POST-FLIGHT INVESTIGATION PROGRAMMES OF RECENTLY RETRIEVED SOLAR GENERATORS

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Abstract

In 1993 two ESA solar power generators were successfully retrieved from Space.

- EURECA with its 10 panel rigid array in August 93, after 11 months in a 500 km orbit.
- One of the two flexible Hubble Space Telescope (HST) arrays in December 93, after almost 4 years in a 600 km orbit.

Both solar generators are undergoing separate Post-Flight Investigation Programmes (PFIP). These programmes cover investigations of all solar array (SA) components and mechanisms. Since both programmes have much in common, most of the component and material investigations are the same. Extremely valuable information on numerous essential subjects, such as atomic oxygen, radiation, meteoroid and space debris environment resulting damage, low cycle fatigue, material degradation etc. are expected to be obtained for both types of arrays. We will also be able to explain and understand the anomalies experienced on both solar arrays in orbit. The paper will outline both Post-Flight Investigation Programmes and will concentrate on reporting the first results and findings.

Keywords: Solar Arrays, Post-Flight Investigations, Thermal Fatigue, Power Degradation, Meteoroid Damage, Space Debris, Material Degradation

1 Introduction

The EURECA and the HST solar generators are the first solar arrays brought back from space after being exposed to the LEO environment for a significant duration (EURECA: 10.8 months, HST: 43.3 months) in a well known orbit and orbit orientation.
After its first mission the Eureca-SA was originally not planned to be investigated in detail. EURECA-SA was designed for 5 missions and the plan was to immediately refurbish it and prepare for a re-launch. However due to excessive power degradation during the first mission a post-flight investigation programme (PFIP) has been defined on short notice. EURECA-SA PFIP benefited from the work already done to prepare the HST-SA PFIP. Already in 1992, its preparation started and the content was optimised during the remaining period until retrieval. Unfortunately only one of the two HST-SA wings could be retrieved during the HST's first servicing mission (Dec. 1993) and brought back to Europe for investigation.
This paper is intended to give an insight into what is being investigated, reports on the preliminary results and what kind of results are expected, but concentrating on photovoltaic related issues only.

2 Post-Flight Investigation Programmes

It is of prime importance to the ESA to study these generators in detail. This provides a unique opportunity to study in depth the mechanical and electrical integrity of a retractable rigid panel array as well as of the flexible HST generator, following exposure to the severe LEO environment. It is expected to obtain extremely valuable and reliable information on numerous aspects, such as atomic oxygen (ATOX), meteoroid and space debris damage, low cycle fatigue, material degradation etc. It will also be possible to explain and understand the anomalies experienced in orbit. It will help to improve future solar arrays for both the rigid panel concepts and flexible arrays resulting in more reliable design and better protection against damaging effects such as random failures (e.g. short/open circuits) etc. The in-orbit performance of future arrays will be more predictable, the predictions more reliable and consequently the SA's can be designed and operated more cost effectively. The knowledge gained from the investigations is also important for the space debris and meteoroid community. The total surface of the retrieved HST wing and the EURECA solar-array is about 170 m^2, and provides a unique opportunity to study the craters of

impacting particles, also to assess the impacts and potential damage and to refine the current meteoroid, and debris models.
Both PFLIPs are co-ordinated and managed by ESA. The investigation team for the HST SA-PFLIP consists of all parties who were involved in the development and manufacturing of the solar arrays, i.e.: ESA/ESTEC, British Aerospace (BAe), Dornier, Contraves and DASA (formerly TST). For the EURECA-SA the team consists of Fokker Space & Systems, DASA Wedel and the same ESTEC team as for HST. They have the expertise for disassembly of the parts they have developed, minimising the risk that evidence is destroyed when handling or investigating the hardware. Where required, institutes and universities (i.e. for meteoroid and debris investigations) as well as the European Space Tribology Laboratory (ESTL) will be involved in the investigations and evaluations of the flight hardware. Most of the material investigations are planned to be done in the ESTEC Materials division.
The key guidelines of these investigations are to ensure that no evidence is destroyed during SA storage and handling, or when samples are being removed. Both PFIPs are now in progress. The EURECA-SA activities will be completed in Aug. 94. The HST-SA PFIP is expected to be completed in the first half of 1995. In May 95, the results will be presented at an HST-SA PFIP symposium at ESTEC.

Although both generators are different in their mechanical construction (rigid panels and flexible roll-out blankets) they have a lot in common. The solar cell assemblies are the same (only cell dimensions are different, table 1) and most of the materials and components used for the electrical network are the same.

Base material	- Crucible crown silicon	Silicon thickness	- HST: 250 μm, EUR 150μm
Base resistivity	- 10 Ohm cm	BOL SCA efficiency	- 14% (1AMO, 25°C)
Junction	- n-on-p shallow diffused	SCA absorptivity	- 0.75 (unloaded)
Back surface field	- p+ doping	SCA emissivity	- 0.83 (hemispherical)
Back side reflector	- Aluminium layer	Cover slide material	- Soft Boro-silicate base glass (CMX)
Contact system	- Ti(Pd)Ag		
Anti reflective layer	- TiOx	Cover slide thickness	- 150 microns
Surface roughness	- ≤1.5 microns	Adhesive for cell bonding	- Silicon, DC 93500 + Primer
Solar cell dimensions HST	- 20.8mm x 40.2mm	Cover dimensions HST	- 21.0 mm x 40.5 mm
Eureca, Charge	- 20.8mm x 59.4mm	Eureca, Charge	- 21.0mm x 59.7mm
Eureca, Load	- 26.8mm x 50.1mm	Eureca, Load	- 27.1mm x 50.4mm

Table 1: Solar cell assembly (SCA) characteristics

YEARS	Isc	Voc	Pmax	Vmax	Imax	I(350)	fluence
0	0.33317	0.60480	0.15409	0.50500	0.30513	0.33217	BOL
1	0.32930	0.59330	0.14911	0.49540	0.30099	0.32802	8.480e+12
2	0.32644	0.58480	0.14554	0.48834	0.29803	0.32470	1.589e+13
3	0.32417	0.57950	0.14329	0.48390	0.29611	0.32220	2.222e+13
4	0.32261	0.57580	0.14181	0.48080	0.29494	0.32071	2.748e+13
5	0.32141	0.57340	0.14075	0.47870	0.29402	0.31965	3.166e+13

Table 2: SCA performance data (HST size)

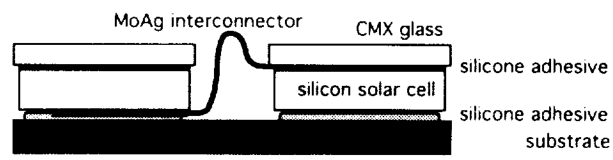

Figure 1: Interconnected SCA

Compared to EURECA, HST SA-1 investigations have the advantage that sufficient hardware can be provided for tests and investigation because there are no plans to re-use the first HST solar array. It is foreseen to completely disassemble and study the mechanisms. All blanket buffers and at least one SPA are planned to be completely dissected and analysed. The remaining parts will be subject to specific examination with small areas cut out as required.

The first activities in the programmes were the in-orbit inspections. Great emphasis was given to the photographic and video coverage during retrieval covering all SA areas and special close-ups of SA-highlights. A similar intensive photographic coverage were carried out after shuttle landing as well as initial insulation and continuity checks. Special attention will be given to the relative position of moving parts and other key features.
Based on previous experience and knowledge the investigation began at the earliest possibility at KSC, where reference samples were cut from both solar arrays, sealed in dry nitrogen and hand-carried to Europe for test and immediate investigation.

A further objective of the PFIP is to study changes of material properties and effects having a direct influence on SA power generation.
Silicon adhesive has largely been used for the blanket protection against ATOX. Those protective layers will experience changes in their material properties and their thermo optical characteristic. This is caused by the radiation environment including UV radiation, thermal cycling and attack by ATOX. Corresponding material investigations will study these type of synergistic effects.

As may be seen from the design description HST-SA has identical substrate surface coatings (DC 93500, fig. 6) on the front and rear side of the flexible blankets. Since the solar cell side was always sun oriented, the effect of the contribution of UV radiation to the synergistic environmental effects can be evaluated.

