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The Relation Between Solar Cell Flight Performance Data and Materials and Manufacturing Data

Report No. 3

Third Quarterly Report

Contract No. NASW-1732

Prepared by

The CARA Corporation
101 N. 33rd Street
Philadelphia, Pennsylvania

S. R. Pollack, Ph.D.
Principal Investigator

G. K. Zin, Ph.D.
L. A. Girifalco, Ph.D.
Staff Scientists

ABSTRACT

This quarter was spent in acquiring data for the flights chosen for study in the last quarter.

Analysis of the environment for the individual flights has begun. This work is progressing with the viewpoint of trying to simplify the environmental specification. The most difficult aspect of the environmental analysis is the specification of the vehicle's thermal history. The vehicles under study are therefore being grouped according to subclassifications based on the nature of the vehicle as the first attempt to find any performance correlations.

All of the specific data for the flights under study have been extracted from the literature obtained from the computer searches conducted earlier. These data are incomplete and inadequate for this study. Examples of the nature of this data were reported in the last quarterly report and are shown in this report.

The data required for this study must be obtained by personal contacts with individuals who have been connected with the various flights. The appropriate individuals to contact have been identified for 75 of the 77 flights included in this study. These people have been and are being contacted to obtain the required data.

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I. Introduction

This document is the third quarterly report in a program to examine the flight performance data for solar cell power systems in satellites, and to try to relate the differences in performance to the materials and manufacturing factors in the solar cell system.

The general method of approach consists of selecting a group of flights whose space environments are all similar, for which sufficient flight performance data exists, and for which information on the materials and manufacturing factors is available. For the selected group of flights, an attempt will be made to relate the differences in performance to specific materials or manufacturing parameters that may be expected to affect performance.

The work is divided into four general phases defined by the following outline:

Phase I:

A. Classify all flights from 1957 through 1967 according to their space environment, so that groups of flights with similar environment can be identified.

B. Ascertain availability of performance data and materials and manufacturing parameters.

C. Generate a coding procedure to facilitate the recording and use of information gathered relative to performance and materials and manufacturing factors.

Phase II:

Select a group of flights based on the work in Phase I.

Phase III:

Acquire and systematize the actual data needed for the flights selected in Phase II.

Phase IV:

Perform analysis to relate materials and manufacturing factors to flight performance of the selected flights.

Phase I and Phase II have been completed and work has begun on Phase III. This past quarter was spent in extracting and organizing the information contained in the literature obtained in our literature search. Visits were made to determine where and in what form the information required by this study exists. It has been determined that the data required for the performance of this contract are contained in documents which do not receive wide distribution. These documents can only be acquired through personal contacts; the flights to be studied and the people associated with them have been organized so that the required information can be obtained. Information of this nature has been requested, and obtained for several flights and is being analyzed so that the remaining flights may be documented in as efficient a manner as possible. The rest of the data required for this study will be requested and obtained in the next quarter. At the end of the next quarter, Phase IV, the analysis and correlation phase will begin.

II. The Selected Flights and Environment

As was reported in the first quarterly report, an examination of the Space Projects Log from 1957 to 1968 yielded approximately 611 earth satellite flights. By applying the conditions that a suitable flight for study under this contract be (a) in orbit and transmitting data for three months or more, (b) have NASA or DOD as the Project Director, and (c) be unclassified, the number of flights suitable for study were reduced to slightly over 200. These flights were listed in the first quarterly report.

A plot of perigee vs. apogee for these flights showed a number of clusters along the 45° line, suggesting that a rational starting point for selecting flights with similar environments could be chosen by defining four major sets of orbits. I (inside orbit) orbits were defined as having perigee and apogee just inside the first radiation belt. The cutoff point for orbit parameters was arbitrarily chosen to be 760 miles, because above this altitude both electron and proton fluxes increase very rapidly with altitude from negligible to quite significant values. The B (first belt orbit) orbits were defined to be the cluster of flights with perigee and apogee at about 2,000 miles, which is close to the maximum of the first radiation belt. The S (synchronous orbit) orbits, with parameters around 20,000 miles, are the synchronous geostationary flights, and the 0 (outside orbit) orbits, with orbit parameters between 60,000 and 70,000 miles, are beyond the radiation belts.

The I orbit flights were chosen to be the subject of this study. These flights can be divided into four subgroupings; thirteen flights with angle of inclination between 28° and 33°; sixteen flights with angle of inclination between 47° and 60°; nineteen flights with angle of inclination between 66° and 71°; and twenty-nine flights with angle of inclination between 79° and 135°. The I orbit flights suffer minimal radiation damage since they are below the maxima in the first radiation belt. However, because of the low orbit, the thermal cycle has appreciable changes in temperature over times measured in minutes. A review of the literature indicates that much more work has been done in examining the radiation effects on solar cells than on any other effect.

An indication of the variability of the radiation environment is given in Table I which gives approximate values for the orbital integration flux for protons and electrons of energies greater than 4 M.eV and 0.5 MeV respectively for several orbits in units of $(cm^2\text{-day})^{-1}$.

	$\theta = 0°$		$\theta = 30°$	
Altitude	ϕ_p(E>4 MeV)	ϕ_e(E>0.5 MeV)	ϕ_p(E>4 MeV)	ϕ_e(E>0.5 MeV)
150 N.M.	0	0	0.3×10^7	2.6×10^8
450 N.M.	0.2×10^8	8×10^9	0.1×10^9	1.4×10^{11}

Table I

Orbital Integration Flux Versus Orbital Parameters

This table shows that there is a considerable variation in the radiation environment, even though the level is much lower than in the Van Allen belt.

