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SOLAR CELL RADIATION FLIGHT EXPERIMENT

SECOND QUARTERLY PROGRESS REPORT

JPL Contract 952351

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TECHNICAL CONTROL STATEMENT

This second Quarterly Progress Report for the Solar Cell Radiation Flight Experiment Project summarizes the work performed during the time period from 2 December 1968 to 14 March 1969, and is submitted to the Jet Propulsion Laboratory for approval. This report contains information prepared by the Hughes Aircraft Company under JPL Contract No. 952351. Its contents are not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or the National Aeronautics and Space Administration.

ABSTRACT

The primary objective of the Solar Cell Radiation Flight Experiment, scheduled for launch on the ATS-E spacecraft, is to provide high accuracy data permitting a technical evaluation of the effects of the radiation environment in synchronous orbit on selected state-of-the-art solar cell configurations. Data from the flight experiment and supplemental ground test program is a continuation of the work performed by other experimenters, and will provide design data required for extended spacecraft missions in synchronous orbit.

The flight experiment consists of two small solar panels containing a total of 80 solar cells representing 16 solar cell configurations and two signal processors required to interface with the ATS-E telemetry system.

The Solar Cell Radiation Flight Experiment was initiated on 14 August 1968 under Jet Propulsion Laboratory Contract 952351 to the Hughes Aircraft Company. The detail design of the Flight Experiment, Project Status and results of tests conducted to date are presented in this report for review by the Jet Propulsion Laboratory.

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1. INTRODUCTION

The primary objectives of the Solar Cell Radiation Flight Experiment, scheduled for launch on the fifth Applications Technology Satellite (ATS-E), are to isolate and identify the solar cell degradation mechanism(s) resulting from particulate radiation and to obtain specific design data applicable to extended synchronous spacecraft missions. The program, which encompasses the design, qualification, and fabrication of the Flight Experiment and a supplemental ground test program, was initiated under JPL Contract No. 952351 on 14 August 1968.

The flight experiment consists of two small solar panels (a rigid panel tangentially mounted to the spacecraft midsection and a flexible panel radially mounted to the spacecraft midsection) and two signal processor units which interface with the ATS-E telemetry subsystem. A total of 80 solar cells representing 16 solar cell types will be mounted on the panels and periodically monitored during flight. When activated by ground command, the flight experiment will provide 12 current voltage points for each solar cell and the temperature of each group of five identical solar cells. The periodic activation of the experiment and reduction of the solar cell data, in conjunction with data from the solar aspect sensors and radiation spectrometers, will permit a comprehensive evaluation of the radiation effects on solar cells.

Solar cells representative of the current state of the art have been selected for the flight experiment for the following specific purposes:

1) Provision of five cells of each type for statistical analysis

2) Investigation of radiation effects on coverslide thicknesses

3) Investigation of coverslide or adhesive darkening effects due to radiation

4) Investigation of the loss resulting from low energy proton damage to exposed solar cell areas and contacts

5) Investigation of radiation effects on the rear surface of three cell configurations

6) Correlation of the observed radiation degradation with the radiation environment as measured by the spacecraft-mounted radiation spectrometers

The supplemental ground test program includes proton, electron, and ultraviolet particulate radiation of state-of-the-art and advanced solar cell types. The results of the ground test program will permit the final selection and optimization of the solar cell configurations for the flight experiment and the data required for correlation of the flight test results.

The detail design of the solar cell radiation flight experiment, status of the program, and results of tests conducted on the solar panels and signal processor units are presented in this report for review and approval by the Jet Propulsion Laboratory.

2. TECHNICAL DISCUSSION

FLIGHT EXPERIMENT CONFIGURATION

The Solar Cell Radiation Flight Experiment consists of the following components:

1) A rigid solar panel tangentially mounted to the spacecraft containing five solar cells each of 13 types and 13 thermistors.

2) A flexible solar panel radially mounted to the spacecraft containing five solar cells each of three types and three thermistors mounted to a flexible substrate.

3) A total of 80 solar cells of the 2 by 2 cm configuration.

4) Two signal processor units which sequentially select the solar cells and load resistors and process the signal into the format for telemetry via the ATS-E encoders.

5) A spacecraft payload regulator which provides the regulated power required to activate and operate the experiment and to protect the spacecraft bus from an experiment failure.

Solar cells for the flight experiment have been selected based on the data resulting from previous experiments, ground test results, and spacecraft flight data. The selection of candidate cell configurations, shown in Table 1, has been heavily weighed toward obtaining design data on state-of-the-art solar cells and toward isolating the major degradation mechanism(s) observed on previous experiments and spacecraft. Five solar cells of 16 types are planned to provide a meaningful statistical sample. The five cells and a temperature sensor or thermistor will be sequentially sampled to provide 12 current voltage measurements of the I-V characteristics. Five cells of three types have been assigned to the flexible panel to evaluate the effect of radiation on the back cell surface and the potential problems to be encountered on the design of large area flexible arrays. The three cell types on the flexible panel are identical to three of the 13 cell types on the rigid panel and will provide the comparative data for data evaluation. Cells of the 2 by 2 cm configuration have been selected for the experiment.

Individual lead wires are provided for voltage and current measurement of each solar cell by the signal processor units. The signal processors utilize four main-frame telemetry channels of the ATS-E encoders.

TABLE 1. LIST OF CELL CONFIGURATIONS

Configuration Number	Cell Type	Resistivity, Ω-cm	Cell Thickness, mils	7940 Coverglass Thickness, mils	Coverslide Gap, mils	Submodule Location
1	N/P	10	12	6	0	Rigid panel
2	N/P	10	12	12	0	Rigid panel
3	N/P	10	12	20	0	Rigid panel
4	N/P	10	12	60	0	Rigid panel
5	P/N (Li float zone)	-	12	6	0	Rigid panel
6	P/N (Li crucible)	-	12	6	0	Rigid panel
7	N/P	10	12	12	0	Rigid panel (solderless bus bar)
8	N/P	10	12	60	0	Rigid panel (solderless grid lines)
9	N/P	10	12	12	5	Rigid panel
10	N/P	10	12	12	15	Rigid panel
11	N/P	2	8	6	0	Rigid panel
12	N/P	10	12	12	0	Rigid panel (no coverslide coating)
13	N/P (pre-irradiated)	10	12	12	0	Rigid panel (no filters, A-R coating, adhesives)
14	N/P	10	12	6	0	Flexible panel
15	N/P	2	8	6	0	Flexible panel
16	P/N (Li float zone)	-	12	6	0	Flexible panel

Two ground commands activate and control the experiment: 1) payload regulator on and 2) payload regulator off. Due to the location of the solar panels on the spacecraft midsection, the experiment will be activated twice to obtain the full complement of data, once when each panel approaches the sun normal position. The elapsed time interval required for each activation is 45 minutes.

Qualification testing of the signal processor unit has been successfully completed, and acceptance testing of the two flight model signal processor units is scheduled for completion by 21 March 1969. Qualification testing of the rigid and flexible solar panels has been initiated.

Spacecraft Interface

The rigid and flexible solar panels will be externally mounted on the spacecraft midsection or bellyband at stations 0 = 254 degrees and 0 = 286 degrees, respectively. The two signal processors will be mounted at station 0 = 243 degrees on the forward spacecraft bulkhead. The payload regulator for the solar cell experiment will be mounted at 0 = 225 degrees on the forward bulkhead.

Each solar panel is thermally isolated from the spacecraft to provide minimum impact on the spacecraft design and thermal balance. Interface drawings and specifications have been prepared and released for the solar cell experiment, and all spacecraft drawings have been released.

In addition to the interface and detail drawings, Hughes has prepared and released the following documents pertaining to solar cell experiment and spacecraft interface:

1) Data Tape Specification defining the format and information required from the experiment for data analysis.

2) Operation Test Plan defining operational sequence of solar cell experiment and recommended operating schedules.

3) Systems Test Plan defining tests to be performed after delivery of the solar cell experiment for installation on the ATS-E spacecraft.

Solar Panels

A total of 80 solar cells of the 2 by 2 cm configuration will be mounted on the rigid and flexible solar panels for the solar cell radiation flight experiment. Sixty-five solar cells will be mounted in groups or modules of five identical cells on the rigid panel and 15 cells, representing three cell configurations, will be mounted on the flexible solar panel. Figures 1 and 2 depict the flight model solar panel configurations, and Table 1 presents the solar cell configurations selected for the flight experiment.

