TESTS TO ASSESS THE VULNERABILITY OF ADEOS-2 AND ETS-8 TO DEBRIS AND MICROMETEOROID IMPACTS

Michael J. Neish, Masato Takahashi, Hironori Maejima, Hiroaki Kusawake, Shirou Kawakita, Tateo Goka

Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba City, Ibaraki Pref. 305-8505, Japan.
E-mail: mike@jaxa.jp, takahashi.masato@jaxa.jp, maejima.hironori@jaxa.jp, kusawake.hiroaki@jaxa.jp, kawakita.shirou@jaxa.jp

ABSTRACT

We summarise a series of impact tests conducted between 3 and 4 km s^{-1} into mock-ups of the high-power harnesses and solar arrays paddles of both the Advanced Earth Observing Satellite 2 (ADEOS-2) and the Engineering Test Satellite 8 (ETS-8), using JAXA's light gas gun at the Institute of Space and Astronautical Sciences (ISAS).

The objectives were to determine the vulnerability of either satellite to space debris and micrometeoroid impacts.

The results of modelling using MASTER-2001 to estimate the risk to the mission posed by an impact are also presented.

As a result of these considerations, JAXA has decided to shield the most vulnerable section of the power harness of ETS-8 with a 1-mm-thick aluminium sheet.

1. INTRODUCTION

The Advanced Earth Observing Satellite 2 (ADEOS-2) suffered a catastrophic power failure on the 24th October 2003 that ended the mission after only ten months. One of the two main working hypotheses into its cause was that a debris or micrometeoroid impact on the high-power harness carrying current between the single solar array and the satellite bus resulted in a sustained electric arc that caused its destruction. The harness consisted of a bundle of wires covered by a sheet of multi-layered insulation (MLI).

The Engineering Test Satellite 8 (ETS-8) is currently scheduled for launch in February 2007 into geostationary orbit, on a ten-year mission for satellite bus operations. Concerns about the high-power harness of ADEOS-2 prompted investigations into the debris hazard to the satellite.

2. TESTS ON ADEOS-2 HARNESS

The high-power harness of ADEOS-2, consisting of a bundle of insulated wires 1 mm in diameter, was covered by a sheet of Kapton MLI (2x25-µm-thick sheets, with 10x6-µm-thick sheets in between). A series of eight impact tests were carried out using the helium two-stage light-gas gun at the Institute of Space and Astronautical Sciences (now part of JAXA). This gun is capable of firing up to about 5 km sec^{-1}. Either soda-lime glass or alumina projectiles (density 2.5 and 4 g cm^{-3} respectively) were used, fired by means of the "shot-gun" technique using a sabot. The tests were aimed at helping to estimate the probability that a perforation through the MLI cover could cause severe damage to the high-power harness, also to assess if impact damage to the arrays proper could have explained a number of power anomalies that occurred prior to the final failure. The wires in the target were not powered up: therefore only physical damage was assessed.

With regard to the harness tests, the objective was to pin-point the kinetic energy required to perforate the MLI, and then the insulation of one or more wires of the harness in a single shot.

In summary, 1-mm soda-lime glass spheres at 3.5-4 km s^{-1} perforated the MLI with ease, and totally ruptured a number of wires in the harness underneath (wires are identical to those of ETS-8, described in Section 3). 500-µm alumina projectiles at 2.2 km s^{-1} also perforated the MLI and just penetrated the harness wires below to expose the bare interiors. A full description of the tests cannot be provided here for space considerations.

The debris scenario was abandoned as the cause of the failure of ADEOS-2 before further tests were conducted. However, the profile of the hazards posed by debris and micrometeoroid was duly raised, and concerns immediately focused on the risk to ETS-8.