UV radiation also tends to cause darkening or reduction in transparency of the transparent silicone adhesives if they are not shielded. DC 93500 is used for gluing the cover slides to the solar cells and a darkened adhesive will reduce the power generated. One important question is, did the CMX cover glass sufficiently shield the adhesive from UV radiation?

Due to the low operation solar-cell string voltage of 37 volts (≈ 100 volts in Voc) plasma interaction or plasma sputtering is not expected to have an influence on the solar array hardware, but nevertheless it will be checked.

It is of interest to check the silicone adhesives for surface hardening and embrittlement, including depth effects, and to which degree the polymerisation chains have been changed, and also if changes caused the unbonding of the glass-fibre cloth from the Kapton foil (fig. 6 and 11).

How well the MoAg interconnector and its interconnections withstood the aggressive environment will be investigated. Are they showing signs of thermal fatigue (loop and weld areas) and to what extent did the silver erode in the ATOX exposed areas?

Comparison between shielded areas (e.g. inside stress relief loop) with respect to the surfaces exposed to the ram direction of the ATOX flux, and how the thermal movement of the interconnector influences the silver erosion are important questions to be answered. The clamped and embedded parts of the interconnectors (e.g. between cover slide and cell) will allow the study of possible creep erosion effects.

Further investigations being performed in the framework of the PFIPs are presented in section 4 together with preliminary results.

3 Solar-Array Design Description

The build-up of the two solar generators are only described to the extent which is needed to understand this paper or expected to be of interest to the SPRAT community. This implies that details of the deployment and retraction mechanisms are not discussed in this paper. For more design details refer to [ref. 1 to 6].

3.1 HST Solar-Array Design

The Hubble Space Telescope (HST) was launched into a 614 kilometre low earth orbit (LEO) on 24 April 1990. The HST is a joint NASA/ESA project. ESA provided two major elements towards the project one being the Solar Arrays (SA). Under the prime responsibility of the European Space Agency, a group of European contractors led by BAe, with DASA (formerly TST) providing the flexible blankets, have developed and built the largest flexible solar generator to date.

It comprises two double roll-out solar array wings (fig. 2, 3) which are deployable and retractable. Each wing is equipped with two solar array blankets (2.4m x 6.34m) carrying the solar cells which are protected from each other by an embossed Kapton cushion whilst they are stowed on a common storage drum.

To unfurl the blankets an actuator motor for each wing drives the four bi-stem booms out (two per blanket, fig. 4), which in turn draw the blanket from the drum by means of a spreader bar fixed between the ends of the two bi-stem booms. The first set of solar array wings were successfully deployed on 25 April 1990 with the Space Shuttle Discovery and HST in a 614 km orbit.

The HST-SA is designed to survive intact for at least five years in a ≈600 km low earth orbit (30000 cycles, +/-100°C). HST-SA is required to deliver at least 4.4 kilowatts of electrical power at 34 volts after two years in orbit. On 5 Dec. 93 (day of SA retraction) the solar array delivered 4.8 kW which is 6 % above predictions.

Each of the four solar array blankets is made up of five identical power generating sections, known as the Solar Panel Assemblies (SPA, figure 8, 11) and four Buffer Assemblies which act as mechanical and electrical interface to the deployment mechanism.

Each of the power-generating SPAs (1.1m x 2.4m) are equipped with 3 solar cell strings, each having 106 solar cell assemblies (SCAs) in series, two of them with 8 single solar-cell rows in parallel and one of them with 7 single cell rows in parallel. The single cell rows for each string are connected via MoAg tapping bars in groups of 14, 15 or 16 cells. All of these groups are protected by flat solar cell shunt diodes (Si wafer 2 cm x 2 cm with Au coated Ag in-plane interconnector and CMX cover) for shadow protection. They are

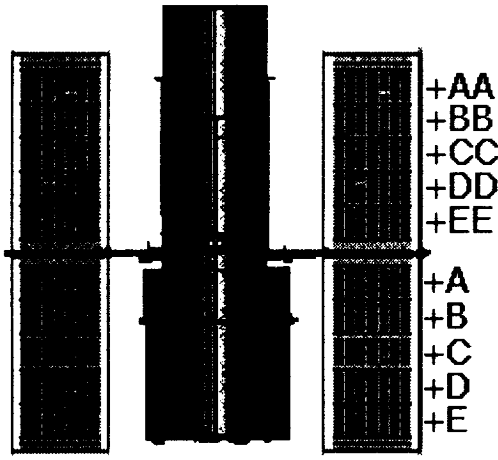

Figure 2: Solar array hot case configuration

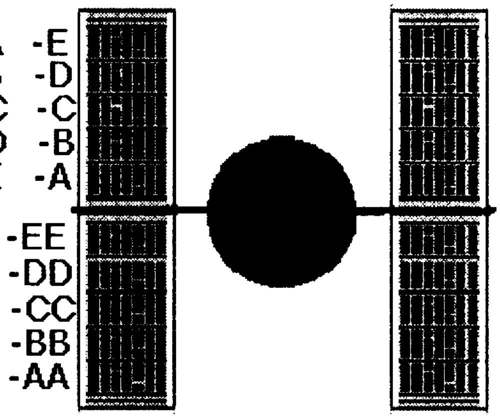

Figure 3: Solar array in cold case configuration

Fig. 4: Bi-Stem Boom

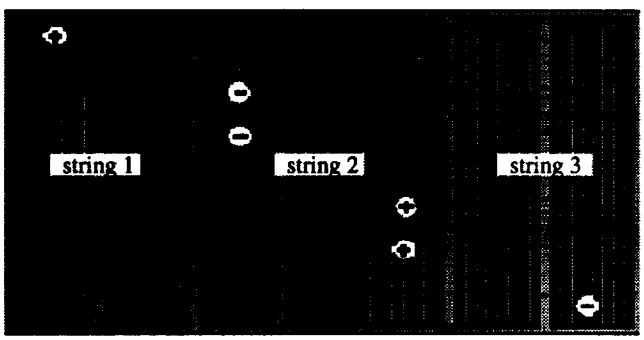

Figure 5: Solar-panel assemblies (SPA)

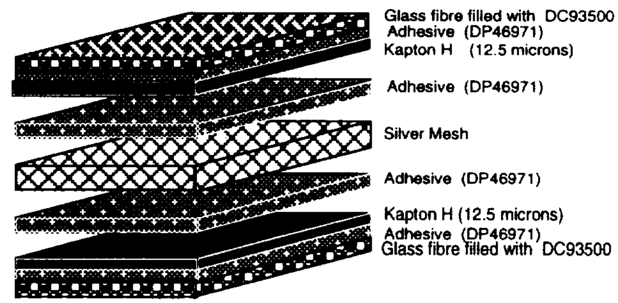

Figure 6: Exploded view of the 0.21 mm - thick, flexible carrier substrate of the SPA, including 50 micron-thick silver mesh for power transfer

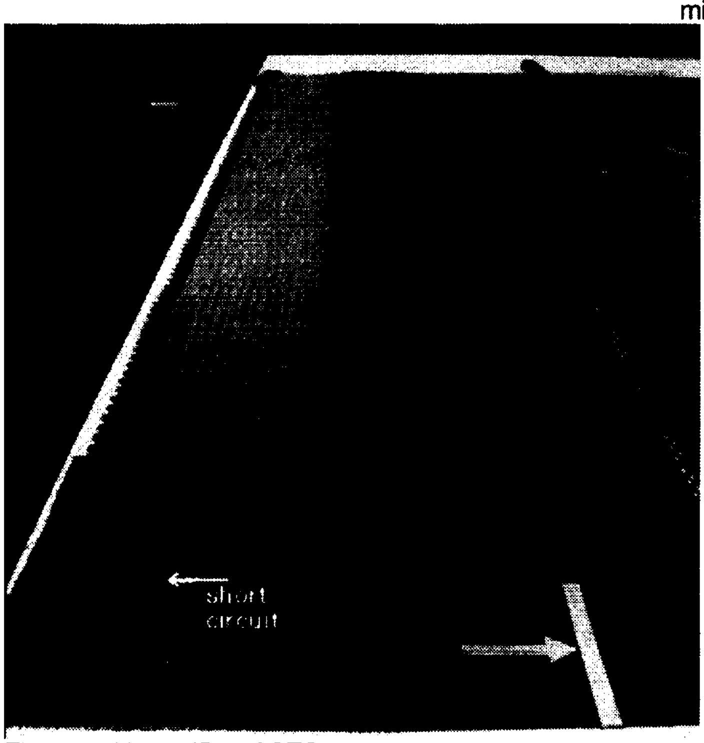

Figure 7: Upper IBA of STSA-1 with Ag power tracks for string connection, discolouration due to UV and location of anomaly