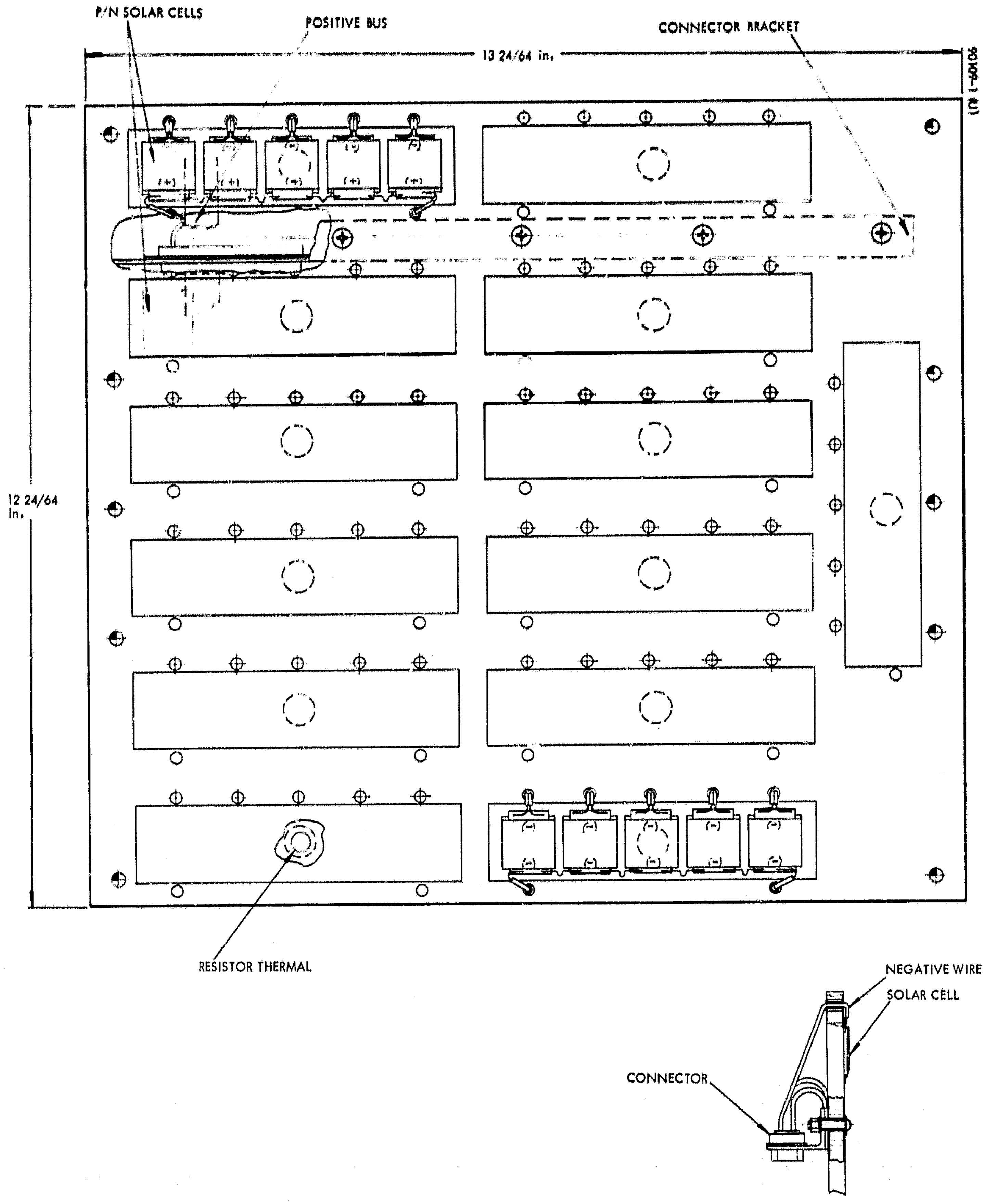


Figure 1. Rigid Panel

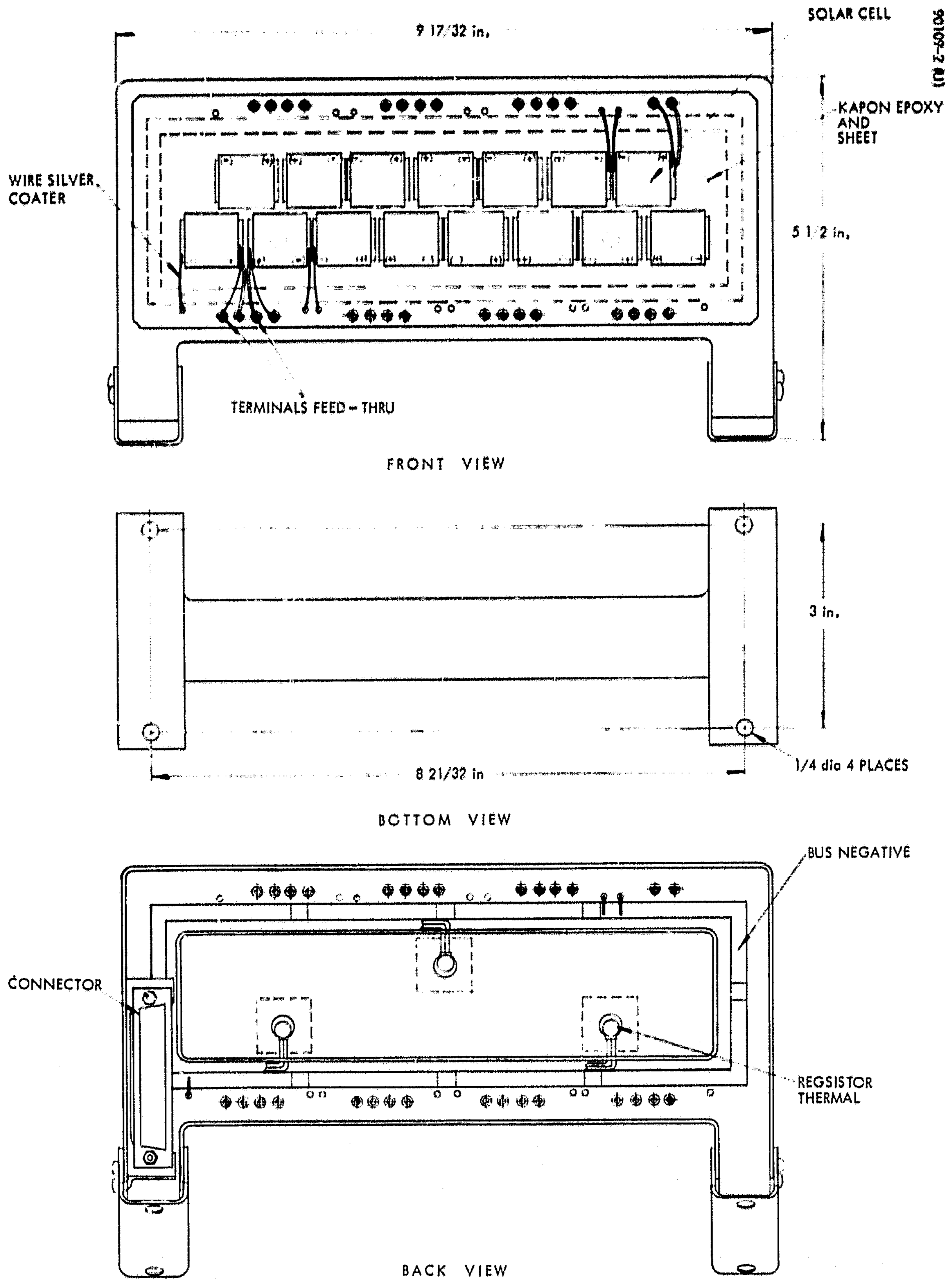


Figure 2. Flexible Panel

The list of candidate solar cells has been revised to reflect the following specific changes from the configuration list presented in the previous report.

1) The configuration with an integral coverslide has been deleted and replaced with a cell with no coatings on the coverslide.

2) The wrap-around cells have been deleted and a cell with a 5 mil exposed area between the N contact and the coverslide has been added. Deletion of the wrap-around cell has been necessitated by the depletion of the inventory during qualification tests.

Fabrication and qualification testing of the rigid and flexible solar panels for the Solar Cell Radiation Flight Experiment has been initiated; however, completion of qualification testing and the start of fabrication of the flight panels has been delayed due to solar cell and coverslide cracking during the initial thermal cycling tests. The results of the thermal cycling tests conducted to date, design changes, and program plans for completion of qualification and acceptance testing of the rigid and flexible solar panels are presented in the following paragraphs.

Rigid Solar Panel

Fabrication of the solar cell modules and the qualification model rigid solar panel was initiated in January 1969, and the completion of qualification testing has been delayed due to solar cell and coverslide cracking problems encountered during thermal cycling of the modules and the rigid solar panel. Design changes and changes in the fabrication processes and test procedures have been incorporated as a result of the failures. The major changes are as follows:

1) Substitution of titanium for aluminum for the module base.

2) Selection of RTV-560 as the solar cell adhesive in place of the Hughes epoxy adhesive.

3) Deletion of thermal cycling testing of individual modules.

4) Redesign of the connector bracket to thermally decouple the bracket from the substrate.

5) Redesign of cell interconnections and wiring.

6) Improved bonding process control.

7) JPL development of alternate fabrication process for backup purposes.

As of this date, the qualification model rigid panel is being reworked to incorporate the above changes prior to restarting the qualification test program.

Module Testing

The initial design of the rigid panel was based on the use of the Hughes epoxy adhesive system, with a fabrication sequence that would permit electrical calibration testing at Table Mountain of individual modules and thermal cycling testing of individual modules.

As initially designed, five solar cells were to be bonded to an aluminum strip or module base using two plies of 0.003 inch thick fiberglass cloth impregnated with the epoxy adhesive. Modules were fabricated to the initial configuration and subjected to thermal cycling between the temperature limits of +200°F to -250°F. Extensive solar cell cracking and coverslide cracking was observed after the initial two thermal cycles on all of the modules fabricated. All five cells on one module, containing 12 mil thick cells with 60 mil thick coverslides, failed in shear in the silicon of the cells. During the test, the modules were placed directly on the LN_2 cold plate in the vacuum chamber and were not restrained from bending. Failure of the modules was a result of the following factors:

1) The stress levels resulting from the differential thermal expansion between aluminum, the fiberglass/epoxy, and the solar cells.

2) The deflection of the modules during the test which, acting like a bimetallic spring, produced excessive stress levels and was the predominate cause of failure.

Additional solar cell modules were fabricated, but were bonded to small substrate specimens prior to test and included alternate design configurations as shown in Figure 3. Each of the modules was cycled five times between the temperature limits of +200°F to -250°F. A control module, fabricated to the initial design configuration with 12 mil cells and 12 mil coverslides, was not bonded to a substrate and failed the thermal test, while the redesigned modules evidenced no damage from the thermal test. Two specimens, configurations 1 and 3 of Figure 3, were subsequently cycled 20 times from immersion in LN_2 to an oven maintained at 230°F. One specimen, configuration 1, was cycled a total of 200 cycles between LN_2 and the 230°F oven.

Panel Qualification Tests

Qualification level thermal cycling tests have been performed to date on the rigid solar panel configurations shown in Figures 4 and 5, and the qualification model panel is currently being reworked to the configuration shown in Figure 6 for further qualification level tests.

Following the successful thermal cycle tests performed on the small test specimens where the modules were bonded to the substrate, Hughes fabricated the first qualification model solar panel to the configuration shown in Figure 4. The module design based on the Hughes epoxy adhesive system

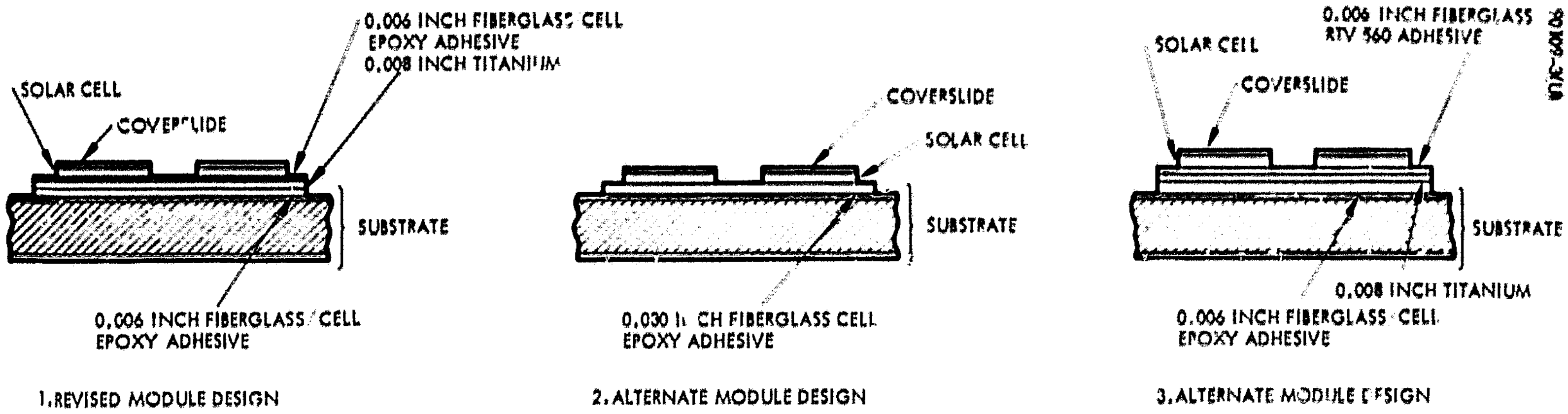
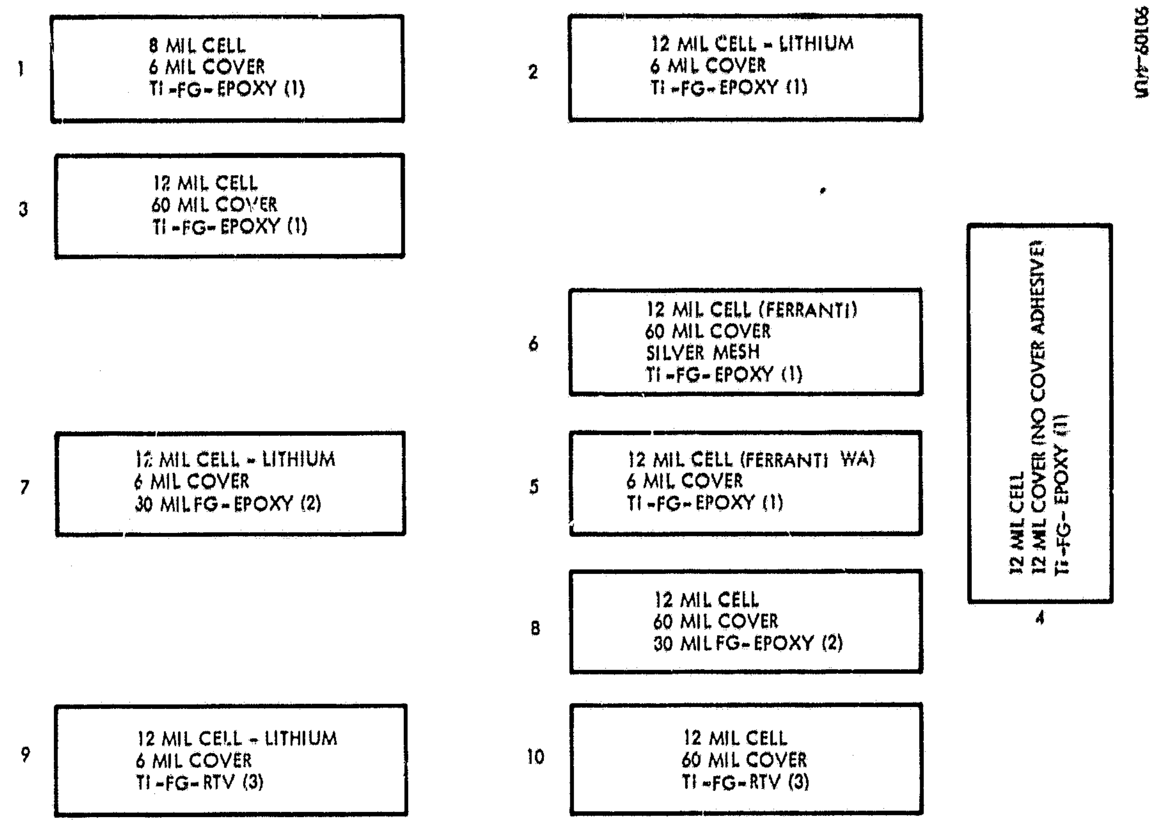