3. ETS-8 POWER LINES AND HARNESS

ETS-8 has two solar arrays each just under 13 m long. Each array is divided into 4 panels, which are in turn divided into 6 sections. There is a hot and return wire running between each section and the satellite bus, each of these with a back-up wire. All the wires from different sections, running along the back face of the array, gradually converge as they approach the satellite bus. At the bus end of the arrays, wires converge to two separate harnesses 4.4 m long, each bearing current from the corresponding half of the array. These two harnesses then converge into a single harness 2.2 m long. A schematic layout of the wires and harnesses is shown in Fig. 1, while Fig. 2 shows the configuration of the four

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

Table 1. Different modes of failure of the power lines and/or harness due to hypervelocity impact.

Modes of Failure	
Description	**Effect**
a) A hit on the harness perforates one or more wires, and results in a sustained arc that causes a power failure	Should a sustained arc or a short-circuit destroy the harness, one-quarter or one-half of the total power will be lost, depending on the harness section hit.
b) A single hit ruptures both the main wire and its backup	$2/88^{th}$ of total power is lost in 20/24 cases, $1/88^{th}$ in the remaining 4/24 cases.
c) A hit ruptures an individual wire, then a later hit ruptures its backup	$2/88^{th}$ of total power is lost in 20/24 cases, $1/88^{th}$ in the remaining 4/24 cases.
d) A single hit on the front face of the solar arrays perforates the array and "blows out" one wire and its back-up in the rear side	$2/88^{th}$ of total power is lost in 20/24 cases, $1/88^{th}$ in the remaining 4/24 cases.

wires of one array section. The wires are arranged side-by-side in contact with one another, as shown in Fig. 2, and are unshielded. There are therefore a total of 96 wires in each array (4 x 24 sections). Loss of one section will result in 2/88 of the total power being lost (in 20 out of 24 cases), and 1/88 lost (in the remaining 4 cases). It is estimated that loss of 4/88 of the total power would impact mission operations.

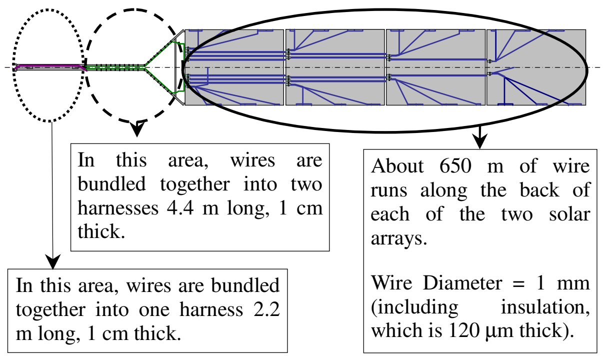

Figure 1. Lay-out of the wires and harness on an ETS-8 solar array.

The different modes of power failure (partial or complete) due to particle impacts are listed in Table 1. The most catastrophic is, of course, a) where a sustained arc induced by an impact on the harness results in 50% or 100% power loss from that array, depending on the harness section hit.

Scenario b), that of a single hit rupturing both the main and back-up wires (hot or return), obviously requires a fairly large particle.

In scenario c), both main wire and back-up are ruptured in two separate impacts. Although the probability may be low, the smaller particle size needed for this may compensate for it to some extent, so this scenario must also be considered.

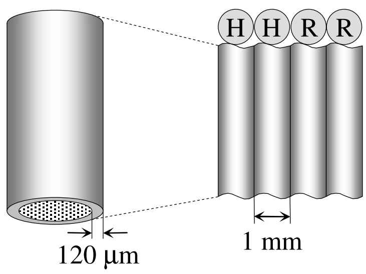

Figure 2. Layout of the four wires carrying current from and to each section of the solar arrays. Wires are 1 mm in diameter, and insulation 120 µm thick.

Scenario d), as shown in laboratory simulations, could be important, as an impact on the solar array front surface that perforates all the way through could cause a significantly larger damage area on the rear face as it "blows out". Should this area coincide with where the wires are situated, significant damage could result.

Other scenarios exist that are not considered here, such as an impact causing a short- circuit between the hot and return wires of the same section, or between a wire and the solar array substrate.

4. IMPACT TESTS INTO ETS-8 POWER LINES AND ARRAY PANEL

A number of impact tests have been conducted in order to help estimate the probability of rupture of the high-power cables and/or the harness, and assess the level of damage sustained by the solar arrays. The same facility as that used for the ADEOS-2 tests was also used here. Projectile materials and shot techniques were also the same.

