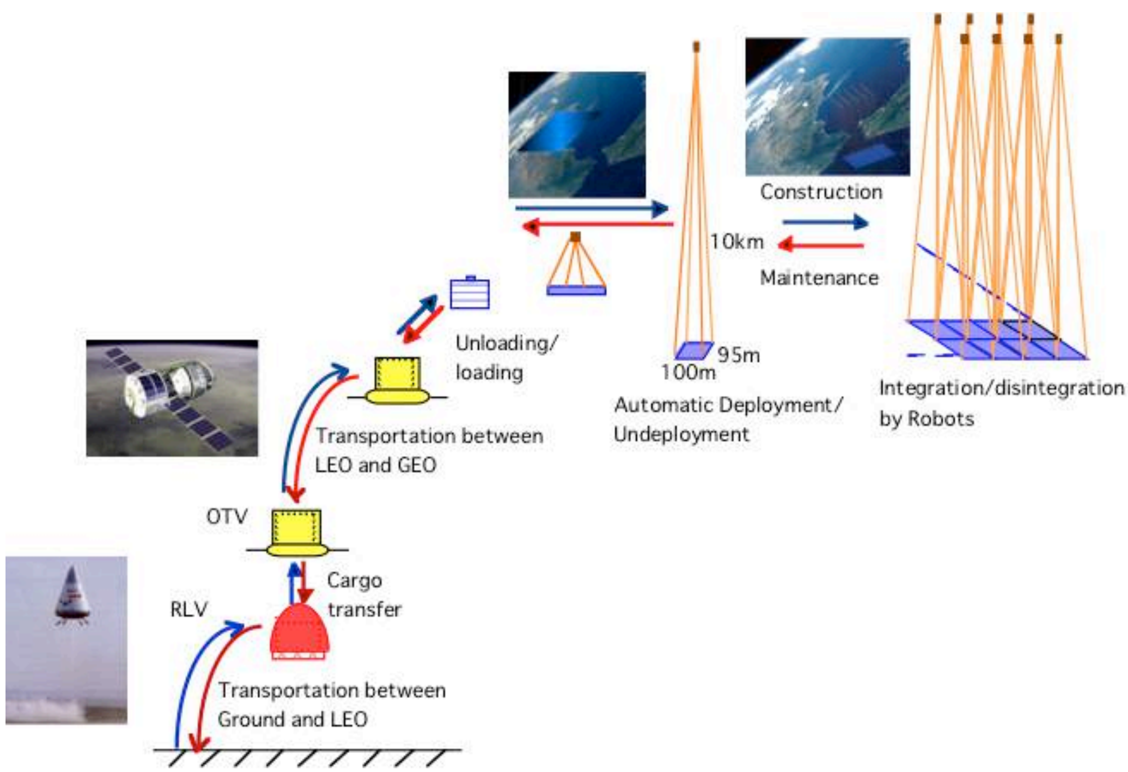

Fig. 6 Construction (blue) and maintenance (red) scenario.

Table 2 Transportation system required for the 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)	50 tons payload capability Ground to LEO (500km) 14 RLVs, 73 round trips/year 2.8 launches/day
Orbit transfer vehicle (OTV)	45 tons payload capability LEO to GSO 35 tons fuel for a round trip 6 months round trip 154 OTVs

maintenance scenario described in Section 3.2, we need RLV and OTV as shown in Table 2 in operation before the start of construction of the commercial SPS which is presumably realized around mid-2030's. The payload in Table 2 includes the SPS unit cargo (45 tons) and the fuel for the OTV, but OTV itself (150 tons, dry mass) is not considered. 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. In order to construct 1 GW class SPS in a year, the RLV needs to be launched every 8 hours (3 times per day). If 14 RLVs are in service, the turn-around time will be 5 days for each RLV. Totally 154 OTVs with a payload capability of 45 tons each are required if we set 6 months for the round trip between the LEO and the GSO. The cargo flow requirement described above (140 tons/day) can be relaxed if we set the maintenance (replacement) period longer than 1 year.

5. Conclusion

Evaluating the radiation effect and probability of the hyper-velocity impact of the debris (meteoroid), the mission life of SPS is estimated to be about 40 years, during that period the capability of the SPS power generation/transmission will be degraded by 15-20 %. The same procedure as that in the initial construction is used for the end of life maintenance, 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 replacement operation starts around the end of life 40 years after the initial construction. The replacement is completed in a year which is the same period as the initial construction. This procedure guaranties that any space junk is not generated at end of life operation. This scenario requires well-established space transportation system between the ground and the GSO consisting of advanced RLV and OTV.

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