Figure 3. Revised Module Design



( ) DENOTES FABRICATION PER FIGURE 3

Figure 4. Rigid Solar Panel Qualification Model 1

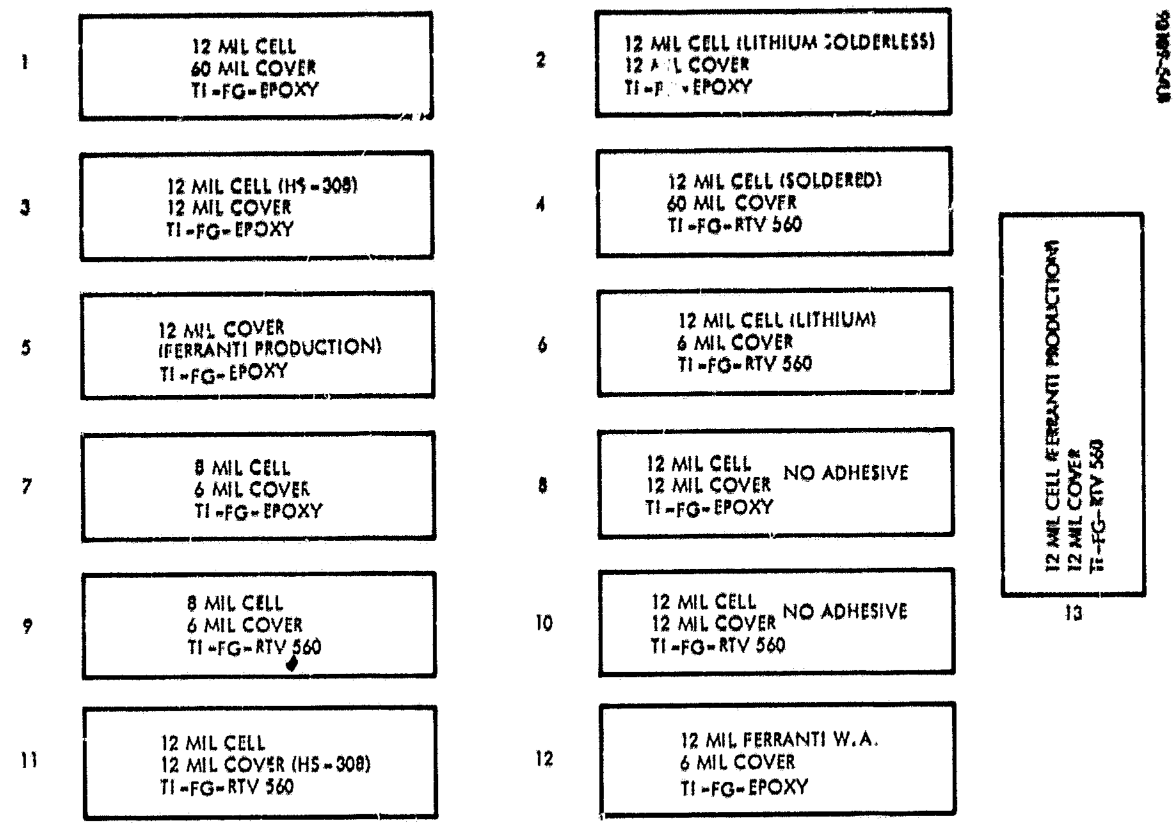


Figure 5. Rigid Solar Panel Qualification Model 2

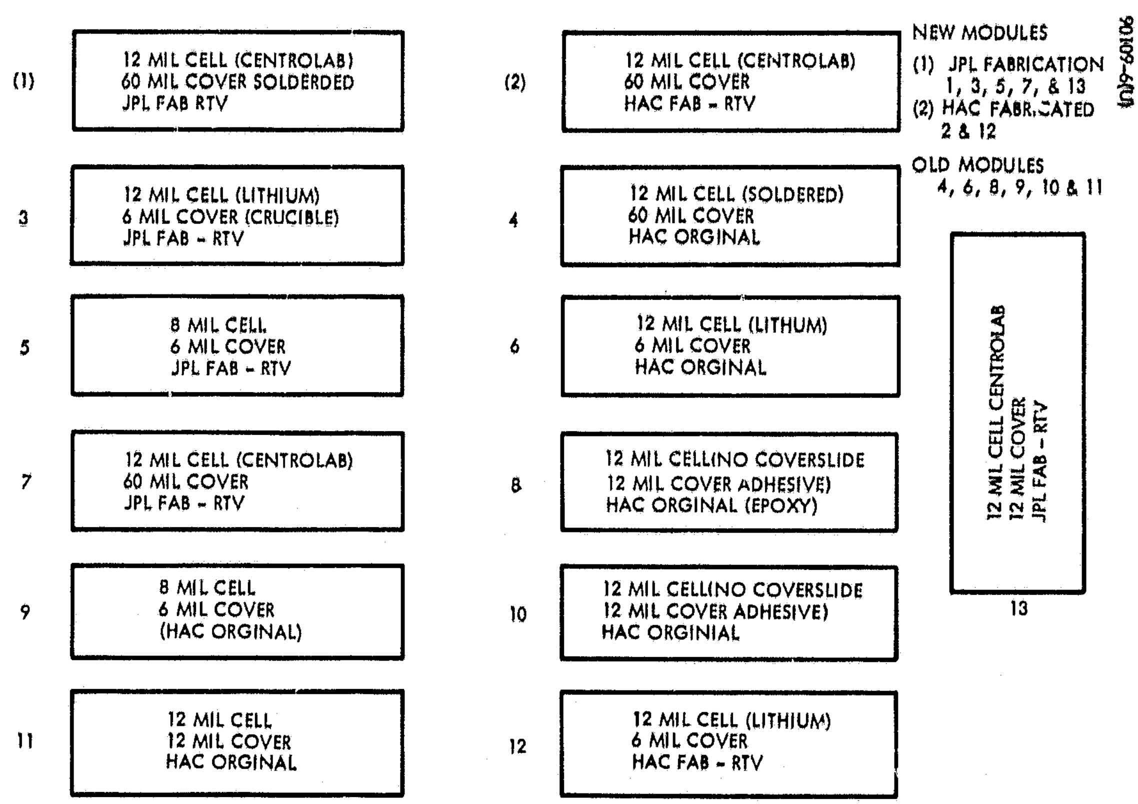


Figure 6. Rigid Solar Panel Qualification Model 3

was selected as the primary configuration, but modules were bonded to the panel using the alternate design and fabrication processes depicted in Figure 3. The completed panel was subjected to 50 thermal cycles between the temperature limits of +200°F to -200°F, and the panel was visually inspected after 10, 25, and 50 thermal cycles.

Cell and coverslide cracking was noted after the first five cycles on the following solar cells:

Module No.	Cell No.	Description
4	1, 2, 3	Coverslide cracking on cells with no cover adhesive
1	1, 2	Coverslide cracks
2	2	Coverslide crack
5	2	Cell crack, adhesive void
7	1, 2	Cell crack, adhesive void

The defects were noted, but cells were not replaced prior to completion of the 50 thermal cycles.

No additional cell or coverslide cracks were noted after completion of the 25 thermal cycles, although module 4 was noted to be delaminating from the substrate.

At the completion of the 50 thermal cycles, extensive failure of the bond between the titanium strip and the substrate occurred, with corresponding cracking of the cells and coverslides. A post-test investigation indicated that the cause of the bond failure was the result of inadequate cleaning of the titanium strip and aluminum faced substrate which resulted from the lack of specific or detailed process instructions.

Following the failure of the initial qualification model configuration, the modules were removed from the substrate. The panel was reworked to the configuration shown in Figure 5 and incorporated the following specific design and process changes:

1) Revised metal mesh interconnect and wiring design to provide added stress relief to the cell contacts.

2) Revised process instructions for cleaning and cell and module bonding.

3) Revised design for mounting of coverslides on modules where no coverslide adhesive is used.

The reworked rigid solar panel was subjected to 50 thermal cycles between the temperature limits of +200°F to -225°F, and the panel was visually inspected after 10, 25, and 50 cycles. Table 2 depicts the results of a visual and electrical inspection after the completion of thermal cycling. All cells bonded with RTV-560 evidenced no visual or electrical degradation, while cells bonded with the epoxy adhesive sustained damage.

The pattern of cell failures in modules 1 and 2 indicated an interrelationship between the connector brackets and attaching bolts and thermally induced stresses. A post-test stress analysis indicated that connector bracket induces a bending moment into the panel and cells during temperature cycling.