The objectives of the tests were to determine

- the level of damage sustained by direct impacts on the power harness by projectiles of a range of sizes;
- if a simple 1-mm-thick Al plate is an adequate shield for the harness;
- the level of damage sustained by impacts into the solar arrays.

Both the harness and solar array targets were powered up to 110 V in most circuits, 60 V for some, and all wires carried 2 A of current. The configuration of the harness mock-up is shown in the schematic in Fig. 3. All eight shots are summarised in Table 2.

Not only physical damage to the wires, but the level of disruption to the power due to arcing, short or sustained, was assessed. The latter is considered very hazardous.

Table 2. Summary of the impact tests conducted on mock-ups of the harness and solar array panels of ETS-8.

Shot #	Projectile Diameter [µm]	Projectile Material	Shield Thickness [mm]	Velocity [km s^{-1}]	Comments
			harness tests		
1	100 (sorted)	soda-lime glass	1.0	3.5-3.6	>8-ms second arc in 110-V circuit; no sustained arc
2	500 (450-600)	soda-lime glass	1.0	3.24-3.36	no arc; no projectiles hit the harness
3	175-250	alumina	1.0	4.17	5-ms second arc in 110-V circuit; no sustained arc
4	100-125	alumina	none	3.25-3.38	no arc
7	500 (sorted)	alumina	1.0	3.30-3.40	sustained arc in two 110-V circuits; short arcs in two 60-V circuits; wires directly hit by projectiles were totally ruptured
			solar array tests		
5	100-125	soda-lime glass	none	3.31-3.43	2-ms second arc in one 110-V and one 60-V circuit; array panel not perforated
6	175-250	soda-lime glass	1.0	3.28-3.40	no arc; array panel not perforated
8	450-600	alumina	2.0	3.27-3.856	no arc; two projectiles completely perforated the array panel

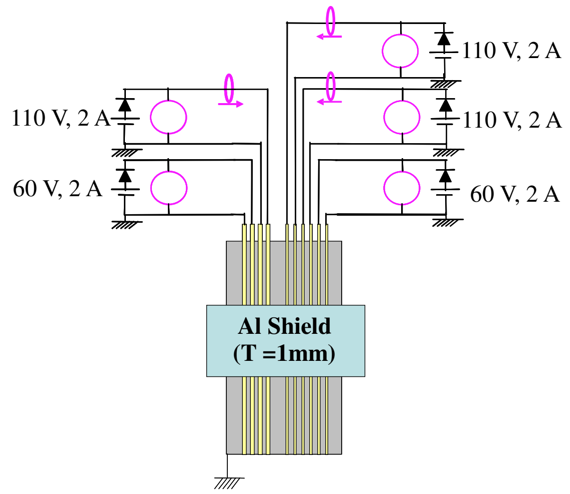

Figure 3. Configuration of the harness mock-up.

Fig. 4 shows images of the results of the most interesting of the tests, shots 7 and 8. Wires hit by the projectiles in shot 7 were completely ruptured. In addition a sustained arc was caused in two of the circuits. This projectile size was therefore deemed to be hazardous to individual wires, and possibly to the harness as well. Shot 8 resulted in complete perforation of the panel. However, no significant disruption to the electric current was observed. The exit hole diameter measured about 2-3 mm across, i.e. 4-6 times larger than the projectile diameter, large enough to cover two wires should the perforation occur directly below them. Complete rupture of two adjacent wires is therefore a possibility.

Before these results can be extrapolated to higher velocities, more impact tests are required to determine whether or not the array panels display a response curve similar to that of bumper shields, something which would forbid simple extrapolation.