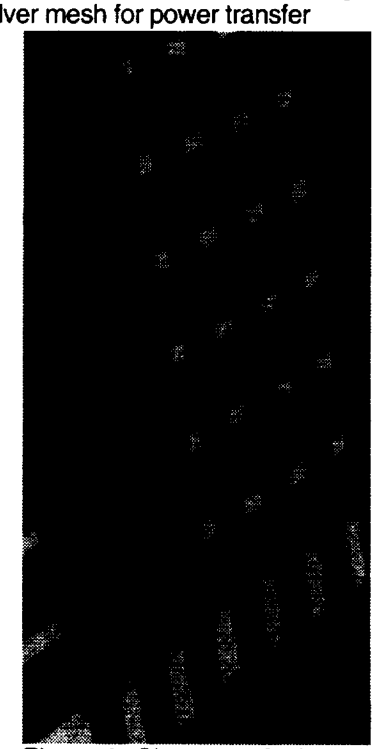

Figure 8: Close-up of short circuit location (rear side)

mounted in the tooling gaps between the solar cell strings. On the Inner Buffer Assembly (IBA), figure 7, the individual solar cell strings are electrically connected by means of 75 micron thick silver foil strips to main and redundant connections for each SPA. They are routed to a flexible printed circuit board which serves as the interface to the harness attached to the deployment mechanism.
The basic carrier substrate of the flexible blankets consists of a 210 µm thick atomic oxygen (ATOX) resistant glass fibre/Kapton compound (Fig 12).
The power is provided by 48760 solar cell assemblies (table 1, 2 and fig. 1) consisting of silicon cell, cover and MoAg interconnector. They are bonded with silicone adhesive RTV-S 691 to the 20 SPA substrates.

3.2 EURECA Solar-Array

The European Retrievable Carrier (EURECA) is a unique, re-usable, user oriented space facility developed to meet the needs of both scientific and application oriented users. The Eureca solar array consists of 2 fully interchangeable wings of 5 panels each (fig. 9. 10).
The panels consist of a rigid aluminium honey comb structure with carbon fibre face sheets of 1.4 m width and 3.4 m length. The thickness of the substrate is ≈ 22 mm (fig. 11).
The panel size requires 6 hold down points of 100 mm diameter in-side the panel area for stowed conditions and 4 edge brackets for the deployment mechanism. On the front side the panels are equipped with the solar cell network bonded with the standard silicone adhesive RTV S-691 to an insulation layer (fig. 11) which protects the structure against the atomic oxygen environment. For the solar cell layout ATOX resistant MoAg interconnector (Ag-coating required for welding) have been chosen. In the area exposed to the environment the silver has been removed from the cell interconnector (except Panel F5 which was planned to be a qualification panel). On the rear side an Aluminium/Kapton/ITO layer is bonded to the panel for protection against ATOX erosion and to improve the thermo-optical behaviour of the panels.

The power conditioning design required that the panels are split into a load (main bus) array part and a charge array part as shown in figure 12.

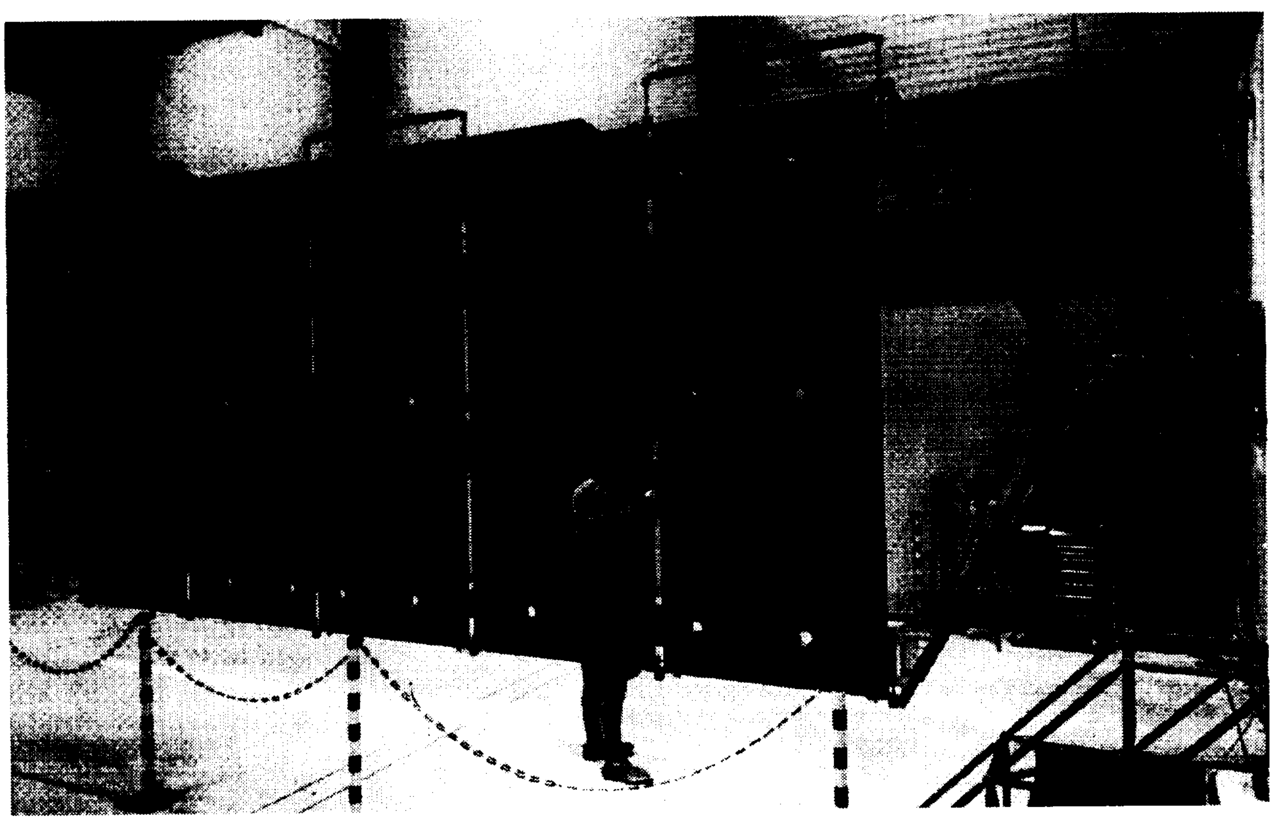

Figure 9: EURECA-SA wing after retrieval at Fokker Space & Systems

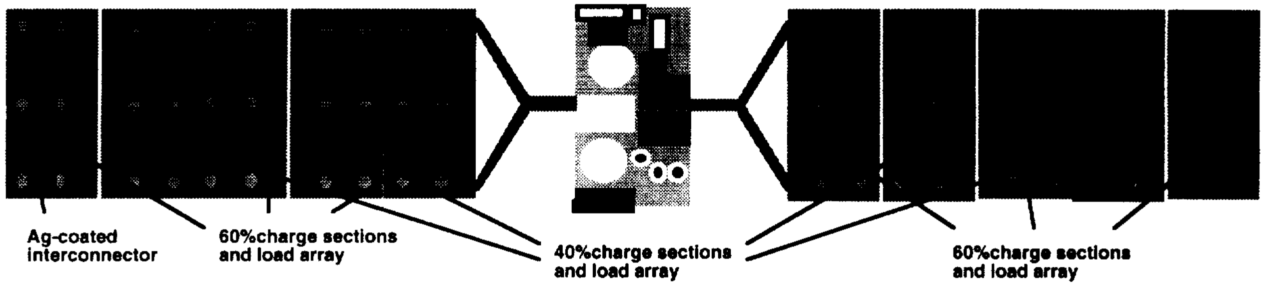

Figure 10: EURECA solar-array configuration (deployed: 1 Aug. 92, retracted: 24 Jun. 93)