TABLE 2. RIGID SOLAR PANEL THERMAL CYCLING RESULTS QUALIFICATION MODEL L

Module Number	Fabrication Process	Cell Number	Comments
1	Ti-FG-Epoxy	1, 4	Cracked cover
2	Ti-FG-Epoxy	1, 2	Cracked cover and cell
3	Ti-FG-Epoxy	5	Cracked cover
4	Ti-FG-RTV	-	OK
5	Ti-FG-Epoxy	1	Cracked cell
6	Ti-FG-Epoxy	-	OK
7	Ti-FG-Epoxy	-	OK
8	Ti-FG-Epoxy	2	Cracked cover; handling
9	Ti-FG-RTV	-	OK
10	Ti-FG-RTV	-	OK
11	Ti-FG-RTV	-	OK
12	Ti-FG-Epoxy	1, 5	Cracked cell
13	Ti-FG-RTV	-	OK

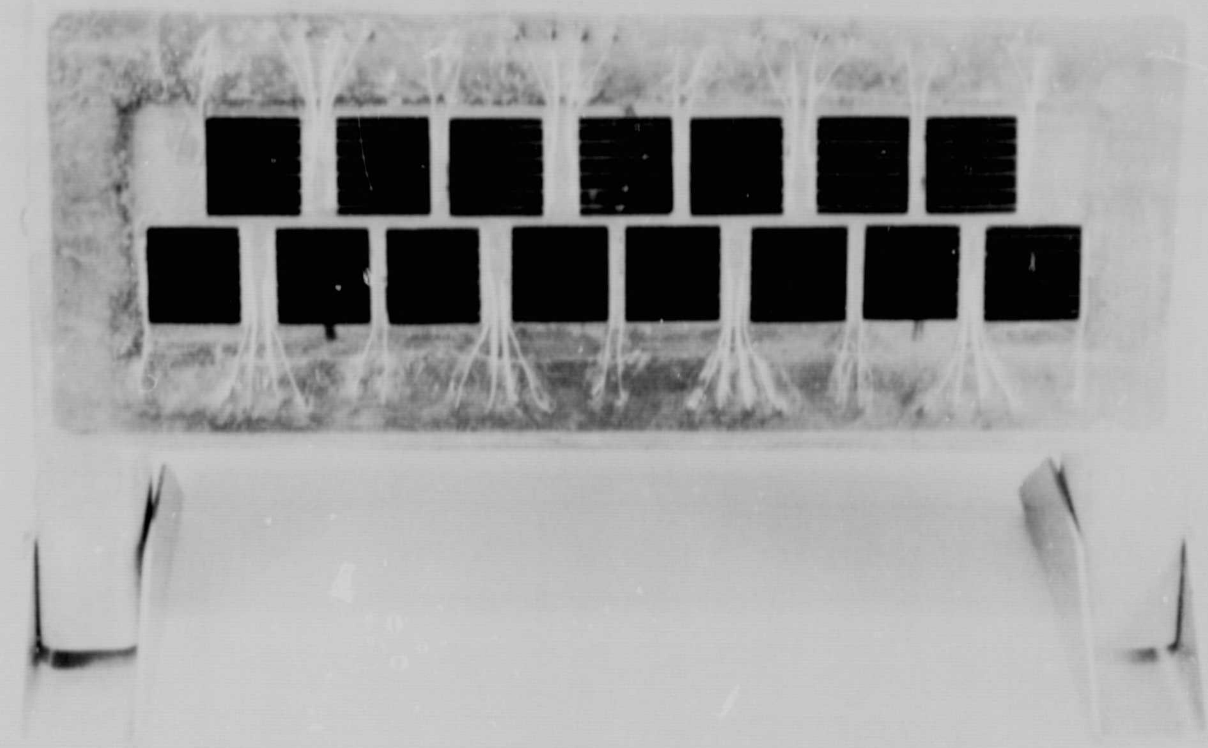


Figure 7. Flexible Solar Panel Qualification Model

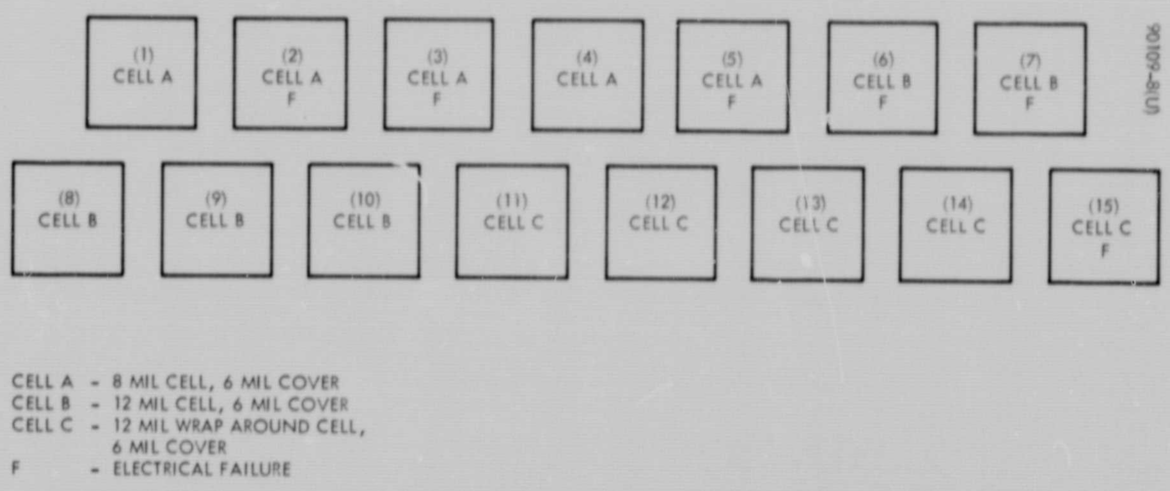


Figure 8. Results of Thermal Test – Flexible Solar Panel

The results of the thermal cycling tests on the rigid solar panel substrate were reviewed with JPL and Hughes management and technical personnel prior to redesign and rework of the panel. Based on the review, the panel will be reworked to the configuration shown in Figure 6 and will contain solar cell modules fabricated and bonded by JPL using an alternate fabrication process. The configuration will qualify with the Hughes and JPL fabrication processes for use on the flight model solar panel. Prior to vibration and thermal testing to the qualification levels, the connector bracket will be locally reworked to eliminate the high stress condition on the cells.

As currently planned, Hughes and JPL will each fabricate a rigid solar panel for flight acceptance testing using the fabrication processes used for construction of the qualification model solar panel. Completion of flight acceptance testing is scheduled for 2 May 1969.

Flexible Solar Panel

The flexible solar panel contains 15 solar cells (five each of three different configurations) for evaluation of the effects of radiation on the exposed back surfaces of the cell. The cell configurations on the flexible solar panel are duplicates of cell configurations on the rigid panel, thereby permitting an evaluation of the relative damage mechanisms.

One flexible solar panel was fabricated for qualification testing and is shown in Figure 7. The panel was subjected to thermal vacuum testing with the rigid panel between the temperature limits of +200°F to -225°F for a total of 100 thermal cycles. Initial cell failures were noted after the first five thermal cycles, and extensive failures were noted after 100 thermal cycles. Figure 8 and Table 3 present the test results.

The primary cause of the failures is the result of wrinkling of the fiberglass/Kapton substrate at low temperatures. Although the substrate was pretensioned during fabrication, the relative displacement between the cell rows permits a wrinkle to form during temperature cycling, thereby overstressing the cell.

The results of the thermal cycling tests on the flexible solar panel were reviewed with JPL and Hughes management and technical personnel. Based on the review, two flexible solar panels will be fabricated for qualification testing. One panel will be fabricated with 16 evenly spaced solar cells bonded to a fiberglass/Kapton substrate, and the bonding of the substrate to the frame will be modified to incorporate greater flexibility. The second panel will be fabricated for test and will eliminate the fiberglass/Kapton substrate. The cells will be mechanically supported by the interconnection to the fiberglass frame.

TABLE 3. FLEXIBLE SOLAR PANEL THERMAL CYCLING SUMMARY

Cell No.	Cell Type	Coverslide Type	Test Results
1	8 mil	6 mil	Cell crack observed after 5 cycles; cell replaced after 50 cycles
2	↑	↑	Cell crack observed after 5 cycles; cell replaced after 50 cycles
1R	│	│	Replacement for No. 1 — visually and electrically good at 100 cycles (50 cycles on cell)
2R	│	│	Replacement for No. 2 — visual crack at 55 cycles (5 cycles on cell); electrical failure at 100 cycles (50 cycles on cell)
3	│	│	Cover crack noted; electrical failure at 100 cycles
4	↓	│	Visually and electrically good at 100 cycles
5	8 mil	│	Visually good, but electrical failure at 100 cycles
6	12 mil	│	Cell separation from substrate at 75 cycles; electrical failure at 100 cycles; contact failed
7	↑	│	Cell separation from substrate at 75 cycles; electrically good at 100 cycles
8	│	│	Visually and electrically good at 100 cycles
9	↓	│	Visually and electrically good at 100 cycles
10	12 mil	│	Visually and electrically good at 100 cycles
11	12 mil Ferranti wrap-around	│	Visually and electrically good at 100 cycles
12	↑	│	Visually and electrically good at 100 cycles
13	│	│	Visually and electrically good at 100 cycles
14	↓	↓	Visually and electrically good at 100 cycles
15	12 mil Ferranti wrap-around	6 mil	Cell separation noted at 75 cycles; back contact separation and electrical failure confirmed at 100 cycles

Signal Processor Unit

Each of the two identical signal processor units has been specifically designed to interface between the solar panels and the ATS-E encoder. Each signal processor will provide voltage-current data for 40 solar cells under 12 load conditions and the temperature of each group of five cells. The design of the signal processor was modified to eliminate the high density connectors and to incorporate an ATS approved connector. An external cable, 34 inches long, with the solder type connectors has been incorporated.

The qualification model signal processor unit, with the high density connector, has successfully completed qualification testing, which included three-axis sine and random vibration testing and thermal vacuum testing. Under vacuum conditions ($P = 2.4 \times 10^{-6}$ Torr), the unit was raised to a temperature of +120°F and allowed to stabilize and a functional test was performed. The temperature was dropped to +20°F and, after stabilization, the functional test was performed. The unit was maintained at each temperature for a minimum of 4 hours. After the low temperature test, the unit was again tested under room ambient conditions. No failure or out-of-tolerance performance was noted during the qualification testing of the signal processor unit.

The qualification model has been reworked for the connector change and is available as the flight spare.

Fabrication of the two flight model signal processor units has been completed. Figure 9 presents details and the final assembly of the signal processor unit. Qualification testing has been initiated and is scheduled for completion by 28 March 1969.

