General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

Report No. DOE/JPL 954995-78/3
Distribution Category UC-63
JPL Contract No. 954995

(NASA-CR-158537) DEVELOP SILICONE ENCAPSULATION SYSTEMS FOR TERRESTRIAL SILICON SOLAR ARRAYS Interim Report, 15 Feb. - 31 Dec. 1978 (Dow Corning Corp.) 78 p HC A05/MF A01 CSCL 10A G3/44

N79-24471

Unclas
25161

INTERIM REPORT

Period Covered: February 15, 1978 - December 31, 1978

DEVELOP SILICONE ENCAPSULATION SYSTEMS FOR TERRESTRIAL SILICON SOLAR ARRAYS

JPL CONTRACT 954995

for

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, California 91103

The JPL Low-cost Silicon Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory California Institute of Technolgy by agreement between NASA and DOE.

by

DOW CORNING CORPORATION
Midland, Michigan 48640

March, 1979

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TABLE OF CONTENTS

		Page
ABSTRACT		2
I.	SUMMARY	4
	- Technology Review	4
	- Generation of Concepts for Screening and Processing Silicone Encapsulation Systems	6
	A. Silicone Based Materials	6
	B. Encapsulation Systems and Structural Materials	7
	C. Selection of Tests and Measurements	8
	D. Stress Results of Encapsulation Concepts	12
	- Future Plans	13
II.	RESULTS AND DISCUSSION	
	A. Technology Review	14
	B. Generation of Concepts for Screening and Processing Silicone Encapsulation Systems	27
	C. Selection of Stress Tests and Measurements	30
III.	CANDIDATE SILICONE MATERIALS	39
IV.	DISPLAY MODULES FOR 11th PROJECT INTEGRATION MEETING	41
V.	PLANS FOR THE FIRST QUARTER OF 1979	45
Bibliography		
Tables I-VI		
Figures 1-22		

ABSTRACT

This study for Task 3 of the Low Cost Solar Array Project (LSA) funded by DOE is directed toward the development of a cost effective encapsulation system for photovoltaic modules using silicone based materials. It is a cooperative effort between Dow Corning Corporation, the major supplier of silicones and silicone intermediates, and Spectrolab, a leading photovoltaic equipment manufacturer.

The technical approach of the contract effort is divided into four sequential tasks:

1. Technology Review - A review of:
   a) The performance of clear silicone and modified silicone materials subjected to extended periods of outdoor weathering.
   b) The experience of the photovoltaic industry using silicone encapsulants.
   c) The industrial experience of protecting electronic devices with silicone materials.
   d) The results of weathering silicone based protective coatings.
2. Generation of Concepts for Screening and Processing Silicone Encapsulation Systems.
   a) Selection of the most appropriate current silicone and silicone based coatings for the intended application.
   b) Identification of viable encapsulation systems and potentially cost effective materials of fabrication.
   c) Selection of stress tests for the encapsulation concepts.

d) Ranking of the encapsulation concepts based on their performance in the screening tests.

3. Assessment of Encapsulation Concepts

a) Fabrication of mini-modules using state-of-the-art technologies and the best encapsulation concepts from the screening test.

b) Tabulation and ranking of the test results based on performance, cost and processability.

4. Evaluation of Encapsulation Concepts

Mini-modules designed to JPL specifications and utilizing the highest ranked concepts from 3. b) will be built, stressed and evaluated.

Based on this methodology, the following candidate silicone based materials have been identified:

As Thin Conformal Coatings -

DOW CORNING® Q1-2577

DOW CORNING® 840 Resin/Rohm and Haas B48N 25/75 Blend

DOW CORNING® 808 Resin

As Adhesive -

DOW CORNING® X1-2561

The candidate structural materials are:

Super Dorlux® substrate

Solatex® superstrate

I. SUMMARY

TECHNOLOGY REVIEW

Two broad classes of silicone materials have been subjected to outdoor weathering environments: silicone and silicone-acrylic resin coatings and elastomeric silicone materials.

The exposure to outdoor weathering varied from 20 years in southern Florida and Wisconsin to four years in Arizona including exposure sites in Texas and Michigan.

The silicone based materials all retained their useful properties after outdoor exposure. The principal change in silicone-based, clear resin coatings due to outdoor exposure was a loss in gloss and the appearance of surface cracks referred to as checking. The major changes in silicone elastomers after outdoor exposure were slightly lower tensile and elongation values with some dirt pick-up and mildew.

A review of the experience of the photovoltaic industry in using silicone materials as encapsulants disclosed the following:

1) Virtually all of the experience in commercial applications was with elastomeric silicone products such as SYLGARD® 184 and GE 615 or gel consistency products such as DOW CORNING® Q3-6527.
2) These silicone products provide adequate protection if: a) a hard cover such as DOW CORNING® R4-3117 or Q1-2577 is used with the elastomeric encapsulants or b) the Q3-6527 gel is covered with glass or placed in a plastic film bag.
3) The use of elastomeric silicone encapsulants without a hard surface cover leads to a reduction in power output due to dirt pick-up.
4) Elastomeric silicone encapsulants delaminate from metal or glass substrates unless primers are used and care is taken during the

fabrication of modules. The proper handling and use of these materials as well as the recommended primers can be found in the manufacturers' product information sheets.

5) Attempts to use high modulus silicone resins such as R4-3117, as thick coatings in direct contact with solar cells failed because of cell and encapsulant cracking caused by differences in thermal expansion.

The general view of the photovoltaic industry is that an improved, lower cost encapsulation system is required to achieve the 1986 DOE volume and price goals of 500 peak megawatts at $0.50 per peak watt. The encapsulation system must be amenable to automated large scale production.

Silicone resins and elastomers have been used successfully for the protection of electrical devices and electronic circuitry for over 30 years. They are well suited for this application because the polymers are free of ionic contaminants and consequently have good resistivity, high dielectric strength and a low dissipation factor.

Although silicones have high water vapor transmission rates, the amount of water they can absorb is low and they retain good physical, chemical and electrical properties when saturated with water vapor.

Good adhesion of the silicone material to the electrical device is necessary to provide corrosion protection in high humidity environments.

Silicone elastomers have been used as sealants in weathering environments for many years and make the construction of free standing glass walls possible. These sealants retain most of their elasticity and strength after 20 years outdoor exposure. Silicone resins are used in silicone-organic paint formulations, and the durability and gloss retention of this pigmented system can be correlated to the fraction of silicone resin used.

GENERATION OF CONCEPTS FOR SCREENING AND PROCESSING SILICONE ENCAPSULATION SYSTEMS.

A. Silicone Based Materials

Based upon the availability, physical properties and cost, the following silicone based materials were identified as possible candidates for silicone based encapsulation systems:

DOW CORNING® Q1-2577 Conformal Coating - A clear silicone resin with good dielectric properties which cures to a tough dirt resistant polymer. Proposed as a clear protective conformal coating and as a cover material containing ultraviolet (UV) absorbers.

DOW CORNING® 808 Resin - A clear silicone resin used as a conformal coating and as an UV screening cover material. This resin is a higher modulus resin than Q1-2577.

Blends of DOW CORNING® 840 Resin with acrylic resins such as B48N from Rohm & Haas - These combinations are proposed as clear conformal coatings and as UV screening cover materials. The purpose of using silicone-acrylic polymer blends is to reduce material cost without an unacceptable decrease in durability.

DOW CORNING® 3140 RTV - A clear, compliant elastomer proposed as an encapsulant. This concept would require an inexpensive dirt resistant cover.

SYLGARD® 184 - A clear silicone elastomer proposed as a conformal coating. This material provides a good reference point based on extensive experience by the photovoltaic industry in using this product.

DOW CORNING® X1-2561 Solventless Resin - A clear resin proposed for use as a conformal coating and a UV screening cover material.

DOW CORNING® 96-083 Adhesive - A clear adhesive proposed for use in bonding cells to glass, wood and metal substrates.

DOW CORNING® Z-6082, Z-6030, Z-6020, 1204 Primer - Organofunctional silanes proposed as primers to provide adhesion of the coatings to substrates.

B. Encapsulation Systems and Structural Materials

1. Materials of Construction

The materials of construction identified as candidates to provide mechanical support were:

Super Dorlux® - An outdoor weathering grade of hardboard from Masonite Corporation. Proposed for use as a substrate support material.

Solatex® - A clear, low iron containing glass from ASG Industries proposed as a superstrate support material.

