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SUMMARY

British efforts and achievements in the field of photovoltaic solar energy conversion in space over the past 14 years are reviewed.

The satellites powered by British solar cells are listed and the Ariel 3 array is described in detail by way of an introduction to the subject.

Silicon cells of conventional thickness have been developed to a conversion efficiency exceeding 11.5% and thin cells with a superior power-to-weight ratio have been developed and manufactured in pilot production. Other achievements are a cheaper and better type of glass coverslip, an ultra-thin integral glass coating and lightweight flexible cadmium sulphide cells.

In anticipation of future multikilowatt power requirements, a prototype lightweight deployable array embodying advanced concepts has been built and qualified for prolonged operation in the geostationary orbit.

Paper presented to the International Solar Energy Society (UK) at Imperial College, London on 6 November 1974.

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CONTENTS

1 INTRODUCTION

The sun, through the medium of the silicon solar cell, has been the primary source of space power ever since Vanguard 1, the 'grapefruit' satellite, was launched in 1958. Improvements in technology have enabled spacecraft powers to be increased from a few watts to tens of kilowatts and mission lives to be extended to several years.

Work on the applications of solar cells in space has been going on in the United Kingdom since early 1960. It has included the development of cells and other array components, radiation damage studies, the assessment of special materials and the development and qualification of array assembly techniques, with particular emphasis on advanced lightweight constructions. Solar arrays have been designed, manufactured and qualified for British and other European satellites and British solar cells have been used in the Intelsat IV communication satellite programme. Details of these satellites are given in Table 1.

Most of this effort has been Government sponsored. The role of RAE has been to initiate, monitor and supervise R & D contracts, and to work in-house, notably in the fields of calibration and measurement, solar cell qualification tests, radiation damage studies and advanced lightweight array development. RAE was originally the design authority for satellite solar arrays, but now acts as technical adviser.

As an introduction to the problems of solar energy conversion in space, it is proposed to start this review by describing in some detail the solar array on Ariel 3, the first British-made satellite. This is followed by an account of developments in silicon and cadmium sulphide cells, coverslips, integral covers, and array technology, with descriptions of relevent solar cell experiments on technological satellites.

2 THE ARIEL 3 SOLAR ARRAY

UK 3 (Ariel 3) was the third in a series of Anglo-American scientific satellites sponsored by the Science Research Council, with NASA providing launch facilities, and the first to be entirely designed and built in this country. Although the satellite was spin-stabilised, the solar array was required to be omnidirectional, that is it had to generate the required power (about 7 W) whatever the attitude of the spin axis to the sun. It was required to withstand pre-launch handling, testing, storage and transportation and severe vibration during the launch. Once in orbit, it had to perform reliably under all operational conditions from full sun to maximum eclipse throughout the planned life of one year. As with all satellite systems, weight had to be kept to a minimum.

The array, of modular construction, consisted of 7392 silicon cells mounted around the body and on the four booms. It was necessary to make allowance in the design for radiation damage and the effects of shadows cast by the body, booms and aerials on the active cells.

The solar cells, developed and manufactured by Ferranti, were of the radiation-resistant n-on-p configuration, with a nominal base resistivity of 10 ohm cm and a conversion efficiency of about 10% in sunlight above the atmosphere. They measured 1 cm × 2 cm × 350 μm thick and had a junction depth of about 0.5 μm.

Fig.1 shows the construction of a 48-cell body module, manufactured by Ernest Turner Ltd. It weighed just under 0.04 kg and delivered just over 1 W in normal incidence sunlight.

Each row of six cells was connected in parallel by soldering the back contacts to a 150 μm printed circuit board and the front contacts to a narrow copper strip in a 'one-shot' operation. Eight matched rows were connected in series and then cemented to an aluminium honeycomb panel, using a silicone cement. Finally, glass coverslips, 150μm thick, were cemented to the cells to provide a highly emissive surface and protect them from micrometeorites and low-energy radiation. The boom modules were similarly constructed, except that the honeycomb was thicker and cells were mounted on both faces.