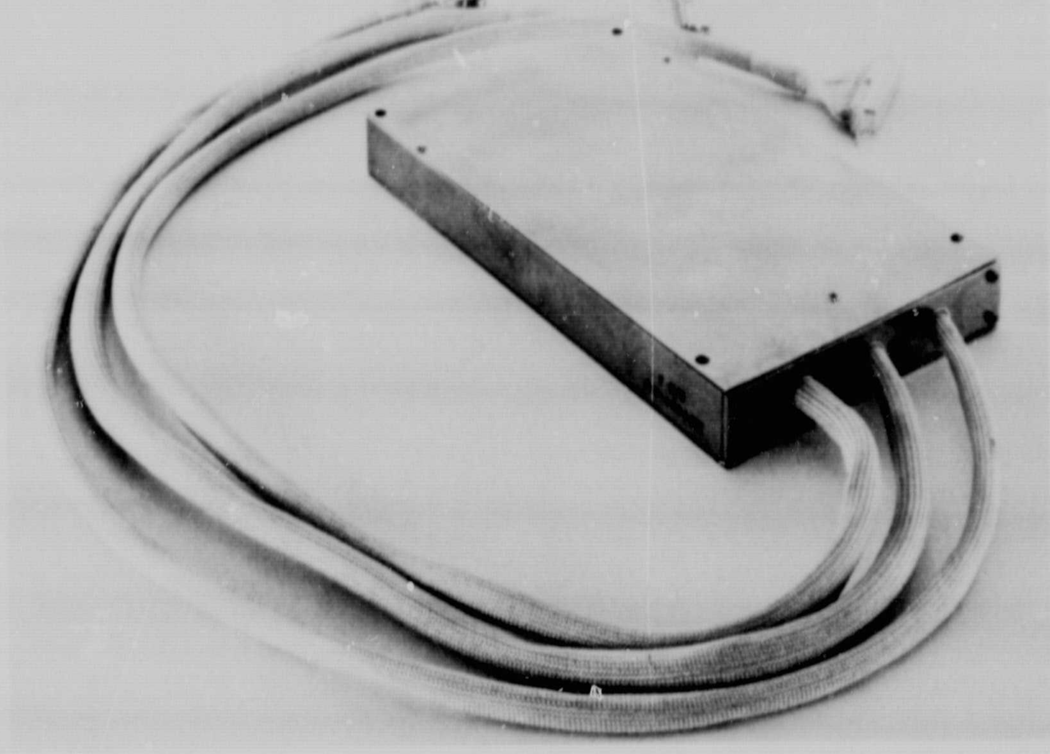
GROUND TEST PROGRAM

A ground test program has been initiated to supplement the flight experiment and will provide data required to finalize the selection of solar cell configurations for the flight experiment. Table 4 presents a summary of the planned tests to be conducted in the ground test phase and the status of each test.

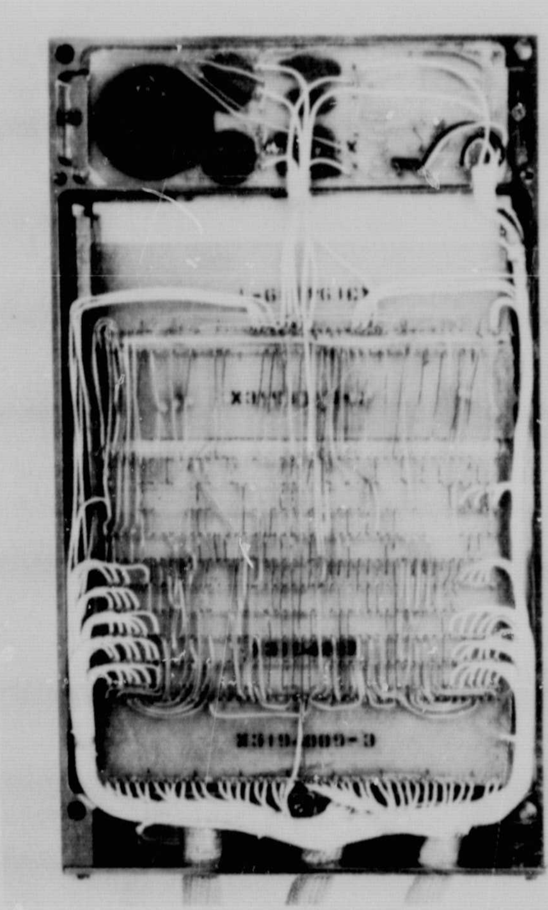
A detailed description of tests completed to date and the test data is presented in the following sections.

Electron Irradiation Effects on Cell Performance as Function of Coverslide Thickness — Test T-4

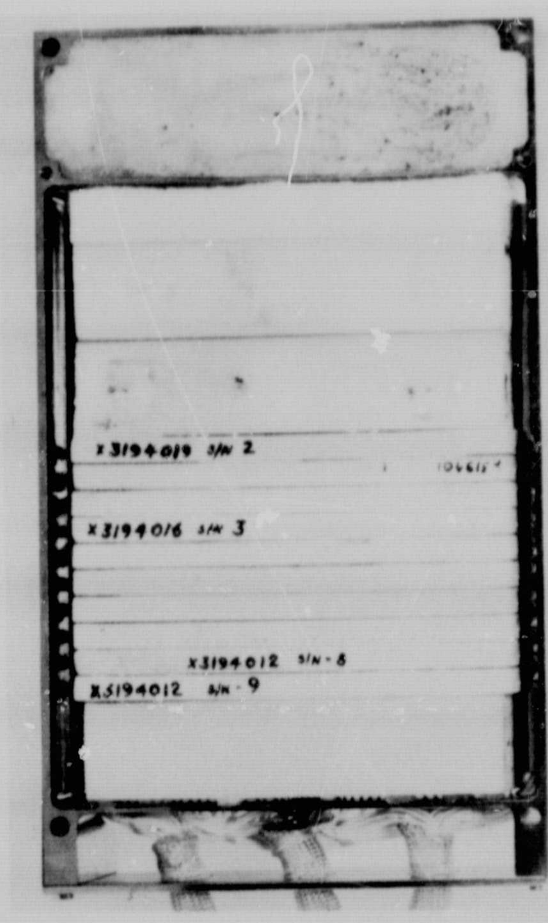
The object of this test was to investigate the effect of the synchronous trapped electron environment on solar cell performance as a function of coverslide thickness.



a) External View
(Photo 4R07945)



b) Internal Wiring
(Photo 4R07947)



c) Encapsulated Modules
(Photo 4R07946)

Figure 9. Signal Processor Unit

TABLE 4. GROUND TEST PROGRAM SUMMARY

Test No.	Description	Status
T-1	Ultraviolet radiation of special cell/coverslide assemblies	Completed; preliminary results reported in first quarterly progress report.
T-2	Ultraviolet qualification of coverslide adhesive	Completed; preliminary results reported in first quarterly progress report.
T-3	Thermal cycle and thermal soak effects on cell performance as a function of coverglass thickness; coverslide adhesive type and thickness and cell grid design	Completed; preliminary results reported in first quarterly progress report.
T-4	Electron irradiation effects on cell performance as a function of coverslide thickness	Five year irradiation level completed; preliminary results reported in this report.
T-5	Electron irradiation of coverglass assemblies	Irradiations in progress.
T-6	Low energy proton irradiation of exposed bus bar areas	Irradiations completed; preliminary results reported in this report.
T-7	Low energy proton irradiation of exposed bar gap areas	Irradiations completed; preliminary results reported in this report.
T-8	Low energy proton irradiation of exposed B' gap areas	Irradiations completed; preliminary results reported in this report.
T-9	Low energy proton irradiation of unshielded cells	Irradiations completed; data not reduced.
T-10	Low energy proton irradiation of cell rear contact surface	Irradiations completed; data not reduced.
T-11	Low energy proton irradiation of "zero-gap" cells	Irradiations completed; data not reduced.
T-12	Electron irradiation of "zero-gap" cells	One year irradiation level completed; data not reduced.
T-13	Temperature coefficient as a function of angle of incidence for irradiated cells	Preradiation calibration completed.

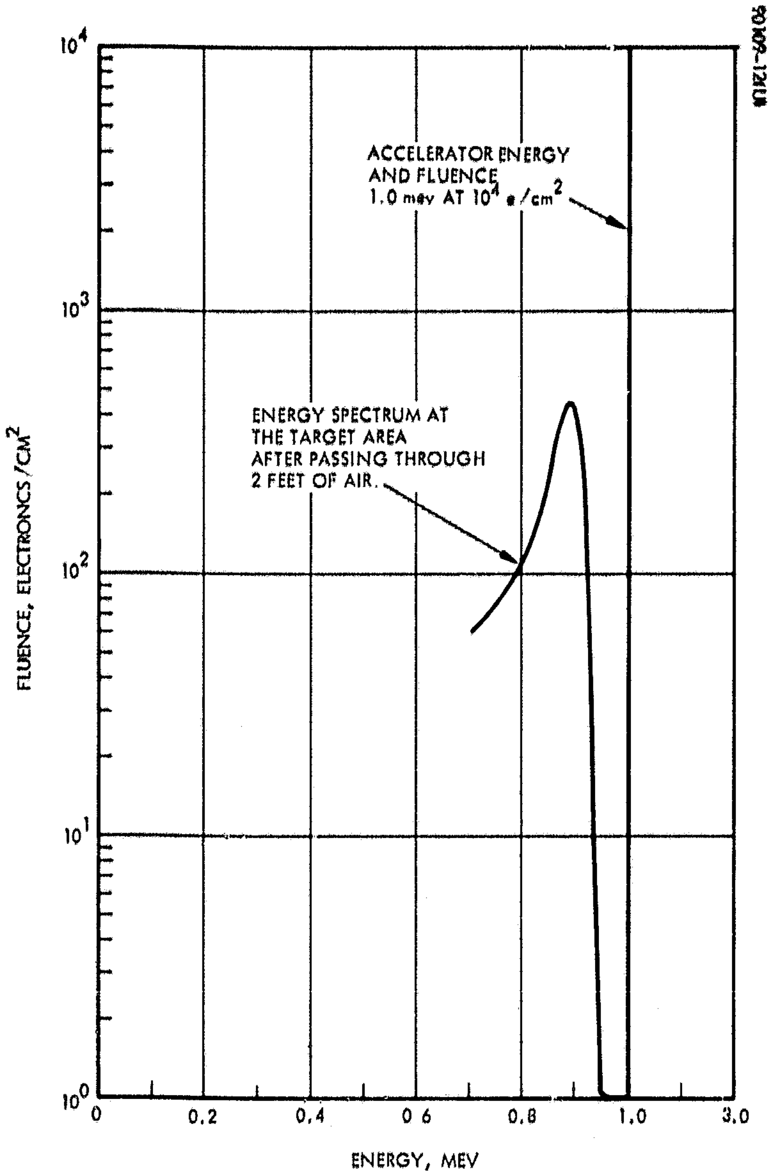


Figure 10. Electron Energy and Fluence Comparison

Test Sample Description

Ten ohm-cm, 2 by 2 cm, 12 mil thick, boron doped, N/P, current production Centralab silicon solar cells were used in this test. Both soldered and unsoldered solar cells were employed. Coverslides were 7940 fused quartz with antireflective coatings and ultraviolet filters. Dow Corning XR6-3489 adhesive was utilized as the coverslide adhesive system. Zero (bare), 6, 12, 30, and 60 mil thick coverslides were applied to the solar cells. The test sample size for the unsoldered cells was five and for the completely soldered cells was four for each coverslide thickness, resulting in a total of 45 samples.

Test Apparatus

The electron accelerator at JPL was used as the source of the electron environment. A detailed description of JPL's accelerator and apparatus to calibrate the environment at the target area will be included in the final report. The solar cell's voltage-current characteristics were measured using the X-25 solar simulator which was furnished by JPL. The X-25 simulator was calibrated and maintained at an intensity of 140 mw/cm^2, AMO using Balloon Flight Standard Cell No. 408. The temperature of the solar cells during measurements was maintained at 25°C using a water-cooled brass cell holder.

Test Procedure

The solar cells were irradiated with the JPL electron accelerator using an electron spectrum representative of synchronous orbit. The synchronous electron environment is based on J. I. Vette's* proposed AE3 environment for electrons at synchronous altitudes. This integral electron environment is shown in Table 5.

The omnidirectional aspect of the environment was simulated by mounting the cells on a rotating cylindrical cell holder. The cell holder was large enough to hold all the samples. The electron beam at the target area was large enough to encompass the entire cell holder, therefore, all the samples experienced the same environment during irradiations.