Metals such as steel and aluminum were considered as substrate materials, however, no system could be envisioned which would be cost effective when the cost of the metal and cost of electrical isolation of the cell-string were combined.

2. Encapsulation Systems

The two encapsulation concepts proposed consisted of a) a transparent superstrate with solar cells adhesively bonded with a thin glue line, coated with a white pigmented conformal coating and b) a solid substrate such as Super Dorlux® painted white with cells bonded to the surface and overcoated with a thin clear conformal coating.

Spectrolab supplied the cell circuits used in this evaluation which were two inch diameter 2-cell circuit-strings using silver ink screened metallization with solder-plated copper ribbon interconnectors.

In support of providing UV protection for low cost pottants which degrade due to photo-oxidation, we are evaluating silicone cover materials for use as carriers of UV absorbers. These cover materials must be dirt resistant, compatible with UV screening agents, durable and effective as thin films.

C. Selection of Tests and Measurements

To assess the value of using the filtered carbon-arc Weather-Ometer® to stress proposed encapsulation systems, several silicone materials with known weathering characteristics were exposed to this UV source and periodically monitored. After 2,500-3,000 hours exposure, the four silicone based resin coatings show signs of degradation. DOW CORNING® 996 Resin shows the largest decrease in properties. Its check rating is four and the 60° gloss has dropped to 85% of the original value. The resin coating in best condition is DOW CORNING® 808. It has a check rating of seven and no loss of 60° gloss. There is no detectable change in the appearance of the six silicone elastomers exposed in the Weather-Ometer® for 2,500 hours. The flexural strengths and moduli of the exposure specimens will be measured after 3,000 hours exposure. The changes caused by this exposure will be compared with the changes which occurred during outdoor exposure.

A review of commercially available UV light sources was conducted and the light source which most closely resembles terrestrial solar insolation is a Xenon Lamp. This light source is relatively expensive and requires sophisticated control to maintain constant output.

Dow Corning uses an Atlas Sunshine Carbon-Arc Weather-Ometer® with Corex D filters as a UV light source for stressing samples. This light source has a time averaged output which closely approximates the solar spectrum at a reasonable cost. The radiation below 290 nanometers is very slight. The output of our Atlas Weather-Ometer® was measured by Roger Estey of JPL and verified the manufacturer's claims.

The importance and significance of stressing materials with UV radiation which are to be exposed in a weathering environment is due to the widespread recognition that the high energy short wavelengths of light, 290-400 nanometers, are the principal causes of light induced changes in materials. Wavelengths below 290 nanometers are undesired because these wavelengths are not present in natural terrestrial sunlight and could cause irrelevant degradation.

Other tests used to screen silicone based materials are:

1) Accelerated dirt pick up measured by the amount of carbon black deposited on a surface from a water suspension.
2) Dirt pick-up measured by the change in short circuit current (I_{sc}) of an encapsulated cell bonded to a glass substrate after outdoor exposure.
3) Initial tangential modulus measured on a free standing sheet of silicone material using an Instron Tensile Tester.
4) Glass transistion temperature (Tg) measured using a differential scanning calorimeter.

These material property measurements are intended to provide a data base to correlate material properties and aging characteristics with module life and performance.

For example, the accelerated dirt pick-up test correlates well with the surface tack of a polymer, but, to date has not shown good correlation to actual dirt pick-up due to outdoor exposure. After five months outdoor exposure, the greatest loss in I_{SC} occurred with the cell coated with DOW CORNING® X1-2561. This material delaminated from the glass substrate and lifted some of the metallization from the cells. This loss could not be related to dirt pick-up, but certainly removed DOW CORNING® X1-2561 from consideration as a candidate conformal coating material.

The greatest I_{SC} loss due to dirt pick-up, 16%, was with RTV-3140 the softest silicone material tested. However, none of the other materials showed a correlation between dirt pick-up and surface hardness. SYLGARD® 184 for example had a 4% decrease in I_{SC} while the blend of DOW CORNING® 840 Resin with Rohm and Haas B48N Acrylic Resin decreased 12%. The best retention of I_{SC} after five months exposure was with DOW CORNING® Q1-2577. The cell covered with this encapsulant lost less than 2% of its initial I_{SC}.

The natural cleaning effect of rain could be observed in the I_{SC} of these exposure samples. After periods of precipitation, measurable increases in I_{SC} were noted.

An important observation made during these outdoor soiling tests was the excellent performance of DOW CORNING® X1-2561 as a cell adhesive. Although this silicone resin failed as a conformal coating, it functioned as an excellent adhesive for the cell. The adhesion to the cell and to the glass substrate near the cell was excellent. The reason for this unexpected adhesion performance is not known but is probably due to reaction of the curing agent with the surface of the cells.

Because of this excellent adhesion, DOW CORNING® X1-2561 will be used as the adhesive in glass superstrate design modules. It forms a clear uniform glue line free of voids.

The outdoor exposure data should give the best indication of module performance.

The initial tangential modulus should correlate with a material's ability to relieve stress at low levels of strain. This measurement is difficult to make and the values obtained to date will be verified.

The glass transition temperature will provide a good indication of the amount of stress caused by changing temperature. There is usually a significant change in the coefficient of thermal expansion at the glass transition temperature and if this transition occurs at normal operating temperatures, it causes stress during temperature cycling. These measurements will be made on the candidates which survive the module stress tests.

Stresses which are of significant importance in assessing the life of PV modules in a weathering environment are the combination of temperature and humidity changes.

The test modules were subjected to the temperature cycling stresses at 95% relative humidity recommended by JPL (see Low Cost Solar Array Project Bulletin 5101-65). Modules which survive this humidity stress will be maintained at 70°C and 95% relative humidity and periodically inspected. This test is used by Spectrolab to measure module durability and resistance to corrosion in environments of high humidity.

The thermal shock test used by JPL (see Low Cost Solar Array Project Bulletin 5101-65) to measure the effects of varying coefficients of thermal expansion between module components will also be used as a screening criterion for encapsulation concepts.

D. Stress Results of Encapsulation Concepts

After fifty-four cycles of temperature from 25°C to 40.5°C at 90-95% relative humidity, the I_{SC} values of all the encapsulation systems using the Super Dorlux® substrate design were close to the original values and there were no visible signs of corrosion. In contrast, all of the cells on modules using the glass superstrate design except for those coated with DOW CORNING® Q1-2577 show decreases in I_{SC} after 54 cycles. All of these samples will be subjected to constant high humidity at 70°C after 75 cycles using the current varying temperature conditions.

The encapsulation systems will be thermally cycled from -40°C to +90°C in the near future.

Based on the outdoor soiling evaluation and the temperature-humidity test results, the best candidate encapsulation systems identified to date are:

Conformal Coating Candidates

DOW CORNING® Q1-2577

DOW CORNING® 840 Resin/Rohm & Haas B48N 25/75 Blend

DOW CORNING® 808 Resin

All of these candidates have functioned well to date on both glass superstrate and Super Dorlux® substrate module designs but must pass the thermal cycling test to qualify as viable candidates.

Adhesive

DOW CORNING® X1-2561

This is the only material to date which has provided a strong, clear, void free bond between the cells and glass. It has been used as the adhesive with all the conformal coatings and has consistently given a good clear glue line.

Superstrate and Substrate

Solatex® Glass

Super Dorlux®

Both of these structural materials have performed satisfactorily to date. The Super Dorlux® has shown some signs of warpage and edge swell. Areas of the panel edges which were coated with conformal coating did not visibly swell so one method to prevent Super Dorlux® from warping and swelling could be to coat the panel completely with a thin conformal coating.

FUTURE PLANS

The encapsulation systems which survive the thermal shock test will be used to fabricate modules built to JPL specifications. These modules will be fabricated with assistance from Spectrolab and provided to JPL for evaluation.

The encapsulation systems which do not survive the thermal shock test will be assessed for their ability to be modified. For example, the DOW CORNING® 840/Rohm & Haas B48N blend could be varied to incorporate a silicone material having lower glass transition temperature if necessary.

The concept of using silicone cover materials as a means of providing UV protection for pottants which photo-oxidize will be assessed by coating UV sensitive polymers with protective silicone coatings.

II. RESULTS AND DISCUSSION

A. Technology Review[1]

The protection of photovoltaic cells requires a material which is durable, will prevent corrosion of metallization and interconnectors, and remain transparent.