The modules were space qualified by subjecting samples to high temperature vacuum, humidity, cold storage, vibration, acceleration, 1000 thermal cycles in vacuum between +80°C and -70°C and 240 cycles between +80°C and -100°C. The final design survived these tests without measurable loss of performance.

Ariel 3 was successfully launched on 5 May 1967 and the solar array, in common with other essential sub-systems, was still working satisfactorily when the satellite re-entered the atmosphere on 14 December 1970 - some 3½ years later.

The series of Anglo-American scientific satellites continued in 1971 with the launch of UK 4 (Ariel 4), which was of similar basic design to Ariel 3. UK 5 (Ariel 5) was launched in October 1974.

3 SILICON CELLS

Since Ariel 3, there has been a continuous programme of silicon cell development, aimed at improving performance, reducing weight, meeting more stringent environmental requirements and reducing production costs. There has been considerable success in fulfilling these objectives.

The Ariel 3 cells lost about 9% of their output when fitted with glass coverslips, due to a poorly-matched antireflective coating of silicon oxides. This cover loss was eliminated by changing the coating to a vacuum-deposited layer of ceric oxide, and subsequently transformed to a cover gain averaging 3% by using titanium oxide.

Further improvements in performance resulted from a reduction of the junction depth to 0.25 μm and the introduction of a finer front contact grid to reduce the series resistance of the device. Conversion efficiencies (air mass zero, 25°C) of over 11.5% have been achieved in the latest 300 μm cells. The total production of satellite solar cells to date amounts to about 300,000.

As part of the lightweight array development programme, the thickness of 2 cm × 2 cm cells has been reduced to 125 μm (±25 μm). This results in a loss of output, because some of the infrared photons which generate carriers in the thicker cell are lost in or near the back contact of the thinner one. However, damage in the silicon caused by energetic electrons and protons in space has the effect of reducing the minority carrier diffusion length in the base region and thus diminishing the number of carriers that reach the junction and contribute to the output current. In a radiation environment, therefore, a point is eventually reached when the response is independent of the physical thickness. Fig.2, showing the effect of 1 MeV electrons on 300 and 125 μm cells, illustrates this fact. The critical fluence of about 10^{15} e/cm^2 corresponds to 5 years irradiation in the geostationary orbit used for communication satellites. At this point, both cells have an efficiency of about 9%.

Ferranti have manufactured nearly 7000 125 μm cells in pilot production and are at present making a further quantity for an American customer. A special feature of these cells is the 'wraparound' contact, which enables both negative and positive connections to be made to the back surface, thus facilitating interconnection and covering. They now lead the field in terms of power-to-weight ratio but are more expensive than the conventional type.

The plated nickel/copper/nickel/gold contacts have been developed to withstand prolonged deep thermal cycling and severe thermal shock (dipping in liquid nitrogen). They have the virtue of being non-tarnishing and easily solderable. Progressive improvements have been made to production facilities and techniques.

4 CADMIUM SULPHIDE CELLS

The cadmium sulphide solar cell is potentially cheaper than silicon and its thinness and flexibility could be exploited with advantage in large light-weight arrays. International Research and Development, Newcastle have developed cells with an efficiency approaching 5.5% and have made considerable progress in improving the reliability and stability of the device in simulated space environments. However, no CdS cells have been flown, even experimentally, on British satellites and they are unlikely to challenge silicon cells in the foreseeable future.

5 COVERSLIPS

Solar cell coverslips must transmit photons efficiently over the response range of the solar cell (0.4 to 1.1 μm) and their transmission must not be significantly degraded by ultraviolet and corpuscular radiation. Furthermore, since the cement used to bond them to the cells is degraded by UV of wavelengths shorter than 0.3 μm, transmission in this region must be negligible.

The conventional radiation-resistant coverslip is made of fused silica, cut to the required thickness and polished. It has an antireflective coating on the front surface and a multilayer UV-reflecting filter on the back.