The electron energy-flux spectrum was simulated in the following manner. The target area was approximately 2 feet from the end of the accelerator. The accelerator was set to produce electrons of a certain energy and flux rate. Due to the electron collisions with the air, the electron energy was attenuated and broadened. That is, a mono-energetic electron beam was spread into an energy spectrum. Displayed in Figure 10 is the comparison of the accelerator's electron energy and fluence with the resulting energy fluence relationship at the target area. Three acclerator energies (0.5, 0.7, and 1.0 mev) were used in the irradiations. By integrating the resulting energy spectrums of the three accelerator energies

*J. I. Vette, et al., "Electrons at Synchronous Altitudes," Models of the Trapped Radiation Environment, NASA SP-3024, Vol. III, 1967.

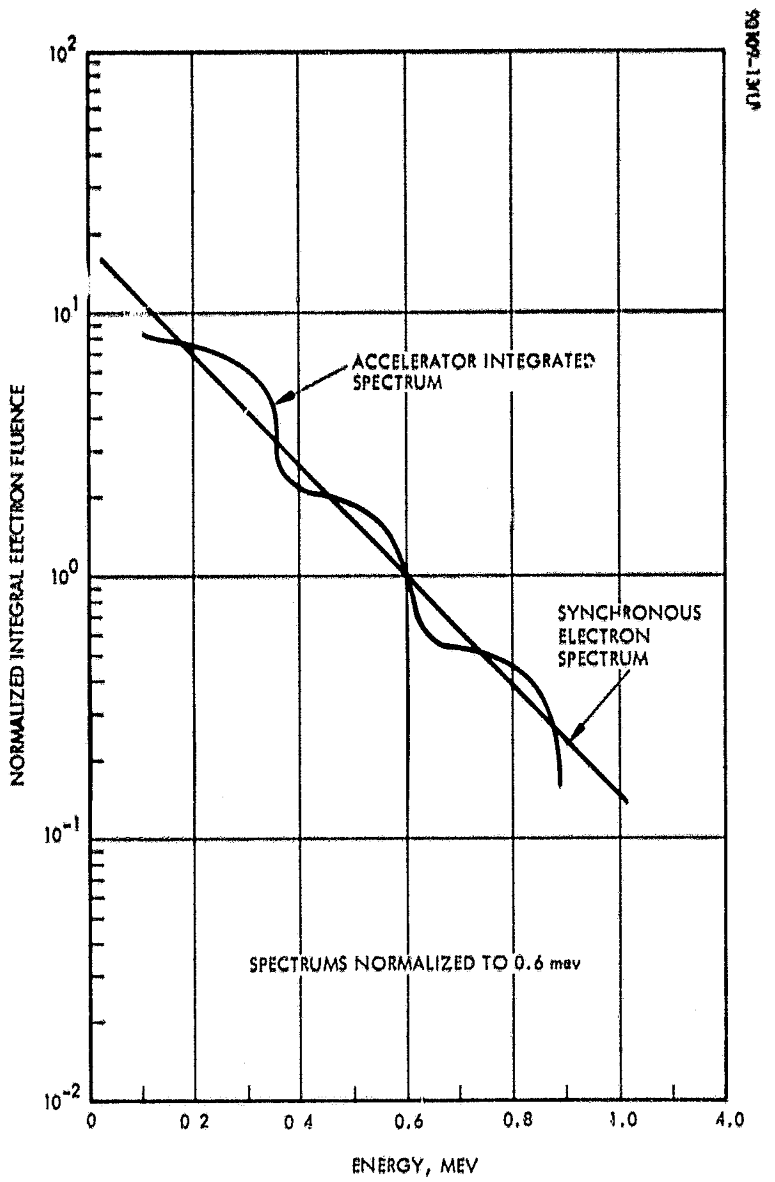


Figure 11. Synchronous Integral Electron Spectrum Comparison

TABLE 5. SYNCHRONOUS EQUATORIAL INTEGRAL ELECTRON ENVIRONMENT

Electron Energy, mev	Integral Omnidirectional Electron Flux, electrons/cm^2/sec
0.01	6.51×10^7
0.02	5.80×10^7
0.03	5.33×10^7
0.04	4.97×10^7
0.05	4.65×10^7
0.10	3.50×10^7
0.20	2.10×10^7
0.30	1.29×10^7
0.40	7.94×10^6
0.50	4.93×10^6
0.60	3.07×10^6
0.70	1.91×10^6
0.80	1.19×10^6
0.90	7.45×10^5
1.00	4.66×10^5

and adjusting the flux at each energy, a simulation of the synchronous integral electron spectrum was obtained. A comparison of the synchronous integral electron spectrum as obtained from the accelerator is shown in Figure 11. The test samples were irradiated at four radiation levels simulating 0.25, 0.5, 1.0, and 5.0 years in synchronous orbit. The solar cell's voltage-current characteristics were measured after each radiation level.

Results

Only preliminary results are being presented in this progress report. Only averages of the results are presented with no statistical analysis. Short-circuit current, open-circuit voltage, and maximum power have been recorded

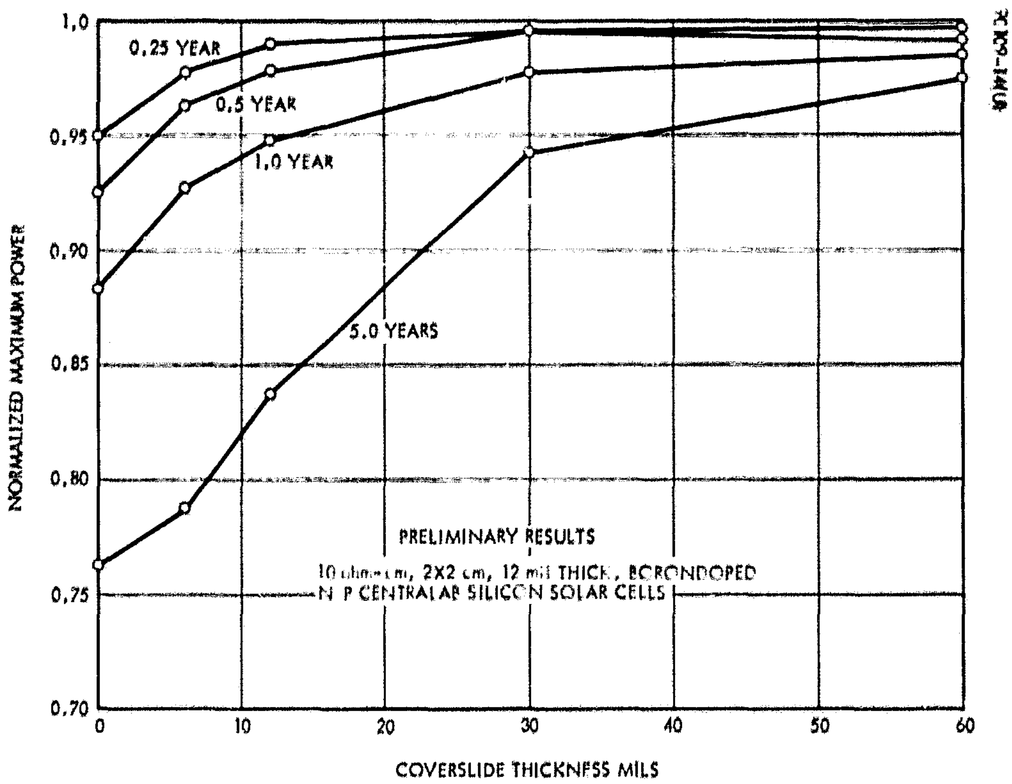


Figure 12. Normalized Maximum Power Degradation

for each cell after each radiation level. Figure 12 shows the preliminary results for the normalized maximum power degradation as a function of coverslide thickness for equivalent time intervals of 0.25, 0.5, 1.0, and 5.0 years in synchronous orbit. These preliminary results are for the Centralab solderless cells. Figures 13a through 13e show the preliminary results for the same cells as displayed in Figure 12 for the normalized response for open-circuit voltage, short-circuit current, and maximum power as a function of equivalent time in synchronous orbit for 0, 6, 12, 30, and 60 mil coverslides. The preliminary results appear to be quite regular with no anomalies. The thicker coverslides appear to better protect the solar cells from the environment.

Conclusion

Until additional data analysis and statistical analysis are performed, no conclusions can be drawn. The preliminary data have been reported at this time to give trends in the data.

Low Energy Proton Irradiations of Small Exposed Solar Cell Areas — Tests T-6, T-7, and T-8

The object of these tests was to investigate the effect of the synchronous trapped low energy proton environment on small exposed solar cell areas. The solar cell areas under investigation were bus bar gaps, bar gaps, and B' gaps. Figure 14 is the terminology chart explaining the solar cell terminology used in this report.

The object of test T-6 was to ascertain the effect of the low energy proton synchronous environment on the bus bar areas; that is, the portions of the bus bar not covered by solder. Simulated in this test were approximately 98, 95, and 90 percent solder coverage of the bus bar.

The object of test T-7 was to ascertain the effect of the low energy proton synchronous environment on small areas of exposed silicon between the bus bar and coverslide. Five different small areas were used to determine the solar cell degradation as a function of exposed bar gap areas.

The object of test T-8 was to ascertain the effect of the low energy proton synchronous environment on the small areas of exposed silicon above the bus bar, the B' gap. Three different small areas representative of current production solar cells were used to determine the solar cell degradation as a function of exposed B' areas.

Test Sample Descriptions

Ten ohm-cm, 2 by 2 cm, 12 mil thick, boron doped, N/P, current production Centralab and Heliotek silicon solar cells were used in these tests. Centralab solderless solar cells were used in the bar and bus bar gap irradiations, tests T-6 and T-7, and Heliotek soldered solar cells were used in the B' gap irradiations, test T-8. Bimetal masks, as shown in