A review of the information available on the long term weathering of silicones concerned with these performance criteria produced relatively few well documented examples.

Although silicones have been used in outdoor applications and are known for their durability and performance in harsh environments, most of the applications in which they are used do not require the combination of corrosion protection and optical clarity.

Silicone elastomers are commonly used in outdoor weathering environments as sealants and roof coatings and have demonstrated excellent durability when used in these applications. Silicone resins provide increased life and durability to outdoor coatings and paints. These applications normally use silicone resins blended or coreacted with organic coating resins in pigmented formulations. The number of examples of clear coatings is quite limited.

For the purposes of this review the silicone materials were classified by their relative phenyl to alkyl contents. The silicone polymers are prepared from silane precursors which are substituted with phenyl and alkyl radicals. The alkyl radical is usually methyl. The designations of phenyl to alkyl content were arbitrarily assigned as: high, medium, low, and negligible.

The reason for using this classification system was the knowledge that the phenyl radical absorbs some radiation between 290 and 400 nanometers and this could be a mechanism for degradation in the weathering environment. A correlation between the phenyl content and the rate of degradation of silicone materials was anticipated.

Performance of Clear Silicones in Weathering Environments

The properties measured on the silicone resin materials weathered outdoors were: gloss, checking, dirt retention and general appearance. These resins were weathered as thin (2-4 mil) films on metal substrates and in one case, on a woven glass mat.

The properties measured on the silicone elastomers were: hardness, tensile, elongation, gloss, dirt pick-up and general appearance. The outdoor exposure samples of silicone elastomers were in the form of strips of sealant and as 1/8" thick strips stretched to 20% greater than their original length and unstressed strips of elastomer.

The gloss measurement is commonly used by the coatings industry and it measures the reflection of incident light off of a sample at a 60° angle.

Coatings commonly degrade during outdoor exposure through the formation of surface cracks. This mode of degradation is referred to as checking. A rating system has been developed for measuring the extent of these cracks called check rating. Below is a chart of this rating system:

Check Rating		Condition
10	-	No visible change
8-9	-	Limited microchecking visible with 3 power microscope
7	-	Entire surface covered with microchecks
4-6	-	0-50% visible checks
1-3	-	50-100% visible checks
0	-	Large cracks over entire surface

A high phenyl/alkyl ratio resin, DOW CORNING® Z-6018 Intermediate in an organic alkyd blend, was weathered 1-3/4 years in Midland and showed a 35% loss of gloss but had a 9 out of 10 overall performance rating when all coating performance criteria such as gloss, chalking, checking, adhesion and appearance were considered.

A high phenyl/methyl ratio resin, DOW CORNING® 901 Resin was used to coat open weave glass cloth. Samples of this coated cloth were exposed in Arizona at Desert Sunshine Exposure Tests Incorporated using the EMMAQUA procedure of concentrated sunlight and water spray. After exposure to 3 million langleys using the EMMAQUA procedure, the sample retained 94% of its original transmission. After 7 years at 45° south at the same location, another sample retained 99% of its original transmission. Transmission was measured from 350-3,400 n.m. normalized to the solar spectrum[2].

A high phenyl/methyl ratio resin, DOW CORNING® 840 Resin, has been blended with B66 acrylic from Rohm and Haas and subjected to weathering. After seven years in Florida it rated 9 in corrosion protection (out of possible 10) and had a 10 checking rate[3]. After 200 hours in the WOM it showed some loss of gloss and after 1,000 hours in the WOM the gloss had dropped from 88 to 51% and checking was rated at six[4].

Weathering data for medium phenyl/methyl category silicone products consisted of: DOW CORNING® 996 Varnish weathered 10 years in Midland with no loss of gloss, no color change and a check rating of six[5]. A DOW CORNING® Z-6188 Silicone Intermediate-Polyester copolymer was weathered 500 hours in the WOM with only some loss of gloss[4]. After 10 years in Midland, DOW CORNING® 802 Resin with a reactive crosslinker showed no loss of gloss, no color change and a check rating of six[5]. In contrast, after five years in Midland, DOW CORNING® 802 Resin with an amine catalyst gave an overall rating

of seven out of ten[5]. This indicates that the type and amount of catalyst is critical to final performance and incorrect catalysis can have deleterious effects on weatherability.

A blend of DOW CORNING® 808 and DOW CORNING® 840 Resin in a 60/40 ratio having a medium to low phenyl/methyl ratio was weathered 10 years in Midland with no loss of gloss with a check rating of six[5].

A low phenyl to methyl ratio resin, DOW CORNING® 808 Resin was weathered six years in Florida 40° south with a 36% loss of gloss, no checking, and no dirt retention[2]. A blend of DOW CORNING® 808 Resin and an unidentified acrylic was weathered for thirteen years in Texas with slight dirt retention, no loss of gloss and no checking[2]. DOW CORNING® 808 Resin was also weathered in an Atlas Filtered Twin Arc Weather-Ometer® (WOM) with Corex D filters for 2,000 hours with a very slight loss of gloss, and fine visible checks[4]. DOW CORNING® 808 Resin was also weathered on metallized Mylar® for 3,600 hours in the WOM and retained 75-80% of its reflectance and showed only slight checking and water spotting.

Another example of a low phenyl/methyl resin, DOW CORNING® X1-2515 Resin, was weathered for 3 million langleys on open weave glass cloth and retained 81% of its original transmission.

There are four examples of silicones with high methyl content and negligible phenyl content that were weathered outdoors from five to twenty years. One of the first lots of clear sealant manufactured at Dow Corning was sent to Racine, Wisconsin twenty years ago. Recently, samples of this sealant which was used on the exterior of a building in Racine were returned to Midland on request. After twenty years there was dirt on the surface (it had never been washed) and slight lowering in durometer hardness reading[6]. The same, clear silicone sealant was weathered 20 years in Midland with no

loss of durometer hardness[6]. An acetoxy cure, clear silicone was weathered five years in New Mexico with a slight loss of hardness and no loss of shear strength[7]. Some DOW CORNING® 780 Building Sealant was exposed for five years in Florida and showed a slight haziness and loss of gloss[2]. A fifth high methyl content silicone, DOW CORNING® 781 Sealant was exposed for 6,000 hours in the WOM and had a slight increase in hardness, increase in tensile strength and decrease in elongation[6,8].

It was determined that coatings weathered for only one to five years, as some reported here, were terminated for a variety of reasons. One was that the resins had been evaluated for coatings applications that required no change in appearance of any kind. The project was terminated if any change was detected. Several weathering studies were terminated for no documented reason. It is important to keep in mind that most of these examples were taken from coatings projects where micro-checking and loss of gloss indicate failure. This may not be the case for array encapsulation, although it does represent a material change after exposure to stressing. Whether it will be detrimental to a photovoltaic cell, particularly in the case of surface phenomena, remains to be evaluated.

All of the silicone based materials exposed to weathering environments showed good resistance to degradation. The silicone resin coatings did show varying degrees of checking and loss of gloss due to surface degradation. The variation in phenyl/methyl ratio did not correlate with exposure in weathering environments, see Table I. This is probably due to the relatively small number of samples and wide variation in weather conditions at the various exposure sites. It was observed that several thousand hours exposure in the Atlas Weather-Ometer® caused more checking and loss of gloss to clear resin coatings than six to seven years exposure in southern Florida.

This indicates that we should be able to observe changes in silicone based resin coatings within a few thousand hours and possibly correlate these changes with degradation due to outdoor exposure.

In contrast, the silicone elastomers which have negligible phenyl content are virtually unchanged after 20 years exposure in Michigan and Wisconsin and after 6,000 hours exposure in an Atlas Weather-Ometer®.

Photovoltaic Industry Experience with Silicone Encapsulation Materials

The photovoltaic industry widely uses silicone elastomers as encapsulants for the protection of cells. The silicone material most widely used in photovoltaic applications is SYLGARD® 184 Resin. Silicone elastomers were selected for this use because of: they are optically clear, they remain flexible in weathering environments, they are compatible with cell circuitry and they provide protection to these electronic devices in humid environments.

However, as a part of the 1986 LSA cost goal of $.50/watt photovoltaic power, the cost of materials used for module encapsulation must be decreased from the current figure of approximately $.79/watt to $.05/watt. This decrease cannot be achieved using current technologies because of the price of the encapsulant, the amount of it used in each module and the current methods used to fabricate photovoltaic modules.