A cheaper and better coverslip has been developed by Mullard Central Laboratories, working with Chance Bros and RAE. The basic material, which is produced cheaply in uniform thin, highly polished sheets by a special flow technique, is the standard Chance CMD microscope glass, doped with 5% of ceria (CeO_2). This level of doping is sufficient to stabilise the glass against heavy doses of electrons, protons and UV and also prevent damaging UV radiation from reaching the bonding cement. To make the coverslips the only processes necessary are to apply the anti-reflective coating and cut to size.

The new coverslips have a superior and more consistent transmission characteristic and are also less fragile than fused silica. They are being marketed by Pilkington-Perkin-Elmer and have been adopted for most of the current European satellite projects.

6 INTEGRAL COVERS

An RF-sputtering technique for applying a uniform layer of low-stress glass directly to silicon solar cells has been developed for the European Space Research Organisation (ESRO) by the Electrical Research Association. Since the glass can be made thinner than is possible in a discrete coverslip, this technique opens the way to further weight reduction. It also eliminates the cover cement and protects the edges as well as the active surface of the cell from low-energy radiation. Further work is necessary before this process can be satisfactorily integrated into the solar cell production line.

7 LIGHTWEIGHT DEPLOYABLE ARRAYS

Power requirements for future communication, navigational and direct TV satellites and large manned orbiting and interplanetary spacecraft are expected to be in the multikilowatt range. For such large powers it is necessary for maximum efficiency to mount the solar cells on large flat sun-orientated paddles, which can be folded or rolled up into a small space for launch and deployed to their working configuration in orbit. Each kilowatt requires a solar panel area of 14 to 16 m^2. Reliability, lightness, small stowed volume, low cost and development potential are the principal design requirements.

The most difficult technological problem, apart from weight reduction, is the severe thermal cycling which the array must withstand in passing into and out of eclipse. The minimum cell temperature in geostationary orbit can be as low as $-190^{\circ}C$.

RAE's prototype lightweight 280 W paddle is illustrated in Fig.3. The solar panels, measuring 4.2 m long × 0.9 m wide overall, are of flexible 50 μm Kapton film, carrying patches of thin (125 μm) silicon cells with wraparound contacts and 100 μm ceria glass coverslips. The supporting framework is of aluminium honeycomb cross-members extending from the sections of an aluminium telescopic mast. The panels are lightly tensioned by springs at the fixing points to keep them reasonably flat. Flat copper-on-Kapton busbars run down the sides of the panels to an inboard connector.

For launch, the panels fold between cell patches into a honeycomb stowage compartment and are interleaved with corrugated 25 μm Kapton, which remains attached to the compartment when the paddle is deployed. The cross-members are the same width as the folded panels and are lightly cushioned on both sides. The whole pack is maintained under a uniform pressure of 2 N/cm^2 by eight ties, which are released simultaneously when deployment is initiated by duplicated pyrotechnic actuators. The mast extends pneumatically, using nitrogen stored at 38 N/cm^2 in the central section. When fully deployed, each section is mechanically latched and the gas is allowed to leak away harmlessly.

Fig.4 shows how the cells are interconnected and mounted on the Kapton film by what is known as the RAE 'solder-through' technique. The silver-plated molybdenum interconnections are soldered to the negative and positive contacts on the backs of the cells through punched holes in the Kapton. This connects the cells into a series - parallel matrix while at the same time buttoning them to the substrate. The absence of mounting cement avoids a serious thermal mismatch and relieves the soldered joints of stresses, thermal and mechanical, which would otherwise be transmitted from the cement and substrate, thus extending their fatigue life under thermal cycling. The backs of the cells are coated with an emissive chromium plating, which was later changed to a silicone elastomer to provide protection against low-energy protons. Windows in the Kapton enable the cells to radiate freely to space and operate at maximum efficiency.

Several tests have shown that flexible panels of this type are capable of withstanding 500 cycles between +80°C and -190°C without damage or performance degradation. This treatment is roughly equivalent to 6 years in geostationary orbit.