A theoretical calculation of the effect of radiation at 300 N.M. (Cooley and Barret)* indicates that the radiation field

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*W. C. Cooley & M. J. Barrett, Space Environmental Effects in Solar Cell Power Systems, January 1968, (Exotech Report TR-025) will cause 7% degradation in maximum power in a typical solar cell array in one year, while test data for Anna 1B, with an orbit in the 700 mile region, indicated degradations in short circuit current after 400 days ranging from 10% to 45% depending on the cover glass thickness.

There are several conclusions of importance to this study that arise from an examination of the near earth radiation environment. The first is that for orbits above approximate 250 N.M., the radiation effects may still be serious, while below this region, they are less important. This, coupled with the variability of the radiation density with altitude and epoch, means that orbital integrated fluxes must be obtained for each of the flights chosen for study. It is clear that the coarse grained classification of environment based on four orbital parameters is insufficient for the purposes of our study. However, it may still be true that the angle of inclination is an adequate representation of the orientation of the orbital plane. This is true to the extent that the radiation flux is symmetrical with respect to the orbital plane. For those flights for which the radiation effects are severe, however, the existence of variations in the radiation symmetry (such as those arising from the South Atlantic Anomoly) will require use of the orbital angular parameters completely defining the orientation of the orbital plane relative to the equatorial plane. Because of this, and because of secular variations, it will probably become necessary to use orbital integrated fluxes for each flight as the appropriate radiation environmental parameters.

The available data on the meteoroid environment has been summarized by Lyle in a report by Cooley and Barrett*. From

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*Ibid.

the data given in their report, a rough representation of the near earth meteoroid flux in $(m^2 - sec)^{-1}$ for particles of mass greater than 10^{-8} gms, is

$$J_M = e^{1.15 \times 10^{-4}(1-R)}$$

where R is the altitude in kilometers. Thus, the meteoroid flux, within the accuracy of the available data, is essentially constant for all the inside orbits of this study.

Estimates of meteoroid penetration and of cover glass cratering indicates that there are a maximum of about 10^3 penetrations $(m^2\ yr)^{-1}$ and a maximum of about 10^5 craters $(m^2\ yr)^{-1}$. Since penetrations may short circuit a solar cell, and since the erosion associated with cratering decreases transmittance, it is clear that the meteoroid flux must be considered in a materials analysis of solar cell performance.

The thermal environment of the solar cells will be the most difficult to specify. Because the time spent in eclipse is a complex function of the orbital parameters, including those completely defining the orientation of the orbital plane, a complete calculation is required for each orbit even to obtain the black body temperature history of the vehicle. In addition, shadow effects, arising from the solar cell array and vehicle configuration, will complicate the situation further.

Since temperature variations of about 80°C over short periods of time can be expected, and since the thermal stresses thereby induced in the solar cell components are considerable, it is clear that the thermal analysis on the chosen flights must be carefully considered.

The thermal fluctuations for the solar array depend on orbit, time of flight, and vehicle configuration. The solar array temperature fluctuations are different, for example, for body mounted cells as compared to paddle mounted cells, and depend on the nature of the stabilization of the vehicle. Therefore, a detailed analysis is initially being made on these subclassifications.

Within the I group, there are four sub-groupings based on orbital parameters. At this point all four sub-groupings are being studied. It may develop that only one or more, but not all four sub-groupings are worthy of extensive study. This decision will be made on the basis of final available data. The work to date has indicated that the materials and manufacturing data can generally be obtained for each flight. The data that is equally important and necessary, and which may not be available, is the flight performance data. This is due to the fact that some flights had no or very limited data telemetered back regarding the condition of the solar array.

The flights that are still within the study for the correlation work are shown in Table II.

Table II

Specific Flights to be Studied

	Flight Name	Int'l. Desig.	Proj. Dir.	Perigee (miles)	Apogee (miles)	Period (T) (minutes)	Inclination (θ) (degrees)
1.	Pegasus 3	1965 60A	NASA	323	336	95.3	28.9
2.	Pegasus 1	1965 9A	NASA	308	462	97.0	31.7
3.	Pegasus 2	1965 39A	NASA	314	466	97.3	31.7
4.	Transit 4B	1961 AH1	USN	582	700	105.6	32.4
5.	TRAAC	1961 AH2	USN	562	720	105.6	32.4
6.	OSO 1	1962 Z1	NASA	344	370	96.2	32.8
* 7.	OV4 3	1966 99A	USAF	188	187	90.6	32.8
* 8.	OV4 1R	1966 99B	USAF	181	181	90.4	32.8
* 9.	OV4 1T	1966 99D	USAF	181	190	90.7	32.8
10.	OSO 2	1965 7A	NASA	343	393	96.5	32.9
11.	OSO 3	1967 20A	NASA	336	354	95.9	32.9
* 12.	TTS 1	1967 123B	NASA	182	300	92.3	32.9
13.	OSO 4	1967 100A	NASA	334	354	95.7	32.9
14.	Tiros 3	1961 P1	NASA	461	506	100.4	47.8
15.	Tiros 4	1962 B1	NASA	441	525	100.4	48.3
16.	Tiros 1	1960 B2	NASA	430	468	99.2	48.3
17.	Tiros 2	1960 II-1	NASA	387	452	98.3	48.5
18.	Anna 1B	1962 BM1	USN	670	728	107.8	50.1
19.	Explorer 7	1959 I-1	NASA	346	676	101.2	50.3
20.	Transit 1B	1960 Γ2	ARPA	232	463	95.8	51.3
21.	Explorer 23	1964 74A	NASA	288	610	99.2	51.9
22.	Explorer 16	1962 BX1	NASA	466	733	104.3	52.0
* 23.	Ariel 1	1962 01	NASA/UK	242	754	100.9	53.9
* 24.	Explorer 17	1963 9A	NASA	158	568	96.4	57.6
25.	Tiros 5	1962 AA1	NASA	367	604	100.5	58.1
26.	Tiros 6	1962 Aψ1	NASA	423	444	98.7	58.2
27.	Tiros 7	1963 24A	NASA	385	401	97.4	58.2
28.	Tiros 8	1963 54A	NASA	430	473	99.3	58.5
29.	Explorer 30	1965 93A	USN/NASA	440	548	102.8	59.7
30.	Transit 2A	1960 H1	USN	389	665	101.7	66.7
31.	Solrad 1	1960 H2	USN	382	657	101.6	66.8
32.	Transit 4A	1961 01	USN	534	623	103.7	67.0