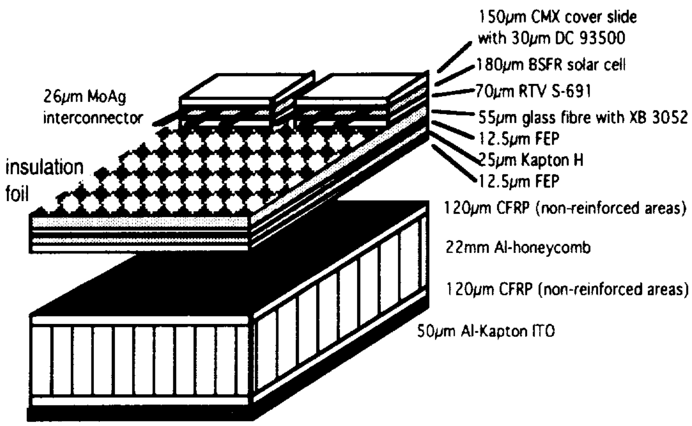

Figure 11: Panel cross-section

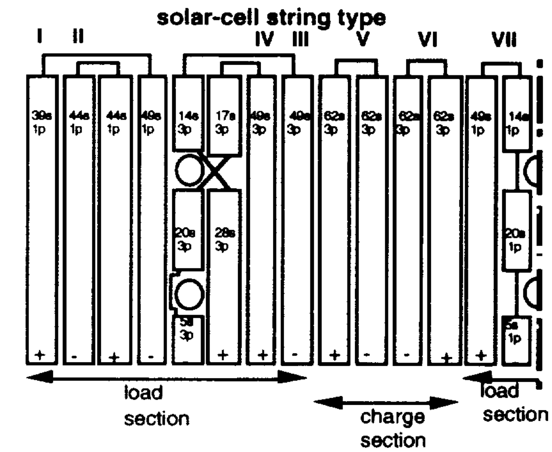

Figure 12: Solar cell string layout of solar array panel (panel half)

Each panel is equipped with 4 charge strings with 124 cells in series (124s). These charge strings are built up of 3 single cell rows with intermediate parallel connection via MoAg - tapping bars in groups of 6 to 12 cells. All these groups or shunt intervals on panels F1, F5, F6 and F10 are protected by flat solar cell shunt diodes (0.2mm x 20mm x 40mm) against local hot spots since shadows were possible on those panels. To reach the optimum cell packing factor the shunt diodes are located on the rear side of the panels.

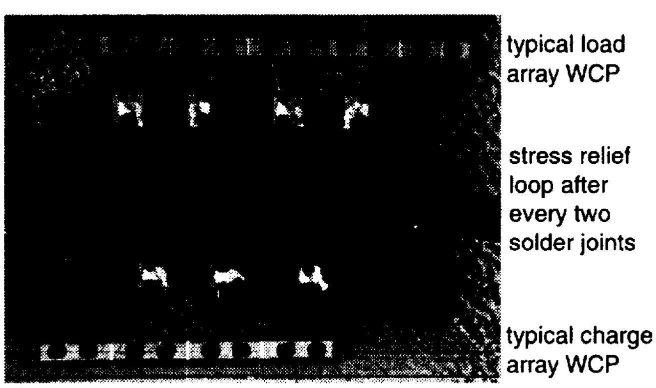

Figure 13: Wiring Collecting Panel (WCP) arrangement

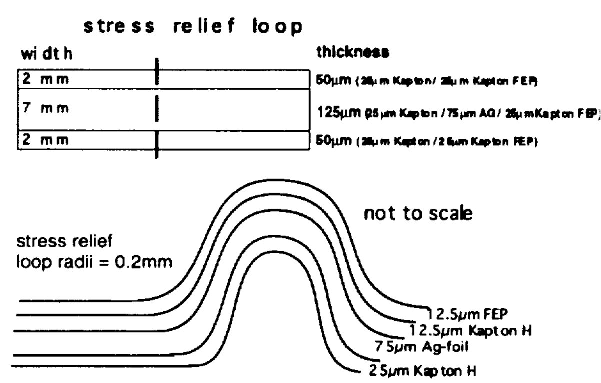

Figure 14: Design details of WCP

The build-up of the load array is following the same shadow protection concept with its shunt intervals but different number of cells per string in parallel. Due to geometrical constraints the cell dimensions for the load array are different to the charge array type.

Load array string are build-up with 91 and 88 solar cells (26.8 mm x 50.1 mm), respectively, connected in series to provide the required power of 2500W after 1 year at 30 V at any condition during the sun-lit phase.

Each of the solar cell sub-strings (Fig. 5) or cell matrices is equipped with silver bus bars (coated with RTV S-691 for ATOX protection) at their ends to form a solar cell string. The solar array strings of the load- and charge array are separately wired through holes in the panel to a wiring collection panel (WCP) on the panel rear side where the individual solar cell strings are connected in parallel (solder connections) to form electrical sub-sections. The WCP design and wiring connection concept is given in figures 13 and 14.

4 Post-Flight Investigation Programme - First Results

4.1 HST-SA In-Flight Power Generation Anomalies

During its almost 4 years in-flight operation there were 5 power generation related anomalies on the 4 blankets. Two disconnected solar cell strings from which one recovered, a short within a solar cell string of SPA -CC (fig. 3) which also recovered, a short between a power circuit and a temperature sensor circuit and a short between two SPAs and structure. The intermittent short circuit on SPA -CC and the last anomaly are on the retrieved wing (-wing or -V2 wing).
Until now there are no results available on the -CC anomaly, however the last failure seems to be traced. The failure appeared on 5 December 1993 while astronauts attempting to close the -V3 Aft Shroud door during HST's First Servicing Mission (FSM), EVA-1.
Having reviewed the anomaly history of both solar array wings together with the recent in-flight data it was concluded that there was a short from the positive rail of SPA-C (SA section 4) to the return rail of SPA-E (SA section 3) and a short from the newly formed SPA -C/-E circuit to structure (fig. 15).
The above shorts are theoretically possible at several locations, due to the physical layout of the blankets. This is limited to SPA-C and the IBA of the upper blanket (-wing). Other theoretically possible failure locations (PCU, diode box, harness) were investigated but the in-flight data was never in agreement with possible failure scenarii.