The prototype paddle, with 21% coverage of real cells, and 79% of glass-covered dummies mounted in the same manner as the real ones, underwent a comprehensive series of space qualification tests in UK and at ESTEC, Holland towards the end of 1972. The programme included performance tests, repeated deployments and stowing in air, hot and cold storage, rapid depressurisation, vibration shock and spin tests, deployment in vacuum at high, low and normal temperatures and thermal cycling in vacuum. The prototype sustained minor damage to a few cells and coverslips, which was attributed mainly to the repeated stowage operations. It was demonstrated that such damage could be easily and cheaply repaired. The total weight of the paddle, fully celled, is 6.25 kg. This gives an end-of-life power-to-weight ratio of 44 W kg^{-1} - more than twice that of the most advanced rigid array and considerably better than other flexible array designs.

8 TECHNOLOGICAL SATELLITES

The X3 (Prospero) technological satellite, launched by a Black Arrow rocket in October 1971 carried six experimental patches of solar cells. Three of these were of thin (125 μm) silicon covered with 100 μm ceria glass and mounted without cement on tightly-stretched Kapton. The other three patches were designed to compare the performance and radiation resistance of ceria glass with plain Chance glass and the conventional fused silica coverslips.

All six patches are still operating satisfactorily after 3 years in orbit, the thin cells showing the expected radiation degradation. The coverslips experiment has shown that all three types are equally resistant to radiation and that, contrary to some expectations, the ceria glass does not raise the operating temperature of the cells.

X4 (Miranda), launched in March 1974, is a 3-axis stabilised technological satellite with a small version of the RAE lightweight flexible solar array giving an end-of-life power of 62 W. The array was engineered by Hawker Siddeley Dynamics and the flexible panels manufactured by Ernest Turner. The cells forming the main array are the conventional 300 μm type, with wraparound interconnects to bring the negative contacts to the back. They are cementless mounted by the RAE 'solder-through' technique. Inboard of the main array cell patches are two experimental patches of the latest Ferranti 125 μm wraparound contact cells, again mounted without cement on the Kapton.

The array was successfully deployed in orbit and telemetered data indicates that it is giving its designed output. Both experimental thin-cell patches survived the launch and one is still working perfectly. Output from the other was lost after an intermittent fault on the second pass, the circumstances of the failure pointing to a fault in the main connector - not in the cell patch itself. This satellite has successfully demonstrated the soundness of the RAE cell mounting, stowage and deployment techniques.

Four more experimental patches of Ferranti 125 μm wraparound contact cells of the latest type, made from silicon of different types, are in orbit on the American Naval Research Laboratory satellite Timation IIIA, which was launched on 14 July 1974. Three of the patches have 100 μm PPE coverslips of ceria glass and the fourth has 25-50 μm integral covers of RF sputtered glass, applied by ERA. All patches are working, but the telemetered data has not yet been fully processed.

9 FUTURE PROSPECTS

It is hoped to continue the work and build on past achievements, so as to make British solar arrays even more competitive in the world market. To exploit the RAE lightweight array concept more fully, with an eye on the future communication satellite market, an outline design has been prepared for an array capable of generating 2 kW at end-of-life on a Thor Delta-launched spacecraft. The design has folding rigid panels inboard of the flexible ones, which provide power during the transfer orbits and also contribute to the array output on station. Plans are being formulated to build and qualify a full-scale prototype, which will also act as a focus for further improvements in the supporting technology.

Table 1

SATELLITES POWERED BY BRITISH SOLAR CELLS

Sponsor	Satellite	Year of launch	Contractor	Function	Description	Array type	End-of-life power W	Cell area m^2
British Government	Ariel 3	1967	BAC	Scientific	Spinning	Body- and boom-mounted	7	1.48
	Ariel 4	1971	BAC	Scientific	Spinning	Body- and boom-mounted	7	1.48
	Prospero	1971	BAC and MSDS	Technological	Spinning	Body-mounted	8	1.34
	Miranda	1974	HSD	Technological	3-axis stabilised	Sun-orientated panels	62	0.72
	Ariel 5	1974	MSDS	Scientific	Spinning	Body-mounted	60	1.80
ESRO	ESRO 2	1968	HSD	Scientific	Spinning	Body-mounted	32	1.38
	TD	1971	HSD	Scientific	3-axis stabilised	Sun-orientated panels	280	3.75
	COS B	1975	BAC	Scientific	Spinning	Body-mounted	84	3.80
Spanish Government	Intasat	1974	INTA and CASA	Scientific	Spinning	Body-mounted	12	0.36
International	Intelsat IV	1973	Hughes	Communications	Spinning	Body-mounted	500	19.6