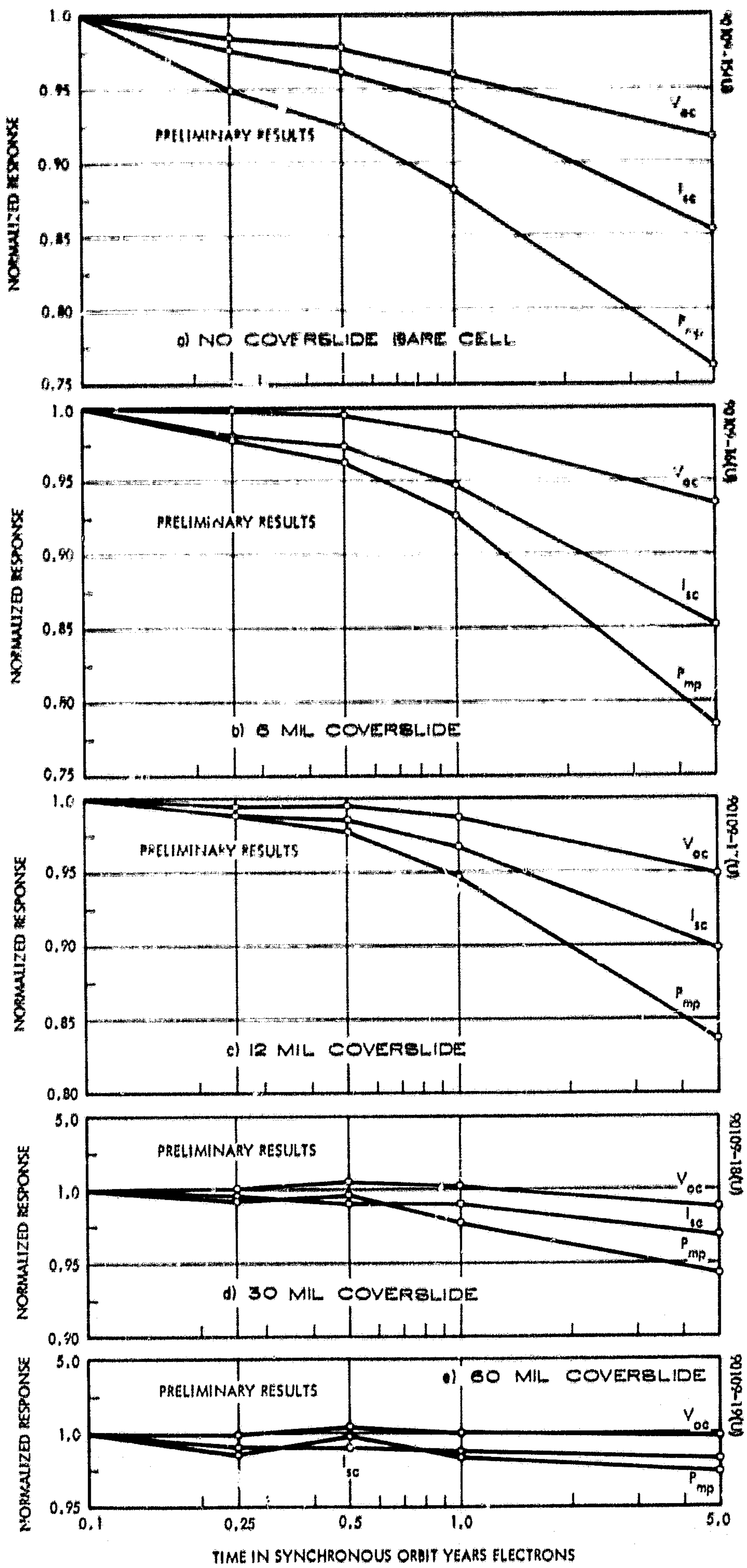


Figure 13. Normalized Response for V_{oc}, I_{sc}, and P_{mp} as Function of Time in Synchronous Orbit

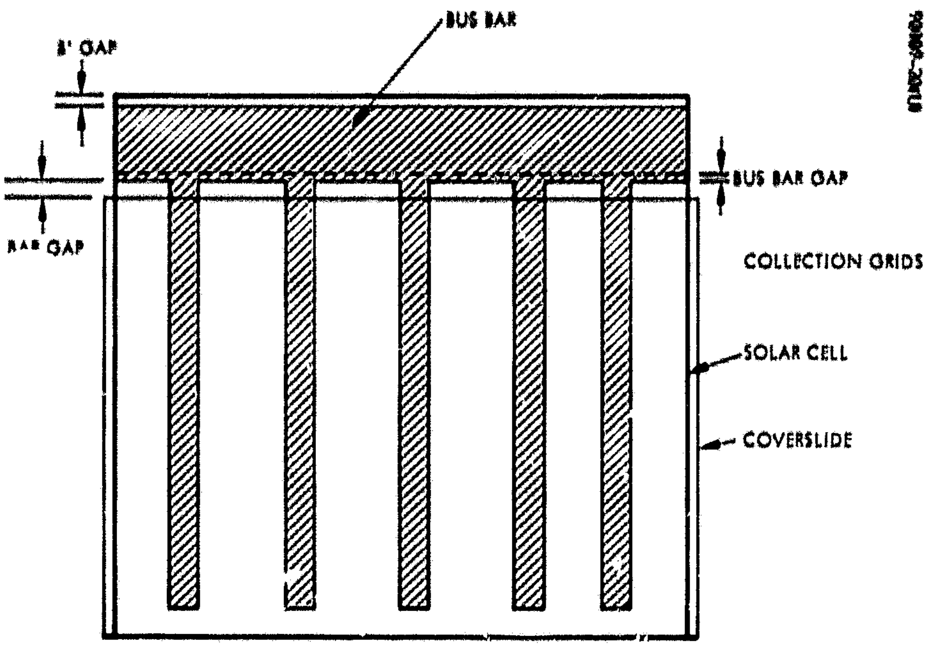
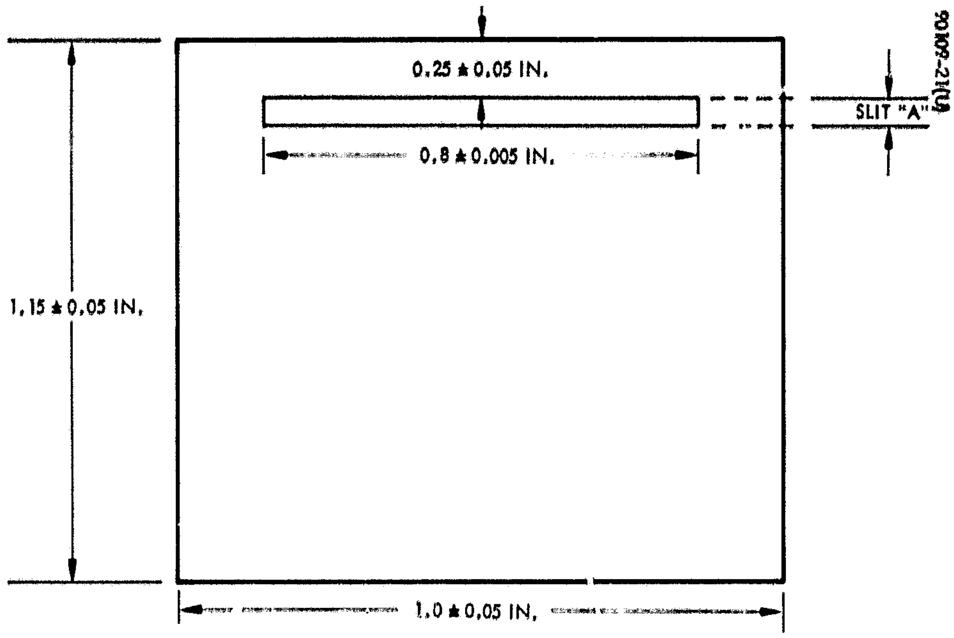


Figure 14. Terminology Chart



SLIT "A"	MATERIAL
0.001 ± 0.0001 0.002 ± 0.0001 0.003 ± 0.0001	0.003 THICK COPPER CORE NICKEL PLATE
0.005 ± 0.001 0.017 ± 0.001	0.010 THICK BERYLIUM COPPER

Figure 15. Metal Masks for Low Energy Proton Irradiations

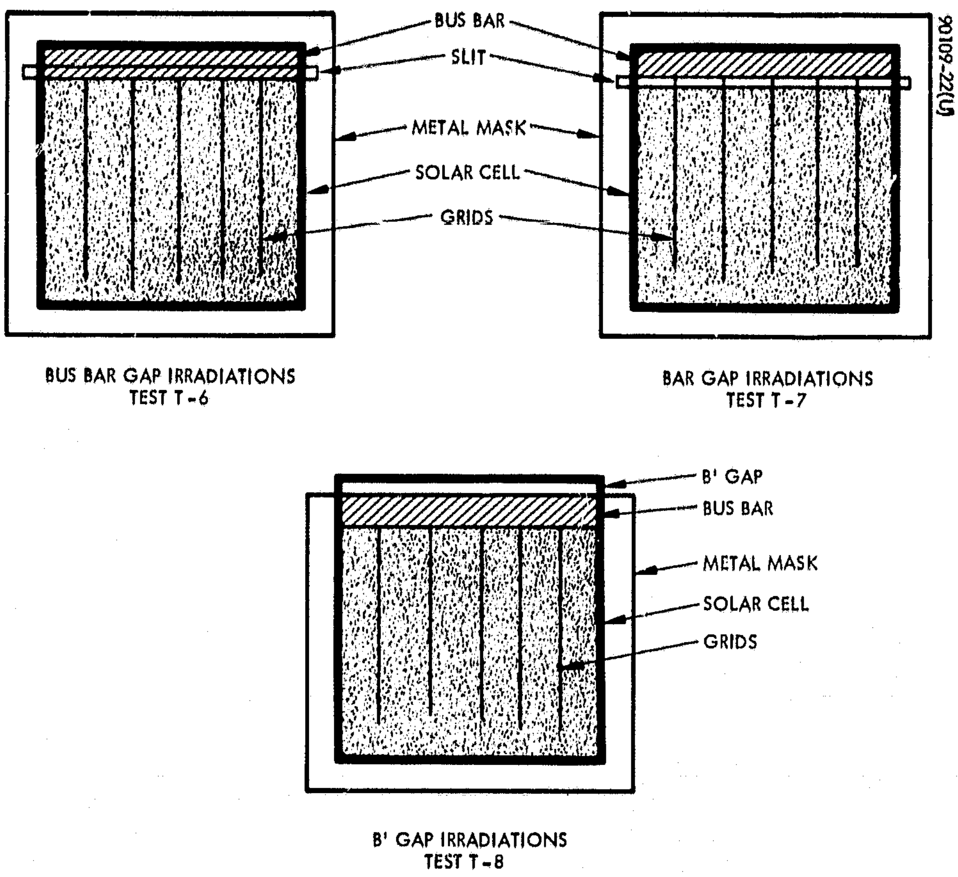


Figure 16. Positions of Metal Masks Over Solar Cells for Low Energy Proton Irradiations

Figure 15 were used in tests T-6 and T-7 to expose small portions of the solar cell areas during irradiations. Brass metal masks were used in test T-8 to cover all portions of the solar cell except the B' areas. Figure 16 shows how the metal masks were placed over the solar cells for each of the tests. The metal masks were fixed to the solar cells before the irradiation with double faced masking tape, thereby making it easy to remove the masks after irradiations for solar cell calibration.

A sample size of five was used for each parameter investigated, resulting in a total sample size of 55 for three tests.

Test Apparatus

The proton Van de Graff accelerator at NASA Ames was used as the source of the proton environment. The proton beam area at the target area was as large as 24 by 24 inches, thereby making it possible to irradiate all the test samples simultaneously. The energy range used for these tests was 0.2 to 1.5 mev. A detailed description of the NASA Ames facility will be included in the final report. The voltage-current characteristics were again measured at JPL on their X-25 solar simulator.

Test Procedure

The solar cells were irradiated with the Van de Graff accelerator at NASA Ames using a proton spectrum representative of synchronous orbit. The synchronous low energy proton environment is based on the published AP5 proton maps as defined by J. H. King*. The proton spectrum used to irradiate the test samples is displayed in Figure 17 and is superimposed on the unidirectional integral synchronous proton flux. The irradiation energies were 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, and 1.5 mev. The irradiations took place in vacuum. The test samples were irradiated at three radiation levels simulating 0.5, 1.0, and 7 years in synchronous orbit. The solar cell's voltage-current characteristics were measured at 140 mw/cm^2, AMO intensity after each radiation level.