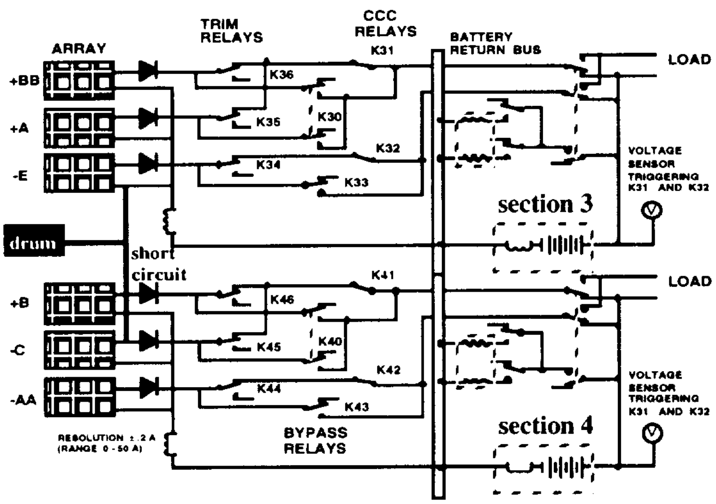

Figure 15: STSA-1 Section 3 and 4 logic with short circuits indicated

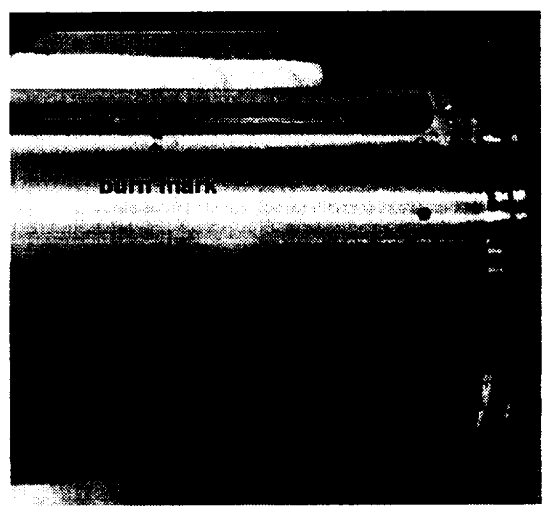

Figure 16: Drum with cut-out and burn mark

After HST SA-1 retrieval electrical health checks were performed at KSC and at BAe. There was a short circuit between SPA-C and -E as well as low resistance between SPA-E to ground. The visual evidence was only available after completion of flash testing and after disassembly of the blankets from the drum. There was a burn mark on the IBA where the SPA-C positive rail crosses the return rail of SPA-E (fig. 7 & 8). The cross-section of the IBA substrate is the same as for the SPAs (fig. 12), except that the Ag-mesh is replaced by: 75μm thick silver strip/ 25μm Kapton/ 75μm Silver strip. The location of the burn mark on the IBA is more visible on the rear side of the blanket at the interface to the flexible harness. This flexible harness is routed to a printed circuit board (PCB) located in a cut-out slot of the drum (fig. 16). Where the IBA is in contact with the edge of the cut-out, the burn mark on the IBA coincides with a burn mark on the drum.
This indicates that the observed shorts during FSM are on the upper blanket at the expected locations, showing also that both shorts (between SPAs and the short to ground) were caused by a single failure.

Presently the following failure modes and conditions (single and combined) are being investigated:

a) Sharp edges on silver wiring strips due to manufacture by guillotine.
b) Manufacturing induced effects (e.g. pre-damaged, torn/bent silver bars, foreign metal inclusion)
c) Wear of IBA, and flexible harness and cushion surfaces caused by cut-out edge and PCB cover.
d) Creep of Kapton (25 micron insulation between power tracks) due to local pressure on the IBA and by the interface to the PCB cover.
e) Thermal cycling effects.
f) Electrical fields.

All non electrical anomalies which were observed are not discussed here but most of them (e.g. tension sensor failure, SA jitter and stick-slip effect) are described in ref. 7.

4.2 EURECA-SA In-Flight Anomalies

Since 14 Aug. 92 (day 227) the solar array has continuously experienced anomalous power degradation due to unexpected in-orbit failures (one short circuit and numerous open circuits).Two examples are given in the following:
On day 263 of 1992 it was observed that during the first minutes after entering eclipse the current sensor of section 2.2 indicated a current from the battery to the solar array (no blocking diodes were put between the SA and battery circuits). Figure 17 shows the actual current profile. The current profile with its obvious sensitivity to temperature changes is typical for a short circuit. An evaluation of the in-orbit data indicated that the short is present at about half the string length of a solar cell string (40% branch of section 2.2) with three solar cells in parallel and 124 cells in series.

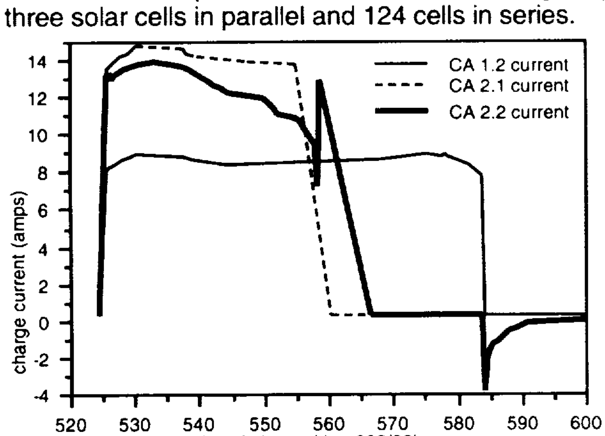

Figure 17: Charge current profile at time short circuit

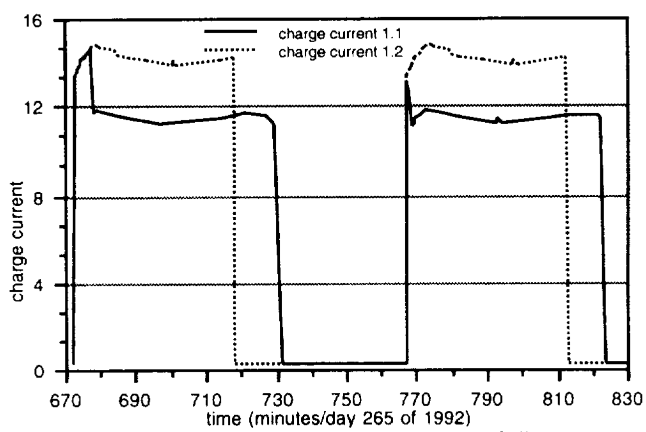

Figure 18: Orbit with first open circuit failure

After retrieval a large burn mark was found at the expected short circuit location on panel F7 (fig. 19). The size of the burn-out area is unexpectedly large and indicates that very high temperatures must have occurred at this spot (>2000 °C). In some areas the glass from the cover and the silicon is melted. Adhesives and insulation foil are carbonised. X-ray photographs also reveal that the honeycomb of the panel has locally been damaged below this area. Experts on arc progression are involved in the investigation of this unusual burn mark. The triggering mechanism(s) of the burn mark is not yet found. Tests are planned to reproduce this anomalous event.

Between 21 Sept. 92 (day 265) up to the end of the mission a certain number of open circuits were observed, first in the charge array sections and later also in the load array. From 21 Sep. 92 onwards sudden drops of ≈1.5 and ≈3 amps were observed in the charge current profile (1.5 amps corresponds to the current generated by one solar cell charge string). In the beginning wing 1 charge sections were affected and only towards the end of mission wing 2 solar cell strings started to fail. In some cases the loss was immediate, in other cases the string toggled before the single or double string was lost. In all cases the first drop in current generation was within the first three minutes after entering orbit day. A typical sample of recorded current profiles, showing an open circuit failure is provided in figures 18. The cumulative charge array power loss during the mission is given in figure 21.

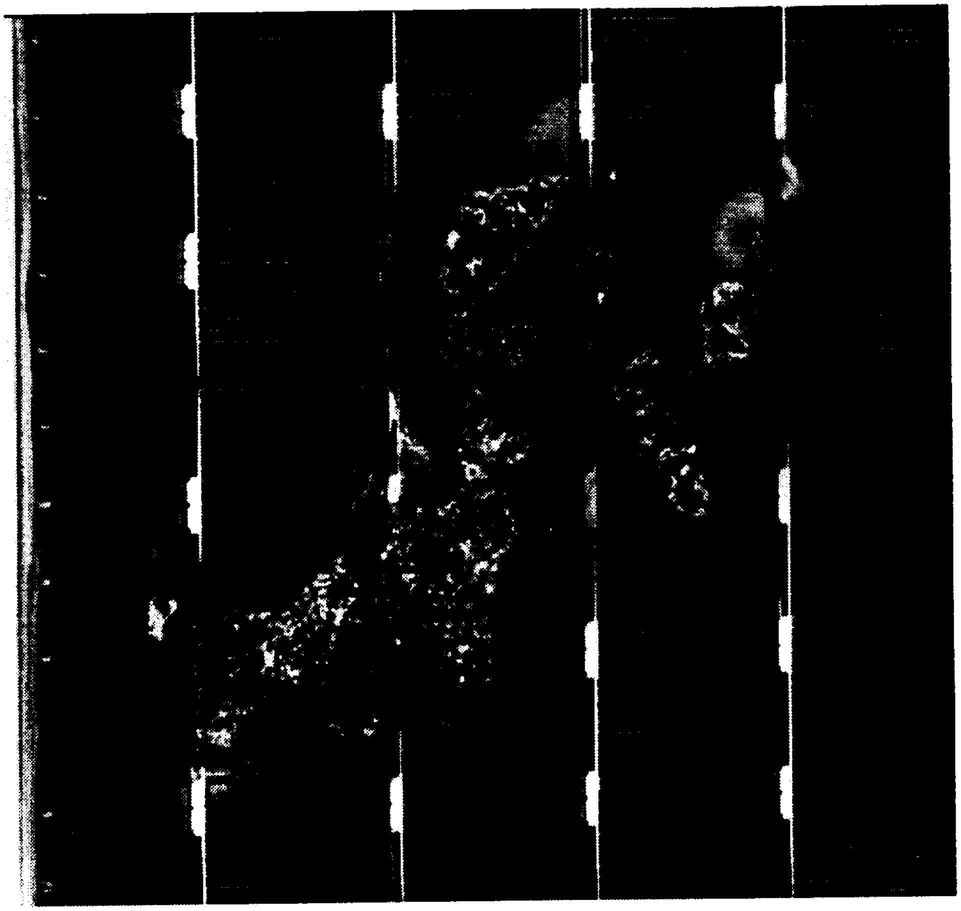

Figure 19, left: Burn mark at short circuit location (shown area is ≈ 10 cm x 10 cm)