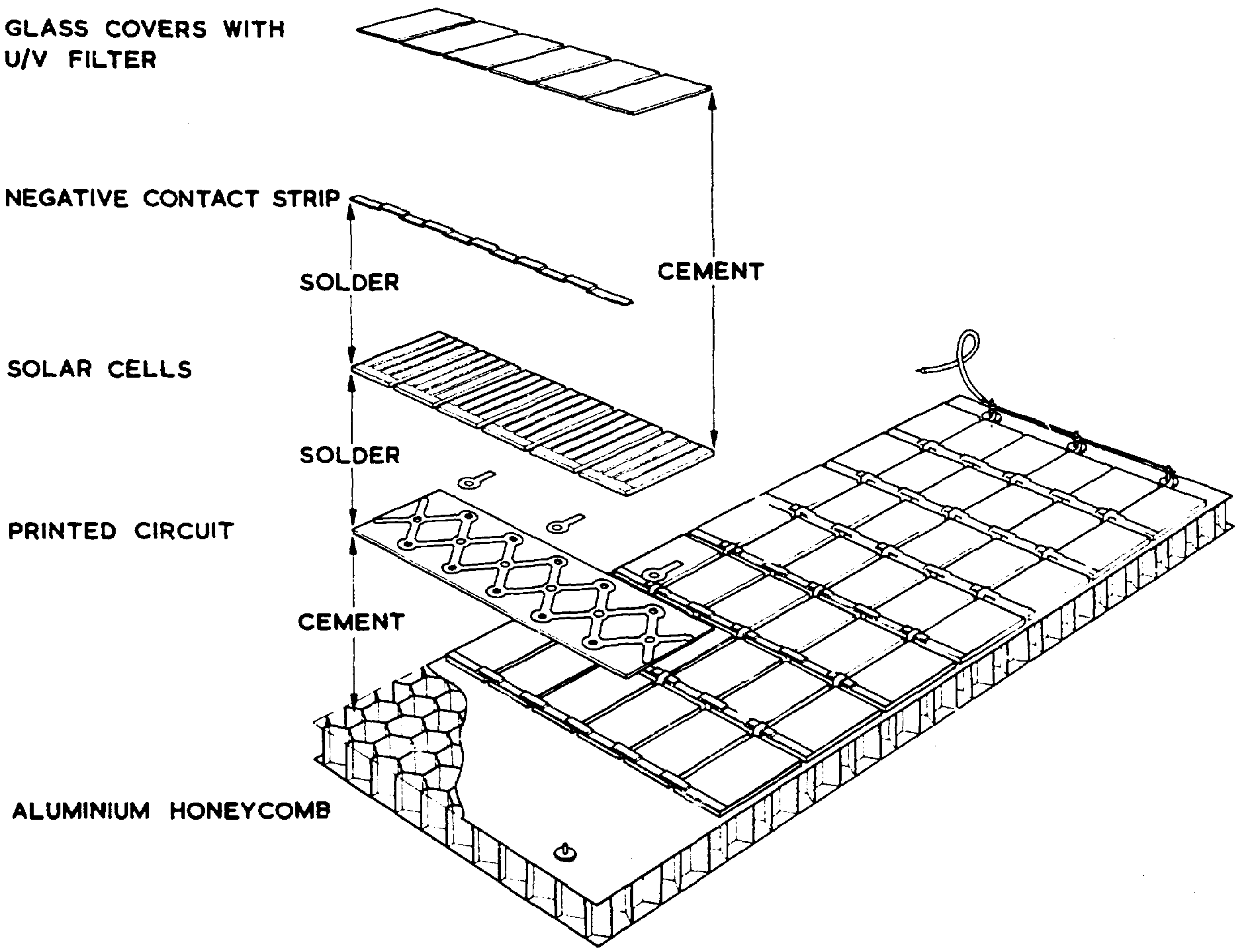

Fig.1 Ariel 3 solar cell module

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