Although the photovoltaic industry has been using SYLGARD® 184 as an encapsulant for many years, some manufacturers have experienced problems using this type of elastomeric silicone encapsulant. The two principal reasons for the failures and dissatisfaction which some photovoltaic array manufacturers have experienced with silicone elastomer encapsulants have been due to:

1) Delamination of the encapsulant from the substrate.
2) Dirt pick-up and retention by soft elastomeric encapsulants with exposed surfaces.

The most common mode of failure of modules encapsulated with SYLGARD® 184 which occurred during the early stages of terrestrial photovoltaic commercialization was delamination of the encapsulant from the substrate. These results were obtained during JPL's Block I procurement of state-of-the-art modules and were widely publicized[9].

Through the use of adhesion promotors and by exercizing more care during the fabrication of modules, this mode of degradation was significantly reduced. This improved adhesion led to a significant reduction in the number of modules which failed because of delamination in the Block II procurement made under JPL's LSA Program.

Another factor which must be considered when silicone elastomers are used as encapsulants without a hard transparent cover is the relatively soft surface which is difficult to clean. The impact of this soil retention on module performance has not been completely resolved; however, a decrease in power output associated with soiling of the encapsulant is frequently observed. The severity of this soil retention is site dependent, i.e., the decrease in power output from modules exposed in urban areas such as New York City is greater than the power loss of modules exposed in rural areas.

To date, no cleaning technique has been devised which will recover all of the original power output of the module. In spite of the number of delaminations noted and the decreases in power output due to soiling which have occurred, it is noteworthy that to date of 3,400 modules deployed at various sites for periods of up to 16 months, only 22 have failed. This is an outstanding performance record[10].

One array manufacturer has improved the cleanability and lowered the dirt retention characteristics of a silicone encapsulated module by overcoating the elastomeric silicone encapsulant with a thin coating of a harder silicone resin[11].

Another array manufacturer is using a soft compliant silicone gel, DOW CORNING® Q3-6527 as an encapsulant under a protective glass cover[12]. Neither of these encapsulation systems have been in use long enough to develop extensive field performance data.

One way to reduce the dirt pick-up is to use a high modulus silicone resin as the encapsulant itself. Modules fabricated by Spectrolab using DOW CORNING® R4-3117 Conformal Coating, a higher modulus silicone resin, had much improved resistance to dirt pick-up; however, the higher modulus silicone resin as an encapsulant cracked during thermal cycling and during outdoor exposure studies[13]. A detailed analysis by JPL on the resin itself provided a rational explanation for this failure mode[14]. The strain during thermal expansion due to a relatively high coefficient of thermal expansion caused enough tension stress to fracture the resin which breaks when slightly elongated.

A rather detailed analysis of silicone elastomer encapsulated modules was made by Spectrolab[15]. They felt that silicone materials were not practical encapsulation materials because of cost, processibility, variability, high permeabilities to moisture and poor adhesion. However, most of the current flat plate array manufacturers are using silicone materials for the protection of photovoltaic modules because:

1) Silicones now provide better protection of photovoltaic cells than any other commercially available material.
2) The array manufacturers have become more familiar with silicones and have learned how to use them.

This contract effort is designed to lower the cost of encapsulation systems currently used in the manufacture of flat plate arrays by developing a cost effective silicone encapsulation system which will correct the deficiencies of previous systems. The concept is to provide a thin conformal coating with intermediate modulus which will be soil resistant and still maintain good adhesion and stress relief during thermal humidity cycling.

Silicones Used in the Protection of Electronic Devices

Electrical components and electronic devices require protection from liquid water. Silicones have been used for many years to provide that protection. Silicone polymers have high water vapor transmission rates therefore an explanation is needed to resolve the dichotomy. Malcolm White of Bell Labs[16, 17] has proposed chemical bonding of silicones to a substrate through silanol interaction and demonstrated that silicones do not allow liquid water to accumulate at the interface of a silicone encapsulated integrated circuit. Sailer and Kennedy[18] have reported similar findings:

> Initially, the choice of silicone-resin conformal coating and a silicone-rubber back-seal for an application where environmental protection is required may not seem prudent. It is well known that the permeability of these materials to most gases including water vapor is quite high; it is higher than many other plastics. The advantage of these materials is not in low transmission rate of moisture, but rather in their low moisture absorption and good chemical and electrical stability while "saturated".
>
> Surfaces coated with silicones have a hydrophobic character which prevents moisture from condensing and creating leakage paths. The low moisture absorption rate of silicones maintains the dielectric strength on coated surfaces and prevents electrical degradation. In short, the use of permeable silicone materials for encapsulation provides a package which "breathes" moisture in and out while attenuating the moisture to non-critical levels.

Sierawski[19], and Sierawski and Currin[20] have shown that the silicone elastomers with the appropriate chemical coupling primer can give corrosion protection in high humidity environments for automotive and solar applications. They have also reported that the silicone gels give corrosive protection and stress relief for the protection of delicate electronic components

Kookootsedes and Lockhart[21] have shown that highly filled silicone encapsulants can also give excellent protection to electronic devices even at elevated temperatures. In this case, the coefficient of thermal expansion of the silicone, because of the filler, has been lowered to 20-40 ppm versus the 100-200 ppm for unfilled silicone resin. Performance after stressing of silicone encapsulated electronic devices and electrical equipment has also been demonstrated by Jaffe[22], and VanWert and Ruth[23]. In both cases, retention of performance and physical properties was shown after thermal cycling and high humidity/temperature stressing. Jaffe also reported good cure under the leads of an electronic device using a silicone RTV.

The requirements for the protection of photovoltaic cells are similar to those needed for the protection of these electronic devices. In addition to providing corrosion protection and stress relief for the interconnects, the photovoltaic application has the additional requirements of optical clarity and durability in a weathering environment.

The processing of silicone polymers removes ionic, corrosive contaminants and silicone materials are known for their inertness and cleanness. The catalyst chosen for crosslinking and curing these silicone materials for encapsulating photovoltaic cells must also be non-corrosive.

Outdoor Weathering of Pigmented Silicones and Silicone Based Coatings

Samples of high consistency filled silicone elastomers have been exposed at 45° south in Florida for twenty years. High consistency is a term used in the rubber industry to describe an elastomer which is prepared from high molecular weight gum polymers and heat-vulcanized. Two of the samples, SILASTIC® LS-53 Fluorosilicone and SILASTIC® 132 showed no evidence of cracking or checking. SILASTIC® 675 showed some cracking at 19 years. However,

SILASTIC® 675 had better retention of tensile strength and elongation than the other two.[24] Selfridge in 1947 molded some of the earliest formulations of Silastic rubber. After 12 months exposure in Midland, he reported no trace of deterioration by the formation of cracks on the samples[25]. He reports that under similar exposure conditions, cracking of "organic base rubbers" was very pronounced.

Silicone resins have been used for many years by the coatings industry to up-grade the performance of durable exterior coatings. Brown reports that substituent groups on silicones can yield different properties in a silicone resin.[26] The organic substituents present in silicone polymers result from the organic groups contained in the silane monomers used to make the polymers. Phenyl and methyl are two common organic moieties on the silane monomers used to make silicone polymers.

Properties yielded by high methyl content:

Flexibility
Water Repellency
Low Weight Loss
Low Temperature Flexibility
Chemical Resistance
Fast Cure Rate
Arc Resistance
Gloss Retention
Heat Shock Resistance
U.V. & I.R. Stability

Properties yielded by high phenyl content:

Heat Stability
Oxidation Resistance
Thermoplasticity
Retention of Flexibility on Heat Aging
Toughness
Air-Drying

The improved durability a silicone resin can impart to a coating was shown by comparison of 30% and 100% silicone coatings with organic alkyds. The 100% silicone lost 4% of its initial 94% gloss after 36 months in Florida. An air drying silicone alkyd lost 30% of its initial 85% gloss.

The air-drying organic alkyd lost 90% of its initial 85% gloss[26]. After testing silicone-polyesters it was found that for identical paint formulations except for silicone content, the formulation with more silicone retained its properties of gloss, non-chalking and non-checking better than that with less or no silicone. Thomas showed similar findings in tests with long oil soya alkyd coatings weathered in Midland, Michigan, and baked alkyds weathered in Florida.[27] In both cases, more silicone gave better performance as rated by retention of gloss.

Finzel has found not only do silicone-organic durable coatings weather better in the Dew Cycle Weather-Ometer® and Florida, but also that each resin system gives its own correlation of WOM effects of stressing to Florida effects of stressing[28].