Table II (Cont.)

Specific Flights to be Studied

	Flight Name	Int'l. Desig.	Proj. Dir.	Perigee (miles)	Apogee (miles)	Period (T) (minutes)	Inclination (θ) (degrees)
33.	Injun 1/ Solrad 3	1961 02	USN	534	634	103.8	67.0
34.	Solrad 7A	1964 1D	USN/USA	563	578	103.5	69.9
35.	Secor 1	1964 1C	USN/USA	563	578	103.5	69.9
36.	GGSE 1	1964 1B	USN/USA	560	585	103.5	70.0
37.	Surcal	1967 53B	USAF/USN	570	582	103.5	70.0
38.	Surcal	1967 53F	USAF/USN	569	575	103.4	69.9
39.	GGSE 4	1967 53C	USAF/USN	569	577	103.4	70.0
40.	GGSE 5	1967 53D	USAF/USN	570	575	103.4	70.0
41.	Surcal	1967 53J	USAF/USN	569	577	103.4	70.0
42.	GGSE 2	1965 16B	USN/USA/ USAF	562	583	103.5	70.1
43.	GGSE 3	1965 16C	USN/USA/ USAF	562	583	103.5	70.1
44.	Solrad 7B	1965 16D	USN/USA/ USAF	562	583	103.4	70.1
45.	Secor 3	1965 16E	USN/USA/ USAF	562	583	103.5	70.1
46.	Oscar 3	1965 16F	USN/USA/ USAF	565	585	103.5	70.1
47.	Surcal	1965 16G	USN/USA/ USAF	564	585	103.5	70.1
48.	Surcal	1965 16H	USN/USA/ USAF	563	586	103.5	70.1
49.	Explorer 22	1965 64A	NASA	549	669	104.7	79.7
50.	Explorer 20	1964 51A	NASA	540	634	103.9	79.9
51.	Ariel 3	1967 42A	UK	306	373	95.6	80.2
* 52.	Discoverer 20	1961 E1	USAF	177	486	95.4	80.4
* 53.	Discoverer 21	1961 Z1	USAF	149	659	93.8	80.4
* 54.	Discoverer 18	1960 Σ1	USAF	143	426	93.8	80.8
* 55.	Discoverer 36	1961 AK1	USAF	148	280	91.5	81.2
56.	None	1962 Σ1	USAF	180	401	94.0	82.5
57.	OGO 4	1967 73A	NASA	256	564	98.1	86.0

Table II (Cont.)

Specific Flights to be Studied

	Flight Name	Int'l. Desig.	Proj. Dir.	Perigee (miles)	Apogee (miles)	Period (T) (minutes)	Inclination (θ) (degrees)
58.	None	1963 38C	USN	667	705	107.4	89.9
59.	Secor 2	1965 17B	USA	206	624	98.0	89.9
60.	None	1964 83C	USAF/USN	639	672	106.3	90.0
61.	None	1964 83D	USAF/USN	639	672	106.3	90.0
62.	Surcal	1965 65B	USN	680	738	108.1	90.0
63.	Surcal	1965 65C	USN	680	738	108.1	90.0
64.	Surcal	1965 65E	USN	680	738	108.1	90.0
65.	Surcal	1965 65F	USN	680	738	108.1	90.0
66.	Surcal	1965 65H	USN	680	738	108.1	90.0
67.	Surcal	1965 65L	USN	680	738	108.1	90.0
68.	None	1963 22A	USAF/USN	463	528	100.7	90.0
69.	OV1-10	1966 111B	USAF	403	479	98.9	93.5
* 70.	Samos 2	1961 A1	USAF	300	350	95.0	97.0
71.	ESSA 1	1966 8A	ESSA	432	521	100.2	97.9
72.	Nimbus	1966 40A	NASA	684	734	108.1	100.3
73.	OV1-12	1967 72D	USAF	342	344	95.6	101.6
74.	OV1-86	1967 72A	USAF	303	390	95.5	101.7
75.	None	1964 48A	USAF	217	226	91.6	115.0
76.	OV1 4	1966 25A	USAF	550	630	103.9	144.5
77.	OV1 5	1966 25B	USAF	613	659	104.4	144.7

* These flights have been eliminated from this study due to either the lack of solar cells on the flight, or insufficient data on the performance of the solar cells.

III. Information and Data Gathering

During the first quarter, two computer search facilities were used to obtain a broad coverage of unclassified reports relating to silicon solar cells in spacecraft. These searches were performed using both NASA and DOD facilities, hoping that all relevant published documents could be obtained in this way. The computer searches included a broad coverage search using "Silicon Solar Cell" as an identifier in both facilities, and a specific search at both facilities in which information was sought on final flight reports, vendor reports on manufacture and testing of solar cell panels and spacecraft power supplies, and flight performance.