Fig. 2

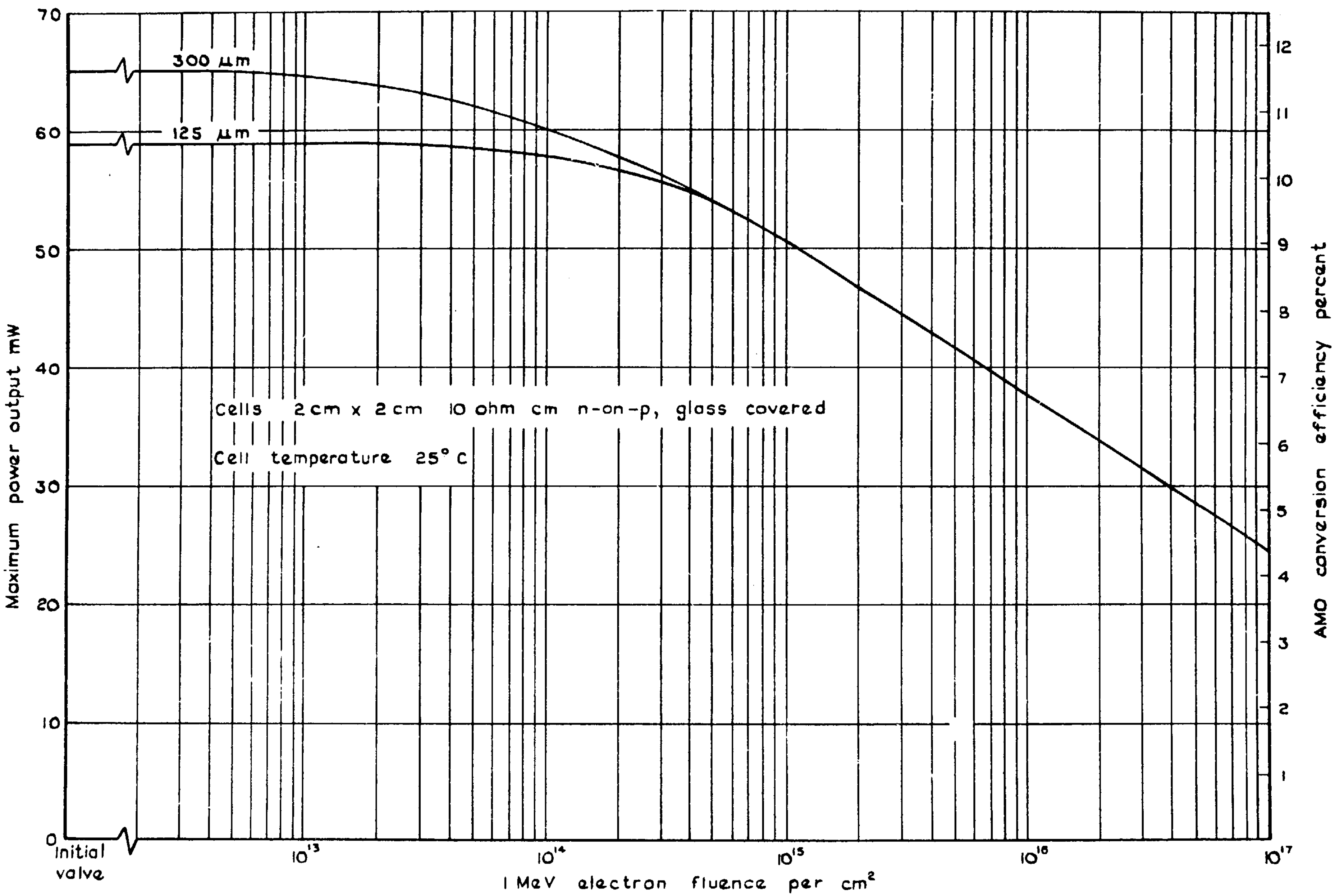

Fig. 2 Effect of 1MeV electrons