Adhesion

One further area investigated in this technology review was the use of chemically coupling primers and chemicals to promote adhesion between dissimilar surfaces. It has been known for at least fifteen years now that organofunctional silanes can chemically react with organic resins, by proper choice of organo-reactive group of the silane, and metal or oxide surfaces through silanols formed on the silane after hydrolysis. Plueddemann has demonstrated the use of organo-silanes to adhere resin to glass in spite of the presence of water and differences in coefficient of thermal expansion (CTE).[29,30]. The improvement in physical properties such as tensile, flexural and compressive strengths of a silane coupled plastic composite after exposure to moisture compared to a control can be as much as double.

Two patents were also found describing the use of organoborates and alkyl or alkoxy titanates for bonding silicones to substrates[31,32]. These substrates include metal and siliceous materials such as glass. Liles reported

successful bonding of a silicone molding compound to metal using an organosilicone hydride[33].

Since good adhesion of the silicone to any substrate will be imperative, state-of-the-art primer technology will be utilized in this study.

B. Generation of Concepts for Screening and Processing Silicone Encapsulation Systems

Silicone Based Materials

Based upon the availability, physical properties and cost, the following silicone based materials were identified as possible candidates for silicone based encapsulation systems:

DOW CORNING® Q1-2577 Conformal Coating - A clear silicone resin with good dielectric properties which cures to a tough dirt resistant polymer. Proposed as a clear protective conformal coating and as a cover material containing ultraviolet (UV) absorbers.

DOW CORNING® 808 Resin - A clear silicone resin used as a conformal coating and as a UV screening cover material. This resin is a higher modulus resin than Q1-2577.

Blends of DOW CORNING® 840 Resin with acrylic resins such as B48N from Rohm & Haas - These combinations are proposed as clear conformal coatings and as UV screening cover materials. The purpose of using silicone-acrylic polymer blends is to reduce material cost without an unacceptable decrease in durability.

DOW CORNING® 3140 RTV - A clear, compliant elastomer proposed as an encapsulant. This concept would require an inexpensive dirt resistant cover.

SYLGARD® 184 - A clear silicone elastomer proposed as a conformal coating. This material provides a good reference point based on extensive experience by the photovoltaic industry in using this product.

DOW CORNING® X1-2561 Solventless Resin - A clear resin proposed for use as a conformal coating and an UV screening cover material.

DOW CORNING® 96-083 Adhesive - A clear adhesive proposed for use in bonding cells to glass, wood and metal substrates.

DOW CORNING® Z-6082, Z-6030, Z-6020, 1204 Primer - Organofunctional silanes proposed as primers to provide adhesion of the coatings to substrates.

Encapsulation Systems and Structural Materials

1. Materials of Construction

The materials of construction identified as candidates to provide mechanical support were:

Super Dorlux® - An outdoor weathering grade of hardboard from Masonite Corporation. Proposed for use as a substrate support material.

Solatex® - A clear, low iron containing glass from ASG Industries proposed as a superstrate support material.

Metals such as steel and aluminum were considered as substrate materials, however, no system could be envisioned which would be cost effective when the cost of the metal and cost of electrical isolation of the cell-string were combined.

2. Encapsulation Systems

The two encapsulation concepts proposed consisted of: a) a transparent superstrate with PV cells adhesively bonded with a thin glue line, coated with a white pigmented conformal coating and b) a solid substrate such as Super Dorlux® painted white with cells bonded to the surface and overcoated with a thin conformal coating.

Spectrolab supplied the cell circuits used in this evaluation which were two inch diameter 2-cell circuit-strings using silver ink screened metallization with solder-plated copper ribbon interconnectors.

In support of providing UV protection for low cost pottants which degrade due to photo-oxidation, we are evaluating silicone cover materials for use as carriers of UV absorbers. These cover materials must be dirt resistant, compatible with UV screening agents, durable and effective as thin films.

C. Selection of Stress Tests and Measurements

An Atlas Filtered Carbon-Arc Weather-Ometer®[34] was used to stress silicone materials with known weathering history. This instrument closely approximates the solar spectrum at a reasonable cost. We reviewed the commercially available light sources for stressing materials at wavelengths between 290-400 nanometers and found that a Xenon light source simulated the distribution of solar insolation better than any other source. However, the intensity of a Xenon Lamp rapidly decays with time. This loss can be compensated by increasing the power to the lamp. Equipment is available from Atlas which monitors the light intensity from the Xenon Lamp and adjusts the power to compensate for loss. This equipment is relatively expensive and the life of a Xenon Lamp is short so the filtered carbon-arc light source was chosen as the most cost effective alternative for long term durability testing. In addition, Dow Corning has used the Weather-Ometer® source for stressing silicone materials and found it a suitable method of accelerating the effects of sunlight on candidate materials. Dr. Roger Estey (JPL) measured the output of the Atlas Weather-Ometer® we are using to stress silicone materials and found that the time averaged output of this source closely approximates the solar spectrum[35]. The intensity was in good agreement with that claimed by the manufacturer.

Weather-Ometer® Stressing Vs. Weathering History of Silicone and Modified Silicone Materials.

Based on the information from the technical review, ten materials with well defined periods of exposure and changes in properties were identified. Samples of these materials or products which closely duplicate them were exposed in an Atlas Sunshine Carbon Arc Weather-Ometer®. The resins were in the form of 2-4 mil coatings on metal panels and in one case as

a coating on open weave fiberglass. The elastomers were exposed as 1/8" thick strips stretched to 20% greater than their unstressed length and in an unstressed condition.

The same properties that were monitored during outdoor weathering are being tracked during artificial weathering. The mode of degradation as a function of time will be monitored and correlation with natural weathering will be made where possible.

As seen in Table I, some of the silicone materials have started to show signs of degradation after 3,000 hours of exposure in the Weather-Ometer®. These materials are DOW CORNING® 808 Resin, DOW CORNING® 901 Resin and DOW CORNING® 996 Resin.

DOW CORNING® 808 Resin has started to check, and its rating was 7 after 3,000 hours exposure. It had a check rating of 10 after 2,500 hours. Check rating values range from 0 to 10. A check rating of ten means no detectable change and 0 means large cracks over the entire surface. A check rating of seven is micro-checking over the entire surface which is not visible to the eye but which is clearly defined using a 3 power microscope. Gloss and dirt retention have not started to deteriorate at 3,000 hours. DOW CORNING® 901 Resin has also started to check but transmission is still 99.5% of original. DOW CORNING® 996 Resin has a check raing of 4 and 15% loss of 60° gloss. These are lower than the appearance ratings obtained at the end of 10 year's exposure in Midland of a similar sample. This is the first silicone material to have a lowering in properties to a level below those obtained after actual outdoor weathering. From this one can conclude that between 2,500 and 3,000 hours in the WOM should provide stress similar to 10 year's outdoor weathering in Midland, Michigan.

The durometer readings on all of the elastomer samples are down slightly, but they are still within the 10% experimental error limit for the durometer test method used. Therefore, they are reported as no change.

Soiling Measurements

1. Accelerated Dirt Pick-up

An accelerated dirt pick-up test was used to evaluate the tendency of cured silicone based materials to become soiled. This test consists of tumbling panels coated with cured resin in a suspension of 2 gms of Raven #11 carbon black (Columbia Carbon Company) in 1,000 gms of water. After tumbling for 45 minutes, the panel is removed, rinsed under running tap water and lightly wiped with a cheesecloth. The dried panel is then visually inspected and rated according to the amount of carbon black adhering to the surface. The ratings are subjective and consequently the panels are ranked by comparing them with another. The ratings can be described as: 10 - no change, 9-7 - slightly gray appearance, 6-4 - moderately black, 3-1 - dark black, 0 - opaque.

This test simulates the dirt pick-up of carbonaceous type material; however, caution must be used in extrapolating this form of soiling to actual outdoor dirt pick-up. Also, no attempt is made to thoroughly clean the surface and so this test does not indicate the cleanability of various surfaces.

This test is also used to determine the extent of cure of coatings. Incompletely cured coating surfaces will pick up more carbon black than well cured coatings. Therefore, it is important that the samples used for soiling measurements be thoroughly cured.