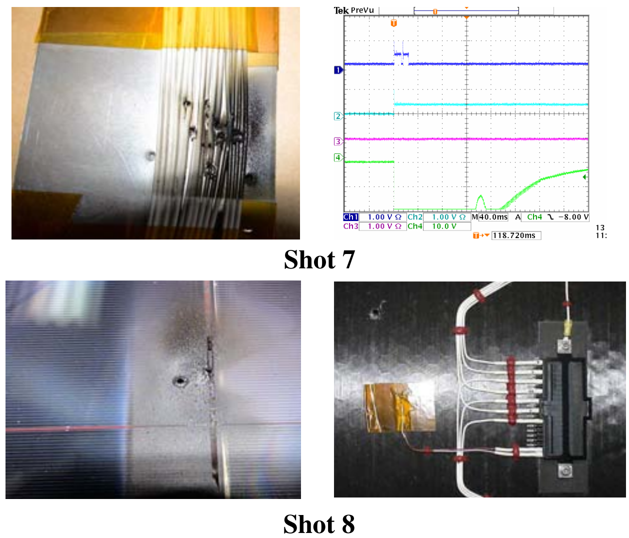

Figure 4. Shot 7, 500-µm alumina beads fired at 3.3-3.4 km sec^{-1}: (left) the target, (right) the oscilloscope trace taken over a period of about 100 ms at the time of impact. Shot 8, 450-600-µm alumina beads at 3.27-3.86 km sec^{-1}: (left) the front face, (right) the rear face showing the exit hole. Images are not to scale.

5. MASTER-2001 SIMULATIONS

Having identified the modes of failure to be considered, MASTER-2001 is used to determine the base particle fluxes that can be used to calculate failure probabilities, wire by wire. Fig. 5 shows the probability of at least one hit on either section of the wire harness in ten years. According to this chart, the probability of a 500-µm particle striking the 4.4-m section of the harness is about 3.4%, and 0.85% on the 2.2-m section. Fig. 6 shows the probability that two adjacent wires are hit by a single impact at least once during the ten-year mission of ETS-8, scenario b). This is meaningful only if a hit on one wire causes damage extending into the adjacent wire. The area of impact is taken to be the shaded region in the inset of Fig. 6, the right-hand half of the left wire, and the left-hand half of the right wire, assuming both are in contact. This is therefore a strip 1 mm wide running along the entire length of each wire/back-up pair..

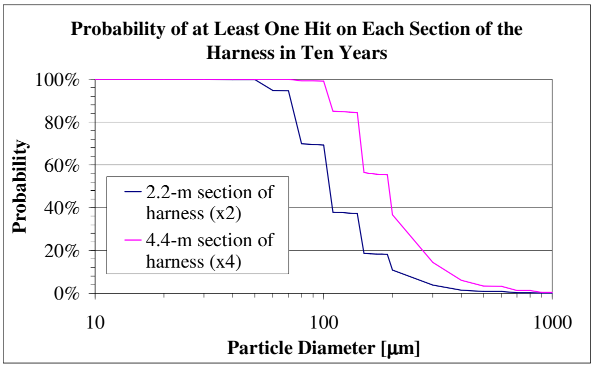

Figure 5. Probability of at least one hit on each section of the wire harness in ten years.

Estimation of the critical size required for a double rupture is difficult using the results of the tests so far conducted, as this will depend on impact angle and velocity. Until more test results are available, $d >= 500$ µm will be taken as a possible critical diameter range.

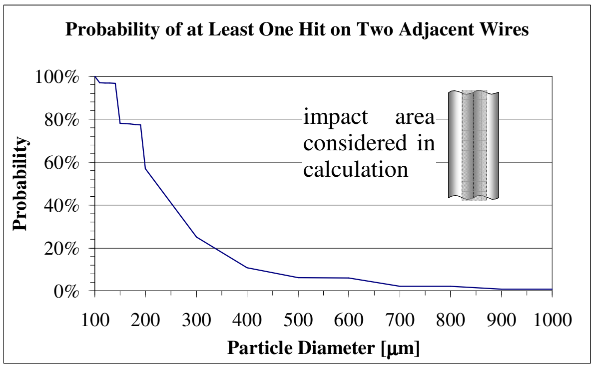

Figure 6. The probability that a single particle strikes two adjacent power lines (hot-hot or return-return) at least once during the ten-year mission of ETS-8.