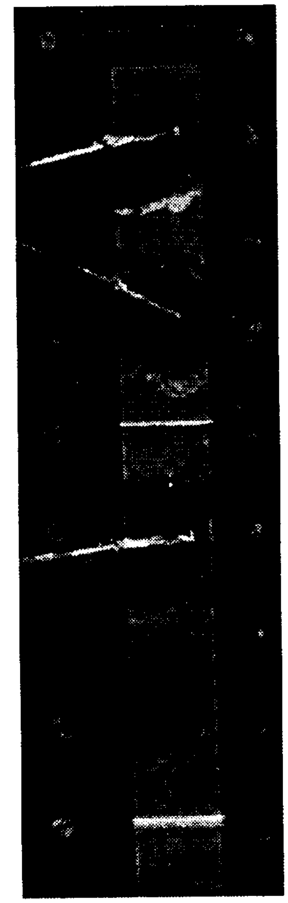

Figure 20, right : Part of a WCP showing early effects from arcing in stress relief loop

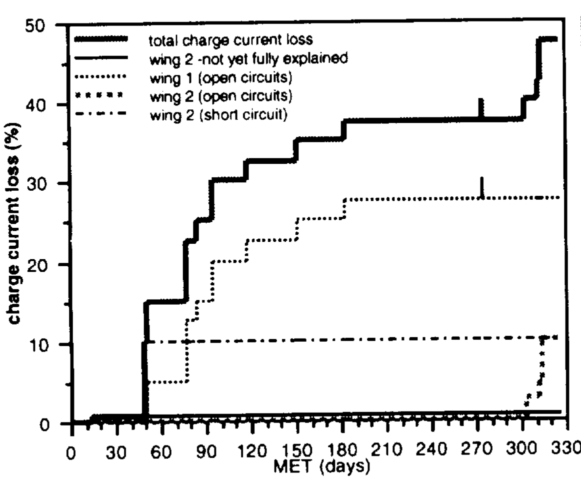

Figure 21: Cumulative charge array power loss during the mission

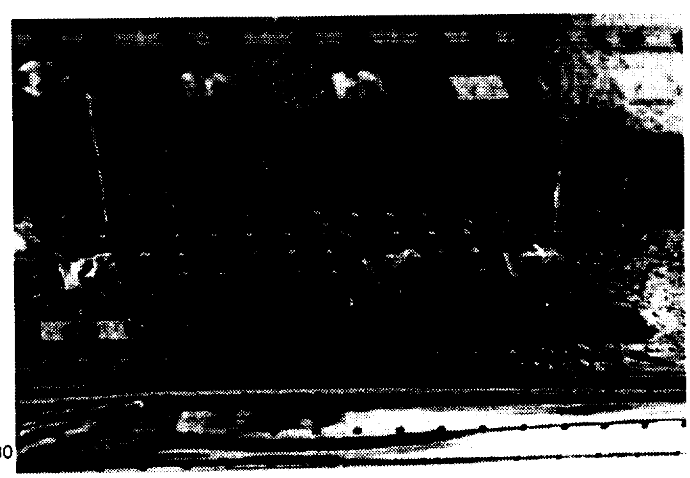

Figure 22: Completely destroyed WCP

Due to the numerous anomalies in the charge array it was also expected that in the load array several solar cell strings could be lost. There is no easy method to measure the load array output because the required power from the load is most of the time below the actual capabilities of the load array and the string/section currents are not measured. Only at times of high power consumption, above the capabilities of the load array, the actual load array performance can be roughly calculated using the total load current and the delta current to be provided by the batteries. The last possibility was in Jan. 93, shortly before all payload experiments were successfully completed. It could be calculated that at this time about 24 % of the load array capability has been lost.

From the investigation into the loss of solar cell strings it was found that the power loss is a result of failures in the wiring collecting panels (silver bus bars) located on the rear side of the panels connecting solar cell strings in parallel. The failure is a common mode failure occurring in all WCPs. The failure occurred in the stress relief loop and all parties involved in the investigation agree that the failure is a fatigue problem due to inadequate bend radii in the stress relief loop. Figure 20 and 22 give an indication from the degree of damage seen on the WCPs. It covers the complete range of damage from broken loops (only detectable with X-rays) still conducting current, first sign of arcing until complete destruction of the WCPs with short to panel structure. Plasma and arcing experts will also study this type of arc progression.
The reason why this has not been detected prior to launch is, that the WCPs were neither tested in a fully flight representative configuration nor were the loops inspected after test to the required detail (X-ray). However, this failure would be easy to correct for a re-flight. The failed components can easily be removed and replaced by reliable WCPs.
Another clear early conclusion from the WCP related investigation is that the acoustic test performed only on wing 1 cannot be made responsible for any of the failures. If a proper design would have been chosen the effects from the acoustic test would not be visible. In our case, we are only "lucky" that we had this weak design allowing us to correlate the acoustic test and the launch environment with fatigue effect as a result of in-orbit thermal cycles. This helps us for the future to better consider the total mechanical stress on the electrical network.

However, in light of the extent of the failures, all payload and mission objectives were met. The flexible nature of the mission planning and payload together with adaptable operational methods allowed work around solutions to be incorporated as the mission and failures progressed.

4.3 Power / Solar-Cell Degradation Studies

For all satellites, reliable solar-array power degradation studies are needed, and it is important that all damaging mechanisms are considered in the power budget predictions. The goal is to fully understand these power degradation effects. This give us the chance to minimise their effects on the solar array during the design phase, or even eliminate them in some cases. For this reason great emphasis will be put in studying all the negative impacts on electrical power generation.
Extensive radiation studies and tests will be performed to predict the total accumulated fluence and evaluate the effects of electron, proton and photon radiation on the solar-cell assemblies.

The most interesting parameters for the Space Telescope cell type, in combination with the 150 micron thick cover and resulting degradation characteristic for 1MeV electrons/cm^2 are shown in table 2.
These are well known and well established characteristics for solar cells radiated with 1MeV electrons. The radiation environment is also well known, but the uncertainty is, if the proton and electron spectrum is correctly converted to the 1MeV electrons. Ground tests for comparison will be done refining the power predictions and power verification method for future solar arrays.

When, solely the effects of radiation are used to evaluate the power during lifetime the resulting total degradation would be under-estimated.
The monitoring of in-flight generated power at the operation voltage does not allow to differentiate between power degradation caused by radiation and other damaging effects. Thus only a total power reduction is observed. The solar cell efficiency also changes with the solar cell operation temperature. Parameters which alter the array temperatures are the cell efficiency itself and the thermo optical properties of the materials used on the outer surfaces of the array.

In addition to the natural environment (radiation temperature, ATOX) further potential impacts on the power output have to be considered. These are solar cell orientation errors, solar cell mismatch, meteoroid and space debris bombardment and random failures, which include open circuits as well as short circuits (not caused by meteoroid and space debris). These effects are considered in the form of current and voltage loss factors applied to the solar cell network. Except for the sun intensity the individual current or amperage loss factors typically considered were based on ground tests and best engineering estimate, but worst case and never expected to occur. Those used for the HST solar generator are summarised in table 3.