In the specific computer search, the names of the NASA and DOD flights in the I, B, S, and O flights were submitted and appropriate identifiers were used with the flight name to perform the search.

These documents, as well as those received from other requests, have been examined and separated into three distinct groups; those that refer to specific flights and have the type of information that is required for this study; those that do not refer to specific flights, but have information that is relevant to this study, e.g. the thermal and radiation effects on cover glasses, and adhesives, etc,; and those that describe some type of problem connected with solar cells but have essentially no specific information that is required for this study. Of the total number of documents received, 58 are in the first class, 150 are in the second class, and 98 are in the last.

These computer searches have been only partially successful, in the sense that they did not yield the comprehensive data that is required for this study. Most of the documents are technical papers, written by authors who are describing special problems. The time involved in sorting and reviewing the documents was enormous, and did not yield the required details. However, it did serve as an indicator of what problems were recognized as significant to solar cell performance, and indicated what techniques were attempted to solve them. In this sense then, they were valuable in providing background data and information.

In the first quarter, the use of coded forms was devised to facilitate the handling and application of the information obtained for use in this study. Two types of codes were generated; a general code to record qualitatively the general availability of data, and sub-codes referring to the availability of specific data. These codes were intended to provide a convenient tool to display and compare the extent of information available for the various flights to aid in the flight selection problem.

The flight selection was based on other reasons in addition to the availability of the information in document form as these codes were intended to indicate. This, of course, was due to the nature of the information contained in the documents received from the computer searches.

However, another type of form was generated, to provide an organized outline for recording the pertinent information for each flight. An example of this form was shown in the second quarterly report as Form C-03. As the contract continues, and if it is determined that it is advantageous to change the format or content of this form, this Form C-03 will be suitably modified so that the appropriate information is presented in the most usable manner.

Examples of the type of information that was extracted from our literature search was reported by the completion of Form C-03 in the second quarterly report for the Pegasus series, the Transit and TRAAC satellites.

During this quarter all of the information that was contained in the literature relating to the specific flights of interest obtained by our computer searches has been extracted and codified. This information now is organized by individual flight and consists of several hundred pages of paste-ups in a loose leaf binder. The most detailed information was obtained for Ariel III, CARA flight #C-51. This information is presented in Appendix I as an example of the nature of the most detailed form of information available from the literature. It should be pointed out that this is not representative of the typical information for each flight. From the literature, data has been obtained for 19 flights that are in content somewhere between that shown in the second quarterly report for the Pegasus series, TRAAC and Transit, and that shown in this report for Ariel III.

Of the total number of 69 flights remaining in the study, 44 are DOD sponsored. Almost no data on these flights have been obtained through the literature search.

The completion of the data acquisition requires personal contacts. In the second quarterly report, a "name tree" was initiated. Table III is an updating of this "name tree".

Table III

Specific Flights with Individual Contact

Flight Name	International Designation	Sponsoring Agency	Individual Contact	Contact Affiliation
Anna 1B	1962 BM1	USN	R.E. Fischell	APL
			J.H. Martin	
			W.E. Radford	
			W.E. Allen	
			J.H. Martin	Heliotek
			J.S. Teener	
			E.L. Ralph	
Ariel 1	1962 01	NASA/UK	L. Slifer	GSFC
Ariel 3	1967 42A	UK	R.B. Bent	S.R.C. Radio & Space Research Station Slough, England
			F.C. Trebel	Royal Aircraft Establishment
			R.C. Cook	
			P.G. Garratt	
Discoverer 18	1960 Σ1	USAF	L. Chidester	Lockheed
Discoverer 29	1961 E1	USAF	L. Chidester	Lockheed
Discoverer 21	1961 Z1	USAF	L. Chidester	Lockheed
Discoverer 36	1961 AK1	USAF	L. Chidester	Lockheed
ESSA	1966 8A	ESSA	A. Schnapf	RCA
Explorer 7	1969 I-1	NASA	J. Boehm	MSFC
Explorer 16	1962 BX1	NASA	F. Martin	GSFC
Explorer 17	1963 9A	NASA	F. Martin	GSFC
Explorer 20	1964 51A	NASA	E.D. Nelson	GSFC
Explorer 22	1965 64A	NASA	W. Allen	APL
Explorer 23	1964 74A	NASA	F. Martin	GSFC
Explorer 30	1965 93A	USN/NASA	F. Martin	GSFC

Table III (Cont.)

Specific Flights with Individual Contact

Flight Name	International Designation	Sponsoring Agency	Individual Contact	Contact Affiliation
GGSE 1	1964 1B	USN/USA	P. Wilhelm	NRL
GGSE 2	1965 16B	USN/USA/USAF	J. Yuen	NRL
GGSE 3	1965 16C	USN/USA/USAF	"	"
GGSE 4	1967 53C	USAF/USN	"	"
GGSE 5	1967 53D	USAF/USN	"	"
Nimbus 2	1966 40A	NASA	K.F. Merten	G.E.
			K.L. Hanson	
			W.J. Schlotter	
			H. Press	
			C. McKenzie	
None	1963 38C	USN	R.F. Fischell	APL
None	1964 83C	USAF/USN	J.H. Martin	
			W.E. Radford	
			W.E. Allen	
None	1962 Σ1	USAF		
None	1963 22A	USAF/USN	R.F. Fischell	APL
None	1964 48A	USAF		
None	1964 83D	USAF/USN	R.F. Fischell	APL
None	1965 65F	USN		
OGO 4	1967 73A	NASA	H. Montgomery	GSFC
			F.B. Shaffer	
			J. Callaghan	
			G.J. Gleghorn	TRW
			A. Krausy	
			R.L. Robinson	
			R.B. Beltz	
			H.G. Mesch	
			A.C. Lee	
Oscar 3	1965 16F	USN/USA/USAF	G. Sharman	Cubic Corp.