The soiling rating of the candidate silicone based conformal coatings ranged from 1 for RTV 3140, a soft silicone elastomer, to 10 for a blend of DOW CORNING® 840 with B66 acrylic resin. These results are shown in Table II. The first measurement made on DOW CORNING® Q1-2577 gave a soiling rating of 2 which was unexpectedly low. This material was re-evaluated using care to insure that it was well cured and the soiling rating was 5.

These same candidate materials have been placed outdoors and the soiling due to outdoor exposure will be compared with the accelerated dirt pick-up test results.

2. Outdoor Dirt Pick-up

The outdoor soiling of candidate encapsulation materials was evaluated by adhesively bonding one cell circuits to the top of 3" x 9" x 1/8" soda lime float glass substrate panels with candidate silicone materials and then overcoating with these same materials. The coatings ranged from five to ten mils in thickness. These samples were exposed on the roof of the Dow Corning Development Laboratory at its industrial site in Midland, Michigan at an angle of 45° south. This site is within 2 miles of 2 major industrial power plants.

The short circuit current (I_{sc}) and open circuit voltage (V_{oc}) of these test samples in the unwashed condition has been monitored for 120 days. The light source for measuring the cells, a 400 watt ELH lamp, is adjusted to 1,000 w/m^2 by adjusting its intensity using a standard reference solar cell from NASA Lewis Research Center. The light source is adjusted to give a I_{sc} of 140 milliamps and an V_{oc} of 478 millivolts at 28°C for the reference cell. The total daily precipitation for this location has been recorded for the past ninety days. Both are graphed in Figures 1-6. To the right of each graph is a

short description of the condition of the sample test module. The I_{SC} and V_{OC} are tabulated with the number of days of outdoor exposure in Table III.

Measuring the I_{SC} of an encapsulated cell after outdoor exposure is the most relevent way to measure the effect of dirt pick up. The wavelengths of solar radiation which power a silicon photovoltaic cell are predominantly outside the visual range so although visual inspection may indicate changes in cell performance due to dirt pick up, this observation may not correlate with changes in module performance.

To date there has been no dramatic loss in I_{SC} of any encapsulated cell exposed outdoors except for the cell coated with DOW CORNING® X1-2561.Solventless Coating. The test module using X1-2561 has delaminated to the point where only one-half the area directly over the cell still has adhesion to the top coat of resin. The I_{SC} of this sample is 61% of the initial value and this loss in current is due to mechanical failure and not to dirt pick up.

All of the other cells have shown extraneous excursions to low I_{SC} values but over the last three months the I_{SC} values of these samples have ranged from a low of 85% of the original value for RTV-3140 to 94% of the original value for DOW CORNING® Q1-2577.

It has been observed that, in general, increases in I_{SC} follow periods of precipitation. This is interpreted as a natural washing effect of the silicone encapsulants by preciptation.

Replicate samples tested in the unwashed condition have been prepared and placed outdoors. Periodically, these additional modules are measured for I_{SC} after washing. The procedure used to wash the panels is to gently wipe the panels with a cheesecloth in a dilute Ivory Snow Soap solution and follow with a water rinse. Graphs of the I_{SC} and V_{OC}

of these washed samples after outdoor exposure are shown in Figure 7-11. The exposure time on these samples has been too short to draw any conclusions.

The design and construction elements of the one-cell circuits used to monitor soiling are shown in Figure 12.

Temperature/Humidity Cycling

Test mini-modules were prepared for temperature/humidity cycling by adhering the photo-active side of the two-cell circuits to 3" x 9" x 1/8" panels of A.S.G. Industries' Solatex® Glass with the candidate silicone encapsulant. The back of the module was then coated with the same resin pigmented with TiO_2. This type of construction is referred to as a superstrate module because the structural element is the clear glass cover over the cells.

Substrate test modules were prepared by painting 3" x 9" x 1/8" panels of Masonite's Super Dorlux® hardboard with TiO_2 pigmented versions of the candidate encapsulants, laying the cells front side up on the coated substrate and then coating the cells and substrate with a clear version of the same resin. The stress conditions used are those specified by the Jet Propulsion Laboratory with all testing done at 90-95% relative humidity. The following temperature cycle was used: 1) room temperature to 40.5°C over a 2 hour period; 2) 16 hours at 40.5°C; 3) 40.5°C to room temperature over a 2 hour period; and then 4 hours at room temperature. The I_{sc} of each cell on each test module was measured separately.

The first five figures are results of five superstrate design modules, each with two cells.

After five cycles, there was no significant change in short circuit current (I_{SC}) of any of the test modules. These test specimens have now been cycled for 54 cycles and there is still no significant change in I_{SC} of the Super Dorlux® substrate modules, see Table IV and Figures 18-22. There are significant changes in the glass superstrate style modules. Except for the two cells coated with DOW CORNING® Q1-2577, all of the 2 cell strings coated with the other candidate materials have at least one cell with lower I_{SC}. See Table V and Figures 13-17.

The I_{SC} of the cells coated with the DOW CORNING® 840/B48N acrylic resin blend are 57% and 82% of the original values. These cells have lost all adhesion to the glass superstrate and there is condensed moisture on the surface of the cells. The cell output and appearance of this encapsulation system was the poorest of those evaluated. All of the other glass superstrate modules had at least one cell with little or no change in I_{SC}. One of the cells on the Super Dorlux® module design was cracked. This cell was probably cracked prior to fabrication of the test module but not observed. It is unlikely that the cell crack is a result of thermal stress because the silicone material used on this module, DOW CORNING® 3140 RTV is a very low modulus material.

The variations in the I_{SC} measurements appear to be quite large and are probably an artifact of the time of sampling. Some of the samples were removed from the chamber at 40.5°C and some at room temperature. This could cause the apparent loss and recovery of I_{SC}. In the future, all sampling will be made during the room temperature portion of the humidity/temperature cycling stress.

The one significant finding to date as a result of this humidity/temperature cycling stress is that only DOW CORNING® X1-2561 Solventless Resin provides a clear adherent glue line for the cells with no loss of

adhesion between the cells and glass superstrate and no bubbles or voids. As a consequence, this material is now considered a prime adhesion candidate.

The silicone materials were applied using conventional spray equipment. This method was chosen because spray coating is a standard industrial process and the facilities for spray coating are available at Dow Corning. The coatings can be applied using several different processes; brushing, dipping, flow coating, etc.

Use of UV Screening Agents in Protective Top Covers

One potential design for a cost effective photovoltaic array is to use an inherently weatherable protective top cover over a low cost, non-weatherable, UV sensitive pottant, such as ethylene vinyl acetate. The top cover would need to be heavily loaded with a UV screening agent to protect the UV sensitive pottant. Silicones could serve as the inherently weatherable top cover. Table VI shows the effects on transmission and cure of incorporating UV screening agents into two of the candidate silicone cover materials.

The addition of 1,000 ppm of: 1,4-dihydroxynaphthalene and 1,4-naphthoquinone, a blend of DOW CORNING® 840/Rohm and Haas B48N acrylic resin causes a decrease in transmission from 200-400 nanometers, the UV region, of approximately 20%. Unfortunately, the transmission from 400-1,800 nonometers which powers silicon solar cells is also reduced approximately 20%. The addition of 1,000 ppm of 2,4-dihydroxybenzophenone to this same resin blend caused a decrease in transmission of 28% between 200-400 nonometers and a slight increase in transmission between 400-1,800 nanometers. These data were obtained on 5 mil thick, free-standing films and normalized to 1 mil.

This ability to transmit light energy at long wavelengths and absorb short wavelength radiation is ideal for a UV screening cover material and, therefore, DOW CORNING® 840/Rohm and Haas B48N silicone-acrylic resin blend containing 1,4-naphthoquinone is a good candidate to be evaluated for its ability to protect an UV sensitive polymer.

Several additional UV screening agents have been ordered and will be evaluated in DOW CORNING® 808 and Q1-2577 as well as the DOW CORNING® 840/ Rohm and Haas B48N silicone-acrylic resin blend.

The addition of 1% of 1,4-dihydroxynaphthalene to DOW CORNING® X1-2561 Solventless Resin caused this resin to prematurely gel. It is easier to add UV screening agents to the other candidate silicone cover materials because they are supplied in solution. The solvent usually dissolves the UV additive and makes it more compatible with silicone polymer systems. Consequently, these solvent based silicone materials have more potential for this application than DOW CORNING® X1-2561.

The effectiveness and durability of an UV absorbing cover material which is obtained by incorporating an UV additive is limited by:

1) the compatibility of the UV absorbing agent with the cover material and
2) its tendency to migrate or volatilize away from the cover site.