Years in Orbit	BOL	1	2	3	4
Calibration Error	.980	.980	.980	.980	.980
SCA mismatch	1.00	.998	.996	.994	.992
Orientation Error	.996	.996	.996	.996	.996
Random Failure	1.00	.982	.970	.960	.950
Meteoroid/Debris	1.00	.995	.990	.985	.980
Total	**.976**	**.952**	**.934**	**.917**	**.901**

Table 3: Current or amperage loss factors for HST-SA deployment on 25th Apr. 1990

The power profile prediction for one typical SA section and actual in-flight data are given in figure 23. After 43.3 months in orbit in-flight data show currents 6% above the prediction.
The in-flight power generation of HST-SA is continuously monitored and recorded. However, only readings taken in "cold case" configuration (fig. 3) are suitable for the power degradation studies. Others solar array slew angles or HST off-nominal roll angles result in undefined reflections or shadows on the solar array. Due to the numerous reorientations of the HST this for the power verification ideal configuration is not frequently approached and also angles close to this configuration had to be used to monitor the power degradation. Additional power generation due to reflections can reach 4 % (total array output).

It is getting increasingly important for economic reasons to adjust these worst case factors, which normally cover all solar array eventualities, to more realistic degradation factors. STSA-1 offers us the possibility to investigate which losses were considered too pessimistic or too optimistic, or may be there are others to be considered in the future.
For example, the effect of particle impacts on the power generation can be checked by a laser scanning the surface of the SCA. The distribution and number of impacting particles can be provided by the corresponding numerical models.
A darkening of cover slide and its adhesive by UV, if any, will be verified by means of spectral response measurements

Reliable power/solar-cell degradation studies can only be performed with the in-flight results from HST-SA because there was no measurable degradation on the EURECA-SA when measuring on solar cell string level using the Flasher Test Equipment. Eureca power output measurements compared to pre-flight data were between +5% and -1.6%. With the known uncertainty due to electrical contact difficulties, all results are within the measurement accuracy of flash test (+/- 1%).

For HST a LAPSS (flash-test) was performed on the integrated solar array blankets. The results are shown in figures 24 to 26 together with the pre-flight data. The Pmax data were intentionally left out because at this test level they are not suitable for power degradation studies. There are too many unknowns due to blanket wiring and harness. The results for the currents are very homogeneous. There are insignificant small variations between the SPAs. The measured degradation for the two operation points (short circuit and at 34 volts) is 3%. This is including all cell damages (particle impacts etc.). The results are as expected, but not in line with the worst case predictions. The worst case relative degradation outlines 10% for these operation points.
For the open circuit voltages the degradation is smaller than expected. It varies between 0.2% and 0.7% (fig. 25, due to the short in SPA -C no measurement available for SPA -C).

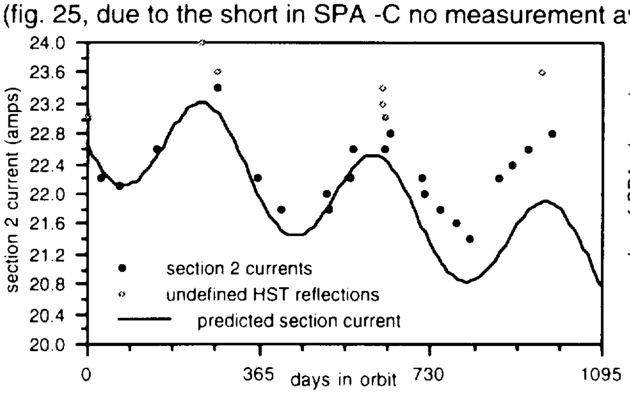

Figure 23. Power profile of SA section 2

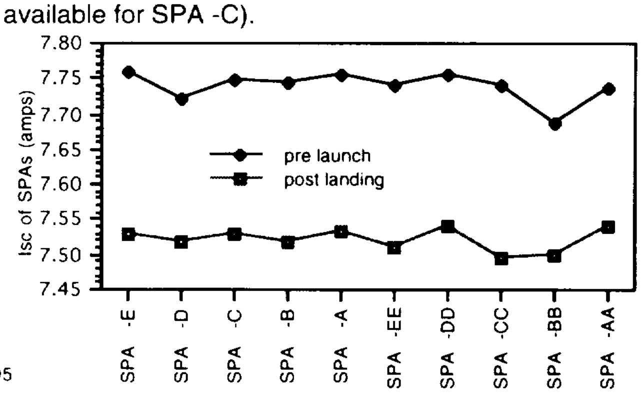

Figure 24. Short-circuit current comparison

Although above results give already a clear indication of the much smaller cell performance degradation when compared with the worst case predictions, more detailed power measurements are planned on SPA level, string level and on individual single cell rows in shunt intervals . The results will be compared with pre-flight data which partly consider the initial matching classes distribution for individual single cell rows in shunt intervals.
Two different standards (JPL ST-05, and Telecom 10/5) were used in parallel during the HST-SA1 programme. Because of the low degradation it will be difficult to reliably assess the actual level, but it will be attempted. To evaluate the relative degradation is much easier.

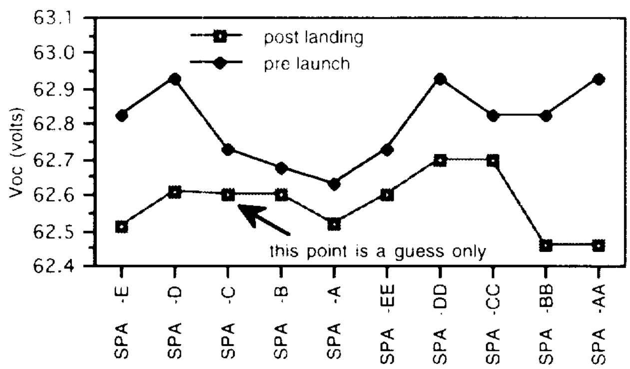

Figure 25. Open-circuit voltage comparison

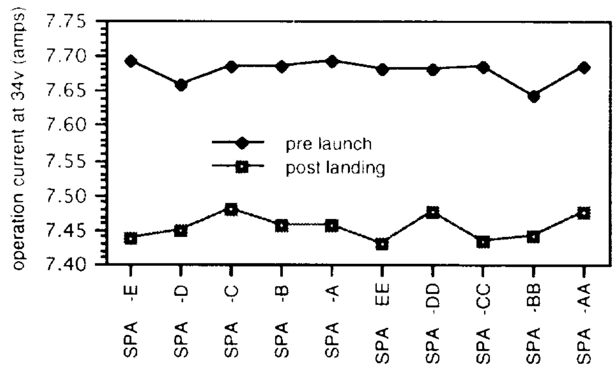

Figure 26. Operation (34v) current comparison

4.4 Results from Material Investigations and General Observations

HST-SA
The blanket compound seems to be in a good bonding state. No delaminations of the carrier substrate were visible from the front side. This is planned to be verified by a vacuum test on a small coupon sample.
The piano hinges are in good shape. No rupture of hinge loops were observed. In one case the hinge rod penetrated the sliding protection substrate (≈ 1 cm). There will be a detailed inspection of the contact point of the hinge rod and the protection substrate, and a measurement of the force needed to push the hinge rod through the restraint tab.
No delamination of the GFRP stiffeners have been observed.
The RTV S-691 coatings show different degrees of discolouration. This is very obvious where the stiffeners and meander bars are next to each other. The coatings on the stiffeners are generally much darker than the coatings applied on the silver bus bars or meander bars. A thickness measurement of the coating might explain this difference

The SCA interconnectors are in good shape. The colour when inspected with unaided eye is similar to the interconnectors seen on EURECA. Since Eureca had the silver removed in the ATOX exposed areas it would be no surprise when on STSA the silver in the ram direction is completely gone. ESTEC Materials division is taking care of this investigation.

The shunt diode assemblies are in good shape. There is no obvious darkening of the DC 93500, but spectral response measurements will still have to be made (i.e. on SCAs). Considering that the gold coated in-plane diode interconnectors were exposed to almost 4 years in the LEO environment they are looking very good. The gold coating was obviously efficient and provided sufficient protection against ATOX.

DC 93500 was also used as ATOX protection for the flexible substrate (fig. 6). Its darkening under UV light is known and it was no surprise to see a strong discolourations of the blankets. The most pronounced discolouration can be seen on the upper IBA (fig. 7). The portion which was exposed to UV light is very dark over a short stripe of ≈ 10 cm, at a location where there were reflections from the cushion roller. Temperature effects on the discolouration are also seen at the location on top of the power tracks. Other areas were less dark. The unexposed areas were almost as new and had the original colour.