Results

Only preliminary results are being presented in the progress report. Averages of the normalized current at 0.44 volt are presented with no statistical analysis. Figure 18a shows the preliminary results for test T-6. Normalized current at 0.44 volt as a function of equivalent time in synchronous orbit for three exposed areas of the bus bar are shown. One, 2, and 4.5 mil slit widths simulating approximately 98, 95, and 90 percent solder coverage of the bus bar are shown. The preliminary results indicate that, even with a slit as small as 1 mil, there is degradation to the solar wall.

*Joseph H. King, "Low Energy Protons," Models of the Trapped Radiation Environment, NASA SP-3024, Vol. IV, 1967.

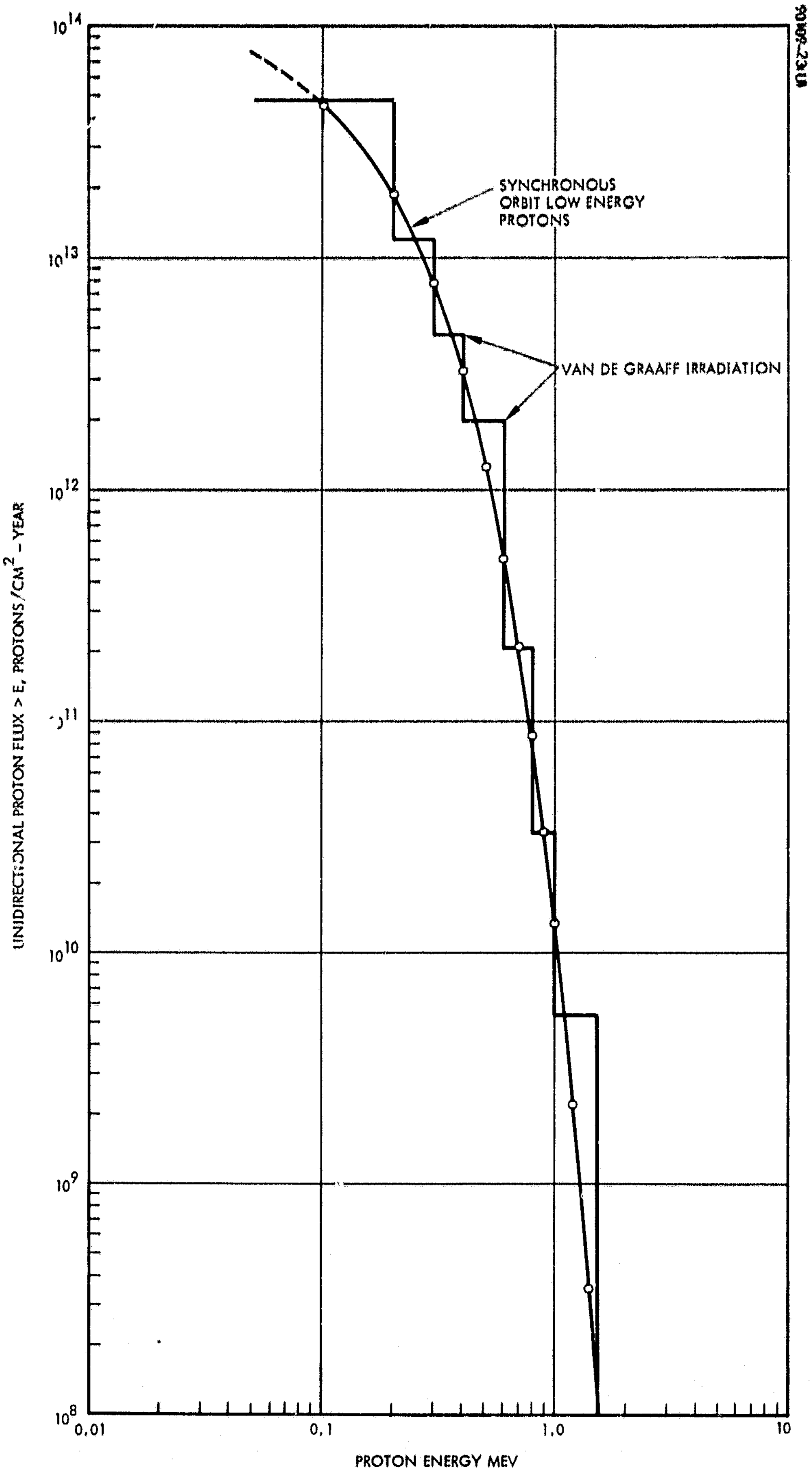


Figure 17. Spectral Content of Proton Irradiations

Figure 18b shows the preliminary results for test T-7. Normalized current at 0.44 volt as a function of equivalent time in synchronous orbit for five exposed areas of silicon solar cells are displayed. One, 2, 3, 5, and 17 mil slit widths simulating the amount of silicon exposed between the bus bar and coverslide were exposed to the environment. Again, a slit as small as 1 mil caused degradation to the solar cells. For the larger exposed areas, there appears to be a recovery in the solar cell performance after a 1 year level.

Figure 18c shows the preliminary results for test T-8. Normalized current at 0.44 volt as a function of equivalent time in synchronous orbit for three exposed B' areas are shown. Four, 7 and 10 mil extensions of the silicon above the bus bar were irradiated. These preliminary results indicate that the B' gap is sensitive to the low energy synchronous proton environment.

Conclusions

Until additional data analysis and statistical analysis are performed, no conclusions can be drawn. The preliminary data have been reported at this time to give trends in the data.

PROJECT MILESTONES

Completion of acceptance testing of the Solar Cell Radiation Flight Experiment, previously scheduled for 28 March 1969, has slipped due to technical problems with the rigid and flexible solar panels. As currently scheduled, acceptance testing of the signal processor units will be completed by 28 March 1969, qualification testing of the solar panels will be completed by 2 April 1969, and acceptance testing of the solar panels will be completed by 2 May 1969. As planned, the qualification model solar panels will be used with the flight model signal processor units for the initial system test, or EPC test, of the flight experiment.

Two flight model rigid solar panels, one fabricated by JPL, will be subjected to acceptance testing. The solar panels will contain an identical complement of solar cells and will be fabricated using the respective fabrication techniques employed by JPL and Hughes for fabrication of the qualification model rigid panel.

Several project milestones have been completed, including:

1) Qualification testing of the signal processor unit

2) Electron and proton radiation tests

3) System test plans

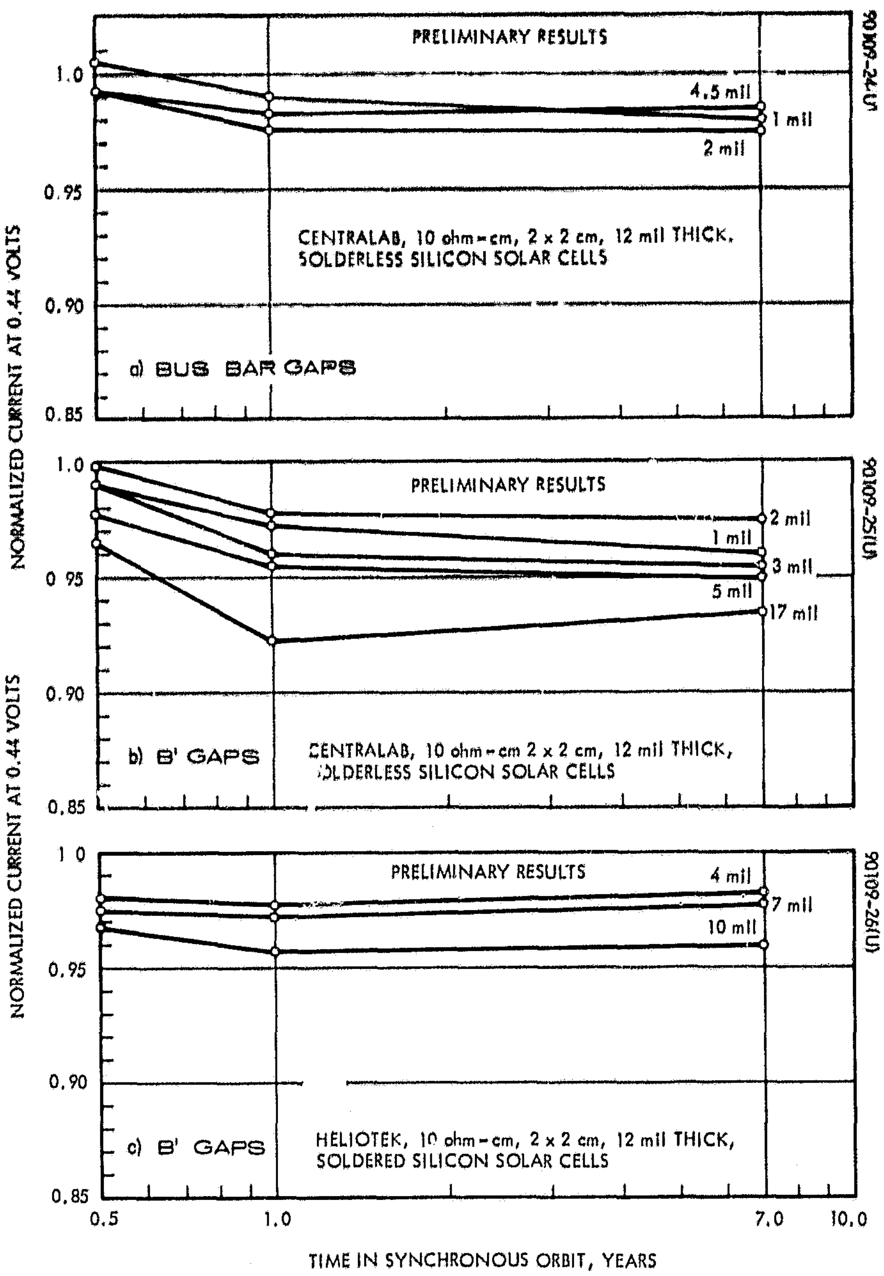


Figure 18. Normalized Current at 0.44 Volt as Function of Time in Synchronous Orbit

The remaining major milestones to be completed are:

1) Qualification testing of rigid and flexible solar panels

2) Acceptance testing of rigid and flexible solar panels

3) Acceptance testing of signal processor unit

4) Delivery of Solar Cell Radiation Flight Experiment

3. CONCLUSIONS

The Solar Cell Radiation Flight Experiment will be activated at planned intervals after launch of the ATS-E spacecraft and will provide accurate technical data for evaluation of the effects of radiation on solar cells in synchronous orbit. The experiment has been specifically designed to interface with the ATS-E spacecraft and telemetry systems.

Qualification testing of the signal processor unit has been completed, but the completion of qualification testing of the rigid and flexible solar panels has been delayed due to solar cell and coverslide cracking during thermal testing. Corrective action has been implemented by Hughes in all areas bearing on the problem, and JPL has implemented a backup program on the rigid panel to provide maximum confidence in the successful completion of panel acceptance testing.

The results of the supplemental ground test program must be evaluated as preliminary data pending completion of data reduction and data analysis.

4. RECOMMENDATIONS

Hughes Aircraft Company recommends that the Jet Propulsion Laboratory review and approve the data presented in this second quarterly progress report.

Hughes requests and solicits comments and recommendations from JPL, NASA, and industry personnel for improvements on the flight experiment and ground test program.

5. NEW TECHNOLOGY

This report does not contain items of new technology developed by Hughes Aircraft Company under this contract. However, many of the cells subjected to evaluation in this program were furnished on a no-cost basis to Hughes and the Government, and the fabrication processes used to manufacture the solar cells may be considered proprietary by the manufacturers.