Table III (Cont.)

Specific Flights with Individual Contact

Flight Name	International Designation	Sponsoring Agency	Individual Contact	Contact Affiliation
OSO 1	1962 Z1	NASA	J. Thole	GSFC
OSO 2	1965 7A	NASA	W. Gallagher	
OSO 3	1967 20A	NASA	W. Downs	Ball Bros. Corp.
OSO 4	1967 100A	NASA	W. Downs	Ball Bros. Corp.
OV1 4	1966 25A	USAF	L. Otten	General Dynamics
OV1 5	1966 25B	USAF	L. Otten	General Dynamics
OV4 3	1966 99A	USAF	R. Dermoret	Martin Company
OV4 1R	1966 99B	USAF	J.I. Barker	WPAFB
OV4 1T	1966 99D	USAF	J.I. Barker	WPAFB
OV1 1D	1966 111D	USAF	L. Otten	General Dynamics
Pegasus 1	1965 9A	NASA	G. Graff	Fairchild-
Pegasus 2	1965 39A	NASA	R. Julius	Hiller
Pegasus 3	1965 60A	NASA	"	"
Samos 2	1961 A1	USAF	F. Ackerman	Lockheed
			L. Chidester	Lockheed
Secor 1	1964 1C	USN/USA	G. Sharman	Cubic Corp.
Secor 2	1965 17B	USA	G. Sharman	Cubic Corp.
		USAF/		
Secor 3	1965 16E	USN/USA	G. Sharman	Cubic Corp.
Solrad 1	1960 H2	USN	P. Wilhelm	NRL
Injun 1/				
Solrad 3	1961 02	USN	G. Peiper	NASA
Solrad 7A	1964 1D	USN/USA	P. Wilhelm	NRL
		USAF/	J. Yuen	NRL
Solrad 7B	1965 16D	USN/USA	"	"
		USAF/		
Surcal	1965 16G	USN/USA	"	"
		USAF/		

Table III (Cont.)

Specific Flights with Individual Contact

Flight Name	International Designation	Sponsoring Agency	Individual Contact	Contact Affiliation
Surcal	1965 16H	USN/USA	J. Yuen	NRL
Surcal	1965 65B	USN	P. Wilhelm	NRL
Surcal	1965 65C	USN	"	"
Surcal	1965 65E	USN	"	"
Surcal	1965 65H	USN	"	"
Surcal	1965 65L	USN	"	"
Surcal	1967 53B	USAF/USN	"	"
Surcal	1967 53F	USAF/USN	"	"
Surcal	1967 53J	USAF/USN	"	"
Tiros 1	1960 B2	NASA	R. Rados	GSFC
Tiros 2	1960 II-1	NASA	W.G. Stroud	
Tiros 3	1961 P1	NASA	E. Cortright	
Tiros 4	1962 B1	NASA	J. Maskasky	
Tiros 5	1962 AA1	NASA	A. Schnapf	RCA
Tiros 6	1962 Aψ1	NASA	R. Scott	RCA
Tiros 7	1963 24A	NASA	"	"
Tiros 8	1963 54A	NASA	"	"
Tiros 10	1965 51A	NASA	"	"
TRAAC	1961 AH2	USN	R.E. Fischell	APL
Transit 1B	1960 Γ2	ARPA	R.E. Fischell	APL
Transit 2B	1960 H1	USN	W.C. Scott	APL
Transit 4A	1961 01	USN	"	"
Transit 4B	1961 AH1	USN	"	"
TTS 1	1967 123B	NASA	P. Burr F. Kelly	GSFC TRW

Some of the people contained in this name tree have been contacted, and further information has been, and is being obtained from them. As was indicated, the details on the materials and manufacturing techniques in most cases can be obtained through these contacts. The performance data is not always available, due to the fact that some flights have insufficient information telemetered back regarding the performance of the solar cells.

The information required for this study is generally contained in different places. The details on the materials and manufacturing techniques can be obtained through the vehicle, solar panel and solar cell manufacturers. The performance data can be obtained in a two-step process. Information about what kind of data regarding the solar array was telemetered back can be obtained from the vehicle manufacturer, generally from the power sub-system manager. Then, the pertinent information can be requested from the appropriate individual in the sponsoring agency that monitored the flight.

A meeting with our contract monitor is being planned for some time in the next quarter, to decide on the best way to present the acquired data for publication in the final report.

SUMMARY

The flights that were chosen for study earlier in the contract were listed, and the purpose of the study was restated. This quarter was spent in acquiring data for the flights to be studied. All of the specific data obtained from the computer searches conducted earlier were codified. These data exist in paste ups in loose leaf notebooks. Examples of this type of data were reported last month, and again this month.

A detailed analysis of the environment for each flight has begun. This analysis can be quite complicated, and efforts are underway to simplify it. The most difficult aspect of the analysis will be the determination of the thermal history of the vehicle. The vehicles under study are therefore being grouped according to subclassifications, based on the nature of the vehicle, as the first attempt to find any performance correlations.