Contrary to the Eureca-SA, no effects from arcing have been observed on the front side (unaided eye inspection). The rear side is not yet accessible. In the framework of our PFIP potential arcing areas will be investigated in detail.

EURECA-SA

As for HST-SA there are no further special observations concerning the bonding integrity to report. There was no significant change of thermo optical properties on solar cell assemblies (SCAs) other power generation related surfaces (i.e. aluminised Kapton ITO).

The investigation has also revealed that the bus bars and their connection method are containing weaknesses in the design which will fail after a re-launch. Some have failed already. However, the total extent of the bus bar failures can only be established after evaluation of the X-ray photographs taken from all critical and accessible areas. To date only the worst areas are visible, since all bus bars are coated for ATOX protection with a non transparent adhesive (RTV-S691). Metallurgical investigations are also foreseen. But from initial observations it can be concluded that the bus bar design is not fully reliable. In addition, the external forces induced from the cables soldered to the bus bars have been underestimated. For EURECA-SA the conclusion is that without correcting the bus bar problem with its interconnection method, a re-launch of the solar array is not possible and a reliable repair method must be found.
The results from the material investigations have not yet been completed, except for the reference samples cut at KSC from panel F5 having silver coatings exposed to ATOX. The results have already been published in reference 3. Different types of silver erosion have been found. Changes of surfaces are discussed which includes contamination (see also reference 8).

4.5 Investigation of mechanisms

HST-SA

After completion of the first checks (at KSC and BAe, Bristol) and a deployment and retraction cycle all three mechanisms (Primary Deployment Mechanism, Secondary Deployment Mechanism, Solar Array Drive) will be dismounted for detailed inspection and investigations.
In general all moving parts will checked against their pre-flight performance, for evidence of wear and damage.
Torques and frictions will be measured where applicable.
The state of lubricant in each bearing will be assessed. Fluid reservoirs and possible fluid creep will be examined as well as surface treatments. Wavy washers/preload devices will be checked for deformation, adhesion etc. Gears will be investigated for state of lubricant gear wear and wear of ceramic gear carriers.
Static adhesion or fretting will be examined on all clamps/end stops.
Electrical contacts will be checked. Motor currents including speed/torque characteristic will be studied as well as brushes and commutator surfaces
The above list is not exhaustive but reflects the detail to which we intend to study the mechanisms.

EURECA-SA

The EURECA-SA deployment/retraction mechanism worked like a clockwork. All deployment - tensioning-retraction cycles, prior to launch, in-orbit and post-flight were in excellent agreement. No adjustments are needed for a re-flight.

4.6 Meteoroid and space debris investigations

The investigation of space debris and meteoroid particles and their distribution is one of the major tasks and of great help to the space debris and meteoroid community in refining their models and knowledge on damaging effects of impacting particles.

EURECA-SA

The meteoroid survey on both wings have been completed in Dec. 93 and the evaluation of the craters is under way. So far it is known that on the outer panel of +X wing 165 out of 3108 solar cells have been hit of which 68 have a larger impact feature than 200μm (see also ref. 9). No particle has penetrated the panels completely. Figure 27 shows typical impact craters from the HST and Eureca solar array.

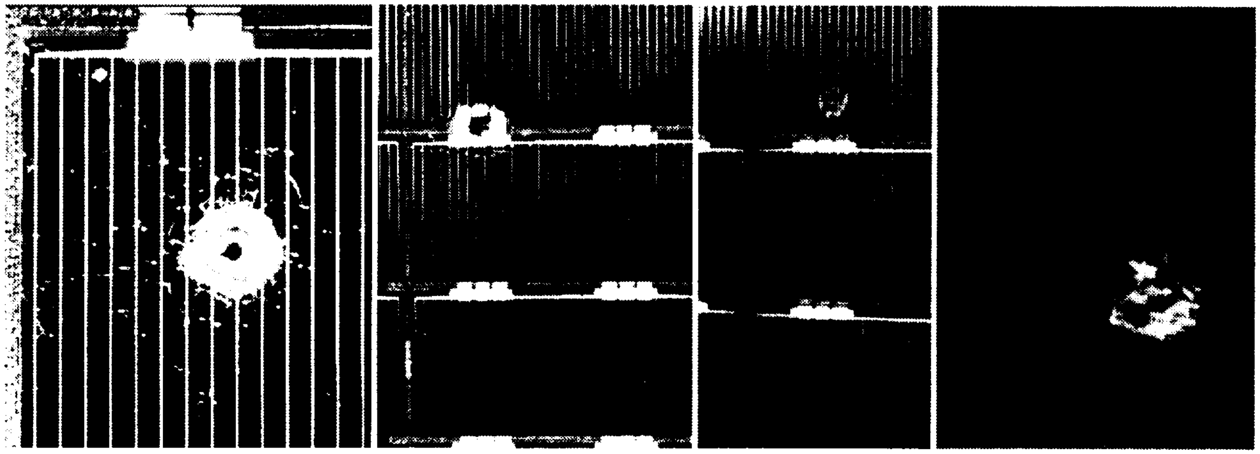

Figure 27. Typical particle impacts
Left: Largest impact feature on EURECA-SA (solar-cell grid finger spacing for all cells = 1.2 mm)
Centre left: Impact on HST blanket with particle penetrating the blanket at the cell interconnector
Centre right: Impact feature on HST blanket (rear side hit, no particle penetration)
Right: Impact feature (≈ 4 mm) of particle penetrating the HST blanket (rear side view)

HST-SA

After an exposure time of almost 4 years in orbit about 40000 particles greater than 10 microns are expected on the ≈ 70 m^2 of the HST-SA1 wing (counting both sides of the array) from which several hundred will penetrate the blankets.

It is foreseen to examine all solar array units for highlights and use only the two blankets (still ≈ 60 m^2) for the systematic documentation of crater and impacting particles. The survey of both blanket front sides have just been completed (10 June 94). Based on the high number of impacts the plan is to document on the 2 blankets impact features ≥100 microns only. The cataloguing and investigation of smaller particles will be limited to one SPA (≈ 5 m^2) and one buffer assembly (≈ 3 m^2). As already mentioned, we will not exclude special highlights and the thermal covers on the mechanisms.

General

The solar array front sides with the solar cell cover slides are an ideal surface to record particle impacts. Depending on speed and size of the impacting particles, the diameter of impact features can be up to 30 times bigger than the particle size.

Through dedicated "in-situ" experiments on spare material calibration measurements are performed to study crater size versus particle size etc.

With some luck we may find a sufficient number of trapped particles allowing us to perform a chemical analyses in order to distinguish meteoroids from man-made objects, with a statistically significant distribution.

A major goal of this investigation is to study which size of craters have an influence on the power generation caused by particles hitting the SCA surfaces. Also if particles can cause short or open circuits between the electrical network and the carrier substrate or trigger some other failure mechanism.

Until now, there is no evidence that any meteoroid or debris impact has caused any of the observed failures. Some of the particles hitting the solar cells have damaged locally the silicon, but the resulting effect is that the chipped off portion or broken portion of the cell simply does not contribute anymore to the power generation. Power measurements on wing level indicate that the remaining cell area functions normally.

5 Conclusion

The solar-array Post-Flight Investigation Programmes for EURECA and HST have already proven to be very valuable for ESA and its future solar-array projects.

The mechanical performance of the retrieved hardware was in excellent agreement with the pre-flight data. The selected materials and coatings for the protection against atomic oxygen are suitable for long duration missions in LEO with high concentrations of atomic oxygen.
Design weaknesses due to thermal fatigue could be identified and design improvements were implemented into the running Polar Platform and ISO project.
The electrical degradation of solar cells was somewhat less than expected.

Ten thousands of particle impacts are recorded on the arrays with several penetrating the flexible blankets. Despite the numerous clearly visible impacts there is no indication that any meteoroid or debris impact has caused any of the observed failures or other unusual power degradation. The loss of power due to local damage of the silicon is not measurable on panel level.

All PFIP activities will be completed by May 1995, and above findings are only a snap shot. The results from the PFIPs will significantly extend the technical knowledge that will lead to better solar-arrays in the future, and are a great help in refining the environmental models and the understanding of damaging effects of impacting particles.

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SESSION V

BLANKET AND ARRAY DEVELOPMENT

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