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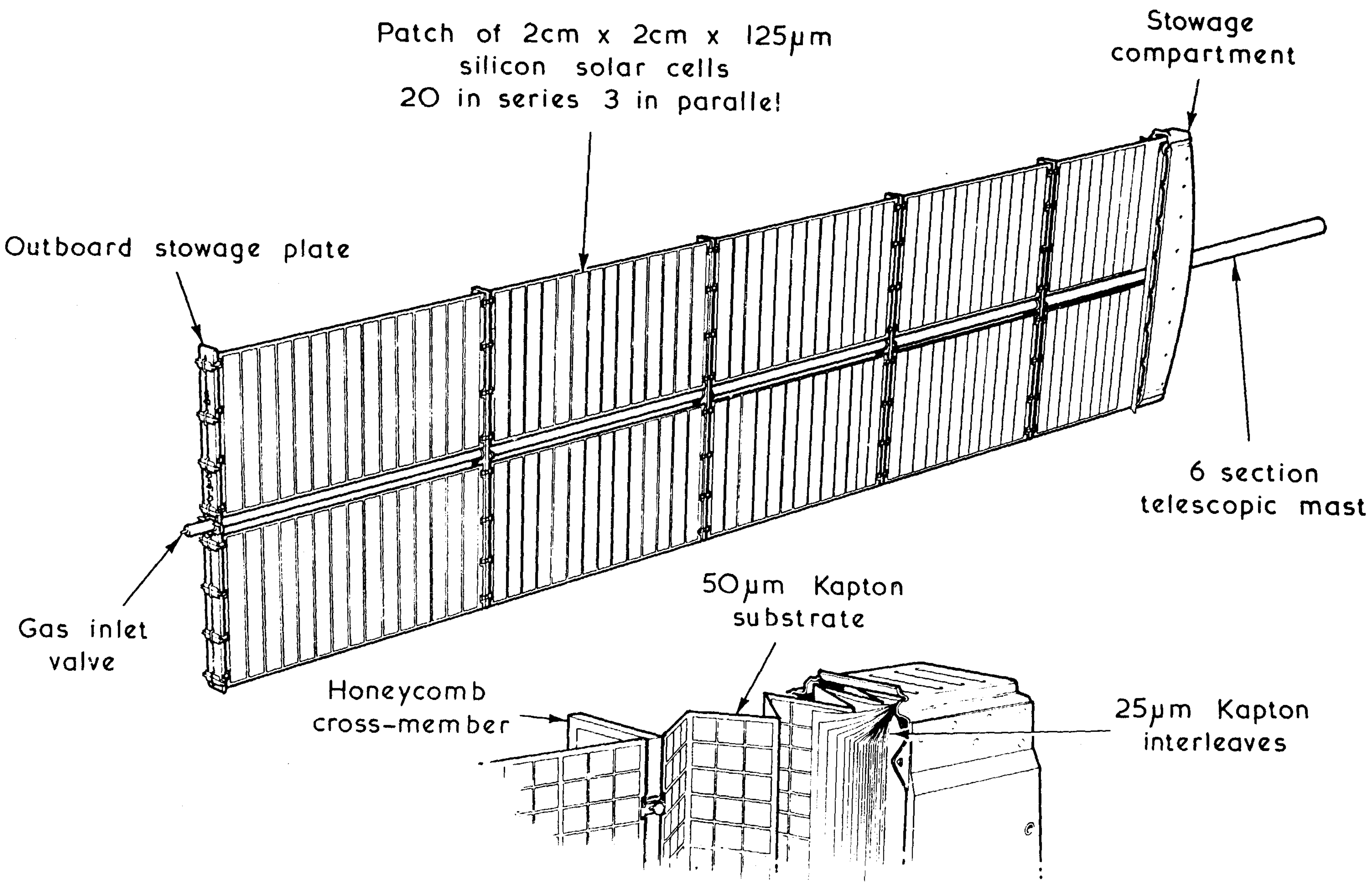