Fig. 7, shows the probability that two adjacent wires are hit by a single impact *exactly twice* during in ten years. The impact surface area also corresponds to that shown in Fig. 6. This corresponds to a loss of 4/88 of the total power (two solar array sections lost), and could therefore have an impact on mission operations. The probability becomes greater than 1% between 200 and 300 µm, at which size complete rupture of two wires, or even a single wire, may not occur – so this scenario does not appear significant. Fig. 8 illustrates scenario c) in Table 1: a particle hits one wire, then another its back-up. The probability is also for ten years, and becomes significant (> 1%) below about 200 µm. From Shot 3 of the impact tests it appears unlikely that this particle diameter would be a threat to a single wire. 4-500-µm particles could be sufficiently large, but from Fig. 8 it can be seen that the probability is low enough that this scenario can be neglected.

If 500-µm particles are also capable of perforating the array panels at higher velocities, scenario d) is at least as probable at scenario b), perhaps even more so, given the greater area of damage on the rear face. This would increase the probabilities in Fig. 6 by a factor of 2 or more.

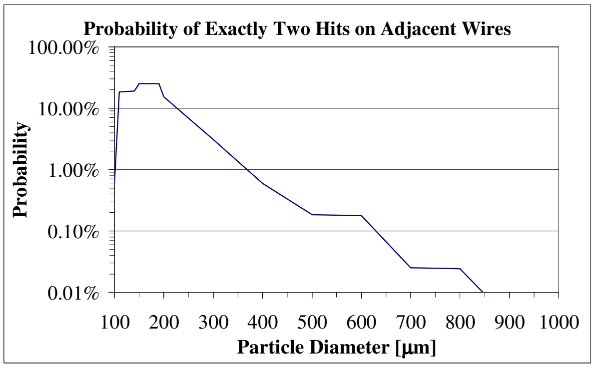

Figure 7. The probability that exactly two adjacent wires are hit by one impact, twice.

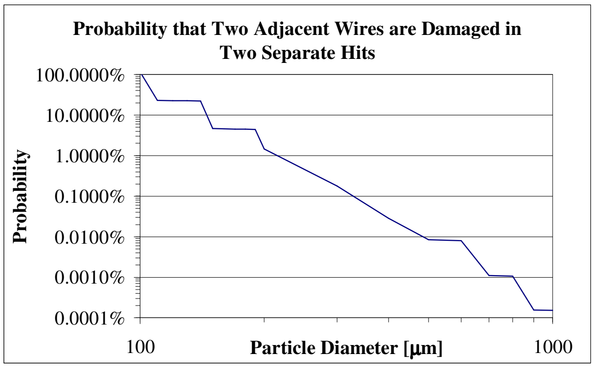

Figure 8. The probability that two separate hits damage a wire and its back-up, as a function of particle diameter.

6. CONCLUSIONS

Based on the impact tests, 500-µm particles could possibly constitute a threat to the power harness, and are also clearly sufficiently large, even at modest velocities, to rupture one wire totally, and possibly cause severe damage to an adjacent one as well. The probability of loss of 4/88 of the total power by hits on the power lines would appear to be quite low from the above calculations. However loss of 2/88 of the power is quite likely, perhaps between 10 and 20% over ten years, and this would leave an uncomfortable safety margin in the event that other problems arise. The ten-year impact probability of a 500-µm particle on the 4.4-m-section of harness is about 3.3%. The 2.2-m section of harness indicated by the dotted oval in Fig. 1 is now to be covered by a 1-mm-thick aluminium plate. This eliminates, at least, the impact probability for this critical section.

7. REFERENCES

Krag, H., Bendisch, J., Bunte, K.D., Klinkrad H., Martin, C., Sdunnus, H., Walker, R., Wegener P. Wiedemann, C. Introducing the ESA-MASTER 2001 Space Debris Model. *Adv. Astron. Sciences*, Vol. 112, Part II, *"Spaceflight Mechanics"*, 2002.