The remaining data required for this study must be obtained from individuals who have been directly involved with the particular vehicle under study. To develop these contacts, a "name tree" was begun and included in the last quarterly report. This "name tree" has been updated, and the appropriate individuals have been identified for 75 of the 77 flights in this study. Some of these people have been contacted, and the required data has been requested from them. The next quarter will be spent in acquiring these data from them. The analysis and correlation phase of the contract will begin at the end of the next quarter.

APPENDIX I

Form C-03

Outline for Recording Pertinent Data

	CARA Flight Number
	C-51
Satellite Name	International Designation
Ariel 3	1967 42A
Sponsoring Agency	
UK	
Prime Contractor	Contract Number
British Aircraft Corporation	
Solar Cell Manufacturer	Contract Number
Ferranti, Ernest Turnor Ltd. (Module Mfgr.)	

Orbit Data

Launch Date: 5 May 1967
Site: Western Test Range
Vehicle: Scout

Perigee: 306 mi.
Apogee: 373

θ: 80.2°
T: 95.6 min.

Solar Cell Data

Type:	N/P
Dimension:	1 x 2 cm.
Resistivity:	10 Ω - cm.
Efficiency:	10% in sunlight above atmosphere
Spectral Response:	

Base Material

Type:	Silicon
Thickness:	0.014 to 0.016 in.
Purity:	
Method of Preparation:	

Another unusual feature is that the cells are processed in disc form, the last operation being to scribe and break the disc to form two cells. The edges thus formed are not perfectly straight or normal to the surface but give a high shunt resistance.

Dopant

Type
Diffusion Depth
Concentration

Junction depth 0.25 to 0.5μ

Cover Slide

Material: Glass
Thickness: 0.006"
Transmission
Vendor

Cover Slide Adhesive

Name & Vendor: G.E. L.T.V. 602
Thickness
Transmission
Preparation
Application
Cure

Cover Slide Coating

Type
Thickness
Transmission & Spectral Response
Application Technique

Front Surface Conductor

Type
Material
Resistivity
Thickness
Application Technique

"Finger" Conductors

Type
Material
Resistivity
Thickness
Dimensions
Application Technique

3 fingered grid on the active surface

Untinned nickel/copper/gold

Solder Contact

Material
Thickness
Resistivity
Application Technique

Untinned nickel/copper/gold contacts which are extremely adherent and easily soldered.

The final design was not achieved without difficulties. The original cells had solder-dipped nickel-plated contacts which gave trouble due to poor adhesion and surplus solder. The cleaved edges sometimes caused the cells to jam in the assembly jigs and occasionally affected the alignment of the connecting strips. These problems were overcome by developing the untinned nickel/copper/gold contact and adjusting the tolerances of the cells, jigs and connecting strips. Thermal mismatch between the connecting strips and the cells was minimized by introducing stress relief loops and making the strips thinner.

At the beginning of the Ariel 3 programme, information on solar cell cements was proprietary, so a comprehensive programme of assessment was carried out on a range of available epoxy and silicone rubber adhesives to select the best materiials for this application. The assessment, carried out by R.A.E. in collaboration with Ernest Turner Ltd., High Wycombe (the module contractor) and the Mullard Central Materials Laboratory, Mitcham, covered electron and ultraviolet irradiation, low temperature bond tests, thermal cycling, practical application exercises and the measurement of physical properties.

The cements finally selected were:

Cover	I.C.I. Silcoloid 201 (G.E. LTV602)
Mounting	Dow Corning Silastoseal A.

A difficulty with the cover cement was that, for this particular application, it had a shelf life of four months, so it had to be purchased and used in small batches.

Solar Cell Module

Dimensions
Number of Cells: 48, 8 in series x 6 in parallel
Type of Overlays
Description of Exposed Area

Interconnections

Wiring Diagram
Material
Processing Technique

Panel

Size
Deployment Technique
Location on Spacecraft
Module Interconnection Details: Five modules in series, for the load array, six in series for the battery array.

Power for the experiments, data handling equipment, tape recorder, telemetry transmitter and command receiver on board Ariel 3 is obtained from two arrays of silicon solar cells.

One supplies the loads through converters and regulators, while the other charges a battery for operation in the Earth's shadow.

The load array feeds busbars at the four line voltages, +12V, +6V, -6V and -12V, through voltage regulators. As most of the power is required at +12V, this line is fed direct, the other voltages being obtained by a dc to dc converter. The average continuous total load is 6.7W and the peak load is 12.7W.

Isolating converters are inserted in the load and battery circuits to permit the positive terminals of both arrays to be earthed. This was necessary to meet a requirement of the Birmingham experiment that no exposed surface should be positive with respect to the satellite frame.

Fig. 2 (Ref. C-51-3) is a two-dimensional development of the system, in which the modules are shown as small rectangles. Each of the four curved doors carries three panels, load and battery panels alternating to form twelve facets around the body of the satellite. Two of the booms (F and H) each carry four load panels made of double-sided modules, while the other two (E and G) each carry four battery panels.

Thus each array comprises fourteen panels and these are connected in parallel through protective silicon diodes. Altogether, there are 7392 cells on the satellite.

Preflight Test Details

Mechanical
Performance
Voc
Isc
Vacuum-thermal
Illumination

Performance assessment

A detailed performance assessment of the system was made by a specially developed computer technique which took into account predicted cell temperatures in various attitudes and orbital conditions, the radiation flux expected during the course of the year and the effect of shadows cast on the arrays by the body, booms and aerials. Earth albedo was not taken into account (except when estimating maximum voltages for safety assessments), any extra power from this source being treated as a bonus. The assessment was refined during the course of development, as more accurate data became available and modifications were introduced leading to the final layout. The final assessment showed that the system was capable of meeting all load requirements after one year in orbit, whatever the solar orientation. An initial capability of about 15 W was necessary to achieve this.