The best way to overcome these deficiencies is to chemically bond or incorporate the UV absorbing moiety into the structure of the cover material. This approach will insure both the compatibility and the permanence of the UV absorber.

III. CANDIDATE SILICONE MATERIALS

The candidate silicone materials that are being investigated in this contract effort are reviewed in Table II. The silicone and modified silicone resins were chosen on the basis of similarity to materials with known weatherability, cost, initial tangential modulus, accelerated dirt pick-up test results and the ratio of the content of organic phenyl substitution or methyl substitution on the backbone of the silicone resin. Of the materials originally listed, the four remaining are the lowest cost and constitute a spectrum of moduli and phenyl/methyl ratios. RTV 3140 has a low rating in accelerated dirt pick-up but it has remained as a viable candidate for use as an encapsulant. The accelerated dirt pick-up of a fully cured sample of DOW CORNING® Q1-2577 Conformal Coating was re-run and found to have an acceptable rating.

Two adhesives were added to the list, DOW CORNING® X1-2561 and 3140 RTV 3140. Some bubbling on the backside of cells was experienced with DOW CORNING® 96-083 Adhesive. Although 96-083 Adhesive has desirable performance characteristics, it has been replaced with the resin and RTV 3140 which do not bubble. The best performance was found to come from DOW CORNING® X1-2561 Solventless Resin, so it has become the main adhesion candidate.

The initial tangential modulus of the silicones and modified silicone resins that were obtained and reported are very dependent on how the line tangent to the start of the curve is drawn.

For the values reported here, the Instron Cross arm speed was run at the slowest rate possible, 0.02 in/min., and the chart paper was run at the highest rate possible, 20. in/min. The initial portion of the curves

obtained was relatively flat. This makes the modulus values more accurate and reproducible. The intial tangential modulus is difficult to measure and the values are extremely sensitive to extent of cure. The values which we have obtained to date will be verified.

IV. DISPLAY MODULES FOR 11TH PROJECT INTEGRATION MEETING

Two display mini-modules described on the next pages were prepared for the 11th PIM. They represented a significantly different concept in protecting solar cells than that presently used by the photovoltaics industry. If these concepts can provide demonstrated protection for solar cells in harsh environments, it will reduce costs by reducing both the amount of materials used and the weight of the module. In addition, the fabrication is amenable to economical mass production.

One mini-module was of a substrate design and was assembled in the following way:

A 12" x 16" panel of Super Dorlux® Masonite from the Masonite Company was sprayed on the back and edges with a 25/75 blend of DOW CORNING® 840 Resin/Rohm and Haas® B48N acrylic resin pigmented with titanium dioxide. The sprayed panel was allowed to air dry and cure for 24 hours. This coating becomes tack-free within five minutes.

Terminal holes were drilled and lined with Elmer's two-part epoxy (amine cure) adhesive and two flathead bolts with nuts were attached and tightened. The front of the panel was then sprayed with the same pigmented DC-840/B48N resin blend and allowed to set ten minutes. A second coat was then applied and the 24-cell circuit was placed on the wet surface. This was allowed to dry for two hours, then the leads were soldered to the flathead bolts which serve as terminals.

In the last step, the front of the panel and cells were overcoated with clear, unpigmented DC-840/B48N resin blend by applying several thin layers. The mini-module was then allowed to air cure for 24 hours.

The estimated materials cost for this mini-module is as follows (in 1978 dollars):

Mini-Module Construction Elements

Super Dorlux® Masonite

Thickness - 0.125 inches (1/8")	$0.11/ft^2

This wood product is designed for outdoor applications. It can be fabricated in the thickness needed for the load bearing application.

DOW CORNING® 840 Resin - $4.32/lb.

This resin is a somewhat flexible clear resin compatible with organic resins. It is used to improve heat resistance and the weathering characteristics of organic coatings.

Rohm and Haas Acryloid B-48N - $1.51/lb.

This resin is a thermoplastic polymer for use in applications that require toughness, flexibility and outdoor durability.

DC-840/B-48N Resin Blend

Thickness (pigmented with TiO_2) - 0.002" (back)	$0.023/ft^2
- 0.004" (front)	$0.046/ft^2
Thickness (clear) - 0.005"	$0.057/ft^2
	$0.236/ft^2

The other mini-module was a superstrate design and was assembled in the following way:

The 12" x 16" Sunadex® glass panel from ASG Industries was thoroughly cleaned, first with toluene and then with acetone. A very thin (≈5μ) layer of DOW CORNING® 3-6060 Primer was applied where each cell would subsequently be placed and was allowed to air-dry one hour. DOW CORNING® XI-2561, an experimental solventless resin, was applied to the front of each cell. The pre-primed glass was then set down on the resin coated cells. This was cured ten minutes at 90°C.

The terminal sites were primed with a solution of DOW CORNING® Z-6040 Silane (1% by weight in toluene). The terminals were then bonded to the glass superstrates with Elmer's two-part (amine cure) epoxy adhesive. After one hour, the cell string leads were soldered to the terminals.

In the final step, the back and edges of the module were overcoated with DOW CORNING® Q1-2577 Conformal Coating containing TiO_2 pigment and allowed to air-dry.

Material costs for this mini-module were estimated as follows on the next page (1978 dollars):

Mini-Module Construction Elements

	Cost
Superstrate Design	
Sunadex® glass from ASG Industries Thickness - 0.125 Inches (1/8") - $0.69/ft^2 Transmissivity - 91.6%	
Note: Solatex® with a transmissivity of 90.1% would be a better choice based on cost.	$0.45/ft^2
DOW CORNING® Q1-2577 Conformal Coating	
Thickness - 0.005 inches (5 mils) - $9.33/lb.	$0.24/ft^2
DOW CORNING® Q1-2577 Conformal Coating is a clear silicone resin with good dielectric properties. The cured coating is dry and resists dirt pick-up. It is flexible over a wide temperature range and has an elongation at -70°C of 43%.	
Transparency, good dielectric properties, flexibility, and surface hardness are properties which make this material particularly well suited for providing protection to solar cells. In this display module, the conformal coating was pigmented with TiO_2 to provide a white reflective background.	
DOW CORNING® X1-2561 Resin	
Thickness - 0.005 inches (5 mils) - ~$10/lb.*	$0.26/ft^2
This clear solventless experimental resin cures by an addition reaction which produces a strong void free material. The optical and physical properties of this resin make it particularly useful in bonding solar cells to transparent superstrates.	
DOW CORNING® Q3-6060 Primer	
Thickness - 5 microns - $46/gallon	$0.15/ft^2
This primer is designed to provide good adhesion between DOW CORNING® X1-2561 type resins and inorganic surfaces.	
*The cost of this experimental product is based on estimates assuming large scale production and use. TOTAL COST	$1.10/ft^2

These display mini-modules will be stress tested at Jet Propulsion Laboratory to determine their performance characteristics. The results of this testing will be reported at a later date.

V. PLANS FOR THE FIRST QUARTER OF 1979

1. The screening effects of UV absorbing agents in silicone based top covers will be completed next quarter. Ultraviolet degradation of top covers containing UV screening agents and their ability to protect UV sensitive polymers used as pottants will be determined.
2. The outdoor dirt pick-up test will be continued during next quarter. We will continue to monitor change in I_{SC} as a function of time and will continue the study designed to assess the cleanability of these encapsulation materials. This study uses replicates of the same samples monitored for dirt pick-up by measuring the output of one-cell circuits. Correlations of artificial to natural weathering conditions will be made where possible.
3. Weather-Ometer® stressing of known weatherable samples will continue as well as tracking their change in properties.
4. Encapsulation of 2-cell circuits with our best encapsulation systems will continue. Temperature cycling of the encapsulated circuits will be started. The effects of humidity and temperature cycling will also be continued until catastrophic failure. A failure analysis will be ongoing during this time and appropriate changes in the encapsulation systems will be made. A failure analysis review and encapsulation system selection will be made in January, 1979. The Spectrolab constant humidity/constant temperature stress test will also be started.

The concepts evaluated to date will be ranked and encapsulation systems for scale-up will be defined.

This document, Pages 1 - 45, including Tables I-VI, and Figures 1-22, constitute this report submitted by William E. Dennis and Mary D. Fey.

BIBLIOGRAPHY

(1) Fey, M.; Dennis, W.; Silicone Encapsulation Systems for Terrestrial Silicon Solar Arrays, First Quarterly Report to Jet Propulsion Laboratory DOE/JPL-954995; July 10, 1978.