Fig.3 280w Lightweight solar paddle

Fig.3

Fig.4

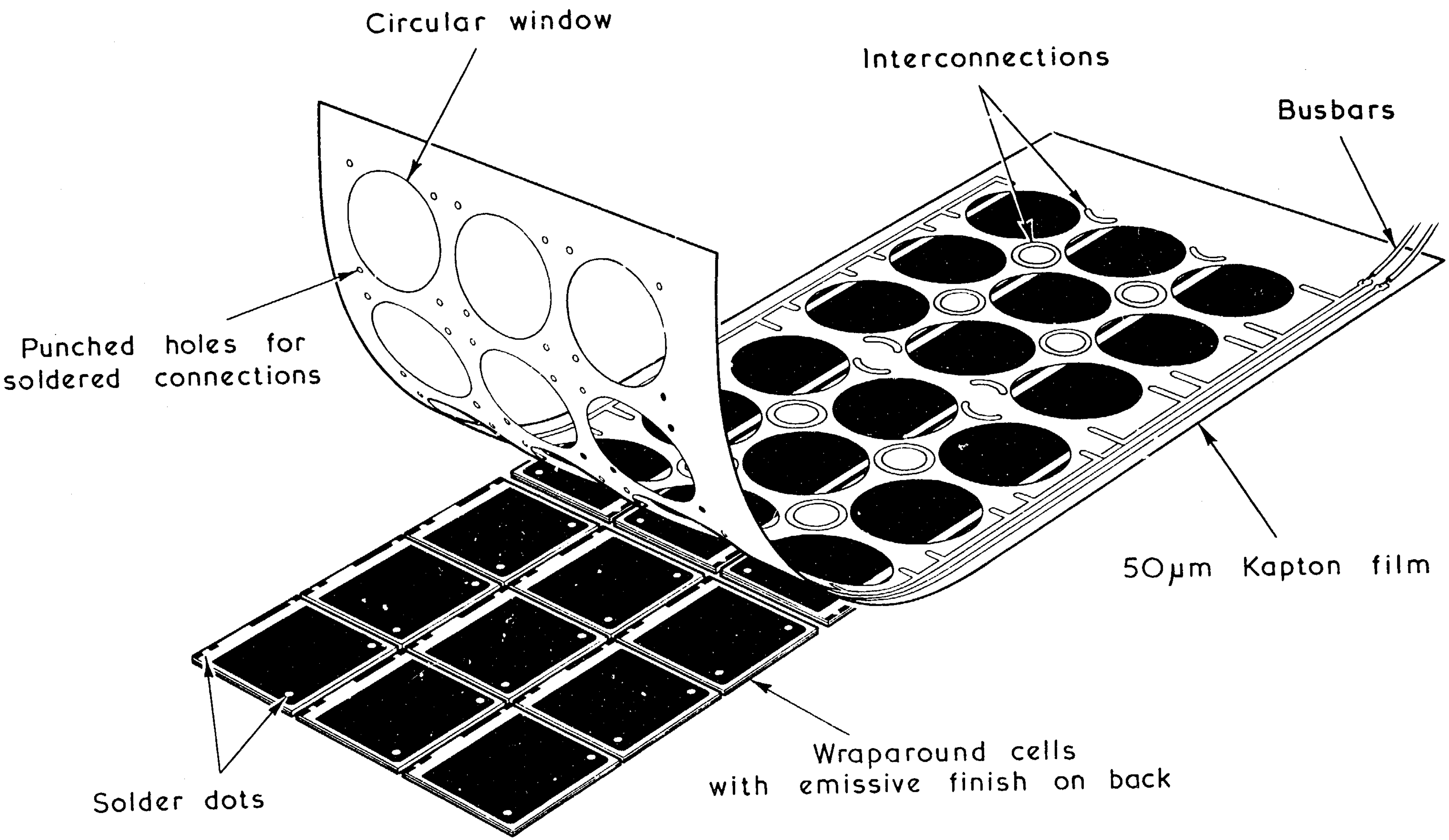

Fig.4 Flexible solar panel

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