As examples of the results of this study, curves showing the predicted end-of-life performance of the load and battery arrays in the design attitude are presented in Figs. 3 and 4 (Ref C-51-3) respectively. Two voltage-current curves are shown in each case, representing the hottest and coldest conditions likely to occur and the load and critical battery requirements are also indicated. The critical battery requirement occurs at the changeover from the constant current to the constant voltage charging mode. As already mentioned, the charging current is automatically reduced at a battery temperature of 40°C. Hence, the locus contains two points at this temperature.

Both load and battery requirements are seen to lie wholly within the output curves.

Module assembly and testing

Fig. 7 (Ref C-51-3) shows the construction of the 48 cell body module. It weighs just under 40 gm. (1.4 oz) and will deliver just over 1 W into a matched load in normal incidence sunlight above the atmosphere.

Each row of six cells, called a "sub-module", is connected in parallel by soldering the back contacts to 0.006 in. printed circuit board and the front contact to a narrow copper strip. The sub-modules are series connected in sets of eight to form 48 cell patches which are then cemented to 1/4 in. honeycomb panels and connected to three Teflon insulted terminals at each end. Finally, a 0.006 in. glass cover slip is cemented to each cell to provide a highly emissive surface and give protection against micrometeorites and low energy radiation.

The boom modules are similarly constructed, except that the honeycomb is an inch thick and cells are mounted on both faces.

The assembly process was designed to facilitate rapid production and maintain a consistently high standard of quality and reliability. Special jigs were used for every assembly stage and only the series connections were hand soldered, the other soldered joints being made in heated jigs under a closely controlled time/temperature cycle.

The modules were tested in accordance with the relevant specification. At the sub-module and uncovered module stages and again after covering, the assemblies were carefully examined at X20 magnification and performance tested in filtered 3000°K tungsten light. The performance test on the completed modules was followed by twenty thermal cycles in vacuum between +80°C and -50°C, a random noise vibration test, repeat performance test and final inspection.

Before any modules were accepted for the flight satellites, samples from production were required to pass type approval tests, which included high temperature vacuum, humidity, cold storage, acceleration, vibration and extended thermal cycling between +80°C and -70°C. Subsequently, body and boom modules survived over 1000 cycles between these limits and 240 cycles between +80°C and -100°C without measurable loss of performance.

Production acceptance testing consisted of an adhesive tape pull-off test on every contact, a dimensional check, visual inspection at X20 magnification and a performance test under a R.A.E. filtered xenon sun simulator.

During manufacture, a 1% sample of each week's production was subjected to quality assurance tests by the Inspection Authority (E.I.D.). These comprised dimensional check, visual examination, spectral response, performance measurement and a destructive soldered contact pull-off test.

To qualify for type approval, samples from the production line were required to pass electron bombardment and thermal cycling test (250 cycles - 80°C to +80°C in vacuum) in addition to the quality assurance tests.

Fig. 6 (Ref C-51-3) shows how the currents at various voltages degrade under 4 MeV electron bombardment. The current at 400 mV, which is near the working voltage of the cells, falls by about 7% after 10 electrons/cm, the flux estimated to be equivalent to the integrated electron flux encountered by the satellite over one year in orbit.

Systems assembly and testing

The final assembly stage was to mount the modules on the doors and booms of the satellite, interconnect them and measure the voltage/current characteristic of each panel in filtered 3000°K tungsten light. This work was done by the main contractor, British Aircraft Corporation, Stevenage, using an illuminator designed by R.A.E. Fig. 8 shows typical characteristics of the load and battery panels as measured at 100 mW/cm and extrapolated to 140 mW/cm, the solar constant. The conversion efficiencies calculated from these curves, which agreed well with similar measurements made on the constituent modules, were 8.8% and 9.0% for load and battery panels respectively.

Pre-launch testing

The solar arrays on the flight satellites were fully tested in natural sunlight at the launching site. Each body module was illuminated in turn (the others being covered) and its voltage current characteristic was traced on an XY plotter in a test circuit plugged into the turn-on connection. The intensity of the sunlight was monitored by a calibrated module mounted in the same place as the panel being tested. The measured curve was then extrapolated to sunlight above the atmosphere.

The boom panels were tested in pairs, in a similar fashion.

The techniques and equipment developed by R.A.E. for solar cell performance testing have been fully described elsewhere.

Panels are connected in parallel through protective silicon diodes. Boom and body modules weigh 78.0 and 39.7 gm respectively and in normal incidence sunlight each side will deliver about 1 W into a matched load. Allowing for shadowing and degradation, it is estimated that after a year in orbit the solar cells will provide a mean power of not less than 5 W with the satellite in any attitude relative to the sun. The solar cells are negative with respect to satellite frame to meet the requirements of the

Birmingham experiment.

At all stages of manufacture cells and modules were subjected to close inspection and test. Individual cells and modules were illuminated by a 2 kW Xenon arc lamp and a final test of the solar array was carried out at the range by exposing one panel at a time to the sun and measuring its output characteristics.

The spin axis of the satellite is expected to precess slowly under the influence of magnetic and aerodynamic torques. To minimize the rate of precession the axial component of magnetic moment was reduced to a low value by demagnetising the satellite in the R.A.E. magnetic facility. A small permanent magnet was fitted to cancel the residual axial component after the satellite had been demagnetised as much as possible.

The aim of the design was to keep the body solar cells and all other items, except the boom solar cells, between -15° and +60°.

Solar simulation tests were carried out on both satellite body and booms in the 2.5 m vacuum chamber facility at the R.A.E. to compare measured temperatures with those obtained by computation. The shroud lining the chamber is cooled by liquid nitrogen and six carbon arc lamps are used to simulate the radiation input from the sun. Agreement to within 5°C between measured and calculated values was achieved.

Flight Details

Orientation
Stabilization: Spin
Unusual Phenomena

Environmental Factors

Thermal Cycling of Panel (frequency, amplitude)
Radiation and Particle Environment
    Electron
    Proton
    Micrometer

Performance Details

I-V Characteristics as a Function of Time
Voc Vs. Time
Isc " "
Fill Factor " "
Maximum Power " "

Spacecraft Structure and Mechanisms

The spacecraft consists of a twelve sided body, mainly covered with solar cell panels, surmounted by a cone to which are attached the telemetry and R.S.R.S. aerials and the Meteorological Office experiment, as shown in Figs. 2 and 3 (Ref C-51-1). Attached to the base of the body are four hinged booms carrying further solar cell panels, sensors for the Birmingham experiment and aerials for the Sheffield and Jodrell Bank experiments. The spacecraft is spin stabilized and weighs 197 lb. During the launching phase the booms are tied down to the fourth stage motor of the Scout vehicle which is stabilized by spinning at 160 rev/min before ignition.

The body structure consists of a central tube with four cruciform vanes of light-weight honeycomb material on which internal equipment is mounted. During the launching phase the base of the centre tube is attached to the Scout rocket separation system by an explosively operated clamp.

The body cells are mounted on aluminium honeycomb in modules of 48 connected in a series-parallel matrix with 6 cells in parallel and 8 in series. The boom modules are similar except that they are double sides with cells on both sides of the boom. The load array consists of 14 panels, each comprising 5 modules in series, mounted on two opposite booms and alternate sides of the body. When the tie-down cord is cut by explosively operated guillotine mechanisms the booms deploy outwards under the influence of centrifugal force. To prevent them from deploying too rapidly and damaging the spacecraft damper mechanisms are used. These consist of a drum mounted on a fixed spindle with a 25 to 1 step up gear train driving an escapement mechanism. Two of these dampers are mounted on opposite booms as shown in Fig. 2 (Ref C-51-1) and the deployment of the booms is restrained by a terylene cord which is wound round the damper drums. This cord passes through ferrules in the boom structure and through a spring loaded tensioner mechanism which allows the booms to move together by bevel gears at their pivots. The de-spin sequence is as follows. At 90 sec after third stage separation, i.e. about 60 sec after fourth stage burn-out, yo-yo weights are released and the vehicle spin rate is reduced from 160 to 90 rev/min. The tie-down cord is cut 30 sec later and the booms move away from the motor, unlocking the damper drums, the Birmingham sensors swing outwards on their hinges and the booms deploy at a controlled speed. The rotational speed of the damper drums is governed by the escapement mechanism, and an equal amount of cord is unwound from each drum if both dampers operate correctly. Both dampers, however, contain sufficient cord to allow the booms to erect fully even if one damper fails to operate. The system was also designed to operate satisfactorily in the event of failure of the yo-yo de-spin system.

When the booms have deployed fully they are locked in position at 65° to the spin axis by detents. Due to the increase in moment of inertia about the spin axis as the booms deploy, the spin rate decreases from 90 to 30 rev/min. Separation from the fourth stage motor occurs after boom deployment is complete at about 4 min after yo-yo release. The Sheffield and Jodrell Bank experiment aerials are released soon after boom deployment commences by the movement apart of retaining fingers attached to adjacent boom tubes.

Alternative designs of damper mechanism were considered during the development stages but any form of damper at the hinge was rejected on account of excessive bending loads being applied to the boom structural members. The de-spin and boom deployment systems were extensively tested at B.A.C. using development and prototype satellites and as a result a number of improvements were made to increase the reliability of the systems. These included a modification ofthe drum locking mechanism and the replacement of nylon cord by stronger terylene cord.

U.K.3, now named Ariel 3, is the third satellite to be launched in a co-operative Anglo-American space research programme. Unlike the first two in the series, which were designed and built in the U.S.A. to carry British built experiments, the U.K.3 spacecraft was designed, built and tested in the United Kingdom. It was launched by a Scout rocket from the U.S. Western Test Range at 9 a.m. local time (4 p.m. GMT) on 5th May 1967. A circular orbit at an inclination of 80° and altitude of 550 km had been specified for the mission; the actual orbit achieved had an inclination of 80.2°, an apogee of 606 km and a perigee of 498 km.

Fig. 1 (Ref C-51-1) shows the organization of the project. The U.S. National Aeronautics and Space Administration (N.A.S.A.) was responsible for providing the Scout launching vehicle, the satellite separation system, range facilities and the use of the Satellite Tracking and Data Analysis Network (STADAN) of ground stations. In the U.K. the Ministry of Technology Space Department at the Royal Aircraft Establishment acted as the research, development and design authority with responsibility for management of the satellite project on behalf of the Science Research Council. The main contractors were the British Aircraft Corporation (B.A.C.) who were responsible for manufacturing the spacecraft, ground check-out and handling equipment and the General Electric Company (G.E.C.) who made the satellite electronic equipment apart from that for the five experiments, which are described in the next section, and the solar aspect sensors. Other contractors are shown on Fig. 1. (Ref C-51-1)

The Science Research Council, through the Space Research Management Unit, was responsible for the overall management of the programme, the co-ordination of the experiments, and the reduction and analysis of the data.

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