(2) Clark, H. A.; Environmental Resistance Data on Silicone Polymers of Utility in Solar Collectors, 1975, International Solar Energy Congress and Exposition, Los Angeles, CA., July 28 - August 1, 1975.

(3) Florida Weathering Summaries, Dow Corning Corporation, Midland, MI.

(4) Filtered Weather-Ometer® Summaries, Dow Corning Corporation, Midland Michigan.

(5) Midland Weathering Summaries, Dow Corning Corporation, Midland, MI.

(6) Brady, S.; Private Communication, Senior Specialist in Low Consistency Elastomers at Dow Corning. Information soon to be published as part of a review of case histories on silicone sealants.

(7) DeLollis, N. J., Outdoor Aging of Adhesive Sealants, Sandia Laboratories, Albuquerque, 1970, SCRR-70-163.

(8) Clark, W.; Private Communication, Low Consistency Elastomers, Technical Service and Development, Dow Corning Corporation and Dow Corning Sealants Data Sheet.

(9) Summary of Block 1 (46KW) Modules Testing, LSSA Project Task Report, 5101-27, May 2, 1977.

(10) Forman, S. E.; Endurance and Soil Accumulation Testing of Photovoltaic Modules at Various MIT-Lincoln Laboratory Test Sites, COO-4094-23 Contract ET76 CO2-4094, Jet Propulsion Laboratory, Sept. 28, 1978.

(11) Private Communication from Solarex Corporation.

(12) Sierawski, D.; Private Communication, Dow Corning Corporation.

(13) Communication from Spectrolab

(14) Cuddihy, E.; JPL in-house memo, 382-193, May 24, 1976.

(15) Large Scale Production Task of the Low Cost Silicone Solar Array Project Final Report P.O.B.Q. - 649005 DRD No. MA006.

(16) White, M. Encapsulating Integrated Circuits, Bell Laboratories Record, March 1974.

(17) White, M.; The Encapsulation of Integrated Circuits, Proceedings of IEEE, Volume 57, No. 9, September 1969.

(18) Sailer, E.; and Kennedy, A.,; "Using Silicones in a Low Cost, High Reliability Microcircuit Package", Electronic Packaging and Production, November (1966).

(19) Sierawski, D. A.; Silicones and the Environmental Protection of Electronics, Society of Automotive Engineers, February, 1978.

(20) Currin, C. G., and Sierawski, D. A.; The use of Silicone Gel for Potting Photovoltaic Arrays, International Solar Energy Society, Orlando, Florida, June (1977).

(21) Kookootsedes, G., and Lockhart, F.; "Silicone Molding Compounds for Semiconductor Devices, "Modern Plastics", McGraw-Hill, N.Y. January (1968).

(22) Jaffe, D.; Encapsulation of Integrated Circuits Containing Beam Leaded Devices with a Silicone RTV Dispersion, "IEEE Transactions on Parts, Hybrids, and Packaging", Volume PHP-12, No. 3, September (1976).

(23) Ruth, T. E., VanWert, B.; Performance Characteristics of Improved Solventless Silicone Resins, "IEEE Proceedings of the 11th Electrical Insulation Conference, September 30 - October 4, 1973.

(24) McIntyre, J. T.; Private Communication, High Consistency Elastomers, Technical Service and Development, Dow Corning Corporation.

(25) Selfridge, R.; Outdoor Exposure Tests of Silastic, DCC Product Engineering Report, May 8, 1947.

(26) Brown, L. H.; "Silicones in Protective Coatings", Treatise on Coatings, Vol. I, Part III, Macel Depler, N.Y. (1972).

(27) Thomas, R. N.; "Organo-Silicone Coatings", Materials Protection 3 (3), March (1964).

(28) Finzel, W. A.; "Correlation of Effects of Dew Cycle Weather-Ometer and Florida Exposure on Highly Durable Coatings", Journal of Paint Technology, from the 11th Biennial Western Coatings Societies Symposium and Show, Anaheim, CA, March (1972).

(29) Plueddemann, E. P.; "Mechanism of Adhesion of Coatings Through Reactive Silanes", Journal of Paint Technology, November (1970).

(30) Plueddemann, E. P.; Reactive Silanes as Adhesion Promoters to Hydrophilic Surfaces, Paper #9, Dow Corning Corporation, Midland, Michigan.

(31) Bobeau, W. J.; Method of Bonding, U.S. Patent #3,053,687 (1962).

(32) Groupon, W. L.; Process for Promoting Adhesion to Difficultly Wettable Polymer Surfaces, U.S. Patent #2,888,367, May (1969).

(33) Liles, D.; Organosilicon Hydride for Bonding Silicone, U.S. Patent #4,082,719, July 14, 1977.

(34) Registered - Atlas Electric Devices

(35) Estey, R.; Interoffice Memo #341-78-4369, Jet Propulsion Laboratory, September 13, 1978.

OUTDOOR VS ATLAS SUNSHINE CARBON ARC WEATHER [illegible]

STRESSING: EFFECTS ON PROPERTIES

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
1. DOW CORNING® 808 Resin	3-4 mil coating on aluminum panels	6 years Florida, 45° south	36% loss 60° gloss, no checking or dirt retention
		3,000 hours filtered WOM	No loss 60° gloss, 7 check rating, no dirt retention
2. DOW CORNING® 901 Resin	6 mil coating on fine weave fiberglass	7 years Arizona, 45° south	99% of original 350-2400 NM transmissio
		4M Langleys - Emmaqua	94% of original 350-2400 NM transmissio
		3,000 hours filtered WOM	No change in transmission
3. B66 Acrylic/ DC® 840 Blend	3-4 mil coating on aluminum and steel panels	13 years Texas	Slight dirt retention, no loss gloss or checking
		7 years Florida, 45° south	High corrosion protection
		3,000 hours filtered WOM	50% loss 20° gloss, no loss 60° gloss, checking - 6, no dirt retention.
4. DOW CORNING® 996 Resin	2 mil coating on aluminum panel	10 years Midland	No loss gloss, no color change, checking rating 6.
		3,000 hours filtered WOM	60% loss 20° gloss (spots from water spray), 15% loss of 60° gloss, checking 4, no dirt retention.
5. LS 53 Rubber	1/8" thick strips-folded, stretched 20%, unstressed	20 years Florida	Slight dirt & mildew, no cracking or checking
		2,500 hours filtered WOM	No change

ORIGINAL PAGE IS OF POOR QUALITY

OUTDORR VS. ATLAS SUNSHINE CARBON ARC WEATHER-OMETER® (WOM)
STRESSING: EFFECTS ON PROPERTIES

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
6. RTV 132U Elastomer	1/8" thick strips-folded, stretched 20%, unstressed	20 years Florida	Some loss of tensile and Elongation, Same as LS 53
		2,500 hours filtered WOM	Slight trace dirt
7. RTV 501 Elastomer	1/8" thick strips-folded, stretched 20%, unstressed	16 years Florida	Slight dirt retention and mildew
		2,500 hours filtered WOM	No checking
8. 55U Silastic® Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight dirt retention and mildew
		2,500 hours filtered WOM	No change
9. Silastic® 675 Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight decrease in durometer, tensile and elongation, some surface cracking
		2,500 hours filtered WOM	No change
10. RTV 781	6 mil coating on aluminum panel	20 years Wisconsin	Dirt pick up, slight lowering in durometer
Building Sealant	6 mil coating on aluminum panel	2,500 hours filtered WOM	No loss 20° gloss, some blisters

SILICONE OR MODIFIED SILICONE	USE	$/lb. SOLIDS (1978 $)	$/ft^2/Mil.	INITIAL TANGENTIAL MODULUS(psi)	ACCELERATED DIRT PICK-UP	PHENYL/ METHYL UP
A. DC® 840/B48N Resin Blend	1. Conformal Coating 2. UV Containing Top Cover 3. Pigmented Bottom Cover	4.32/1.51	.012	43,500	9.5-10	High
B. DC® 808 Resin	Same as A	5.08	.026	27,500	5	Low
C. Q1-2577 Conformal Coating	Same as A	9.33	.052	2,450	5	Low
D. RTV 3140	As a pottant	11.19	.06	--	0-1	Negligible
PRIMERS						
A. Z-6082 Silane		4.30	.005/5μ	--	--	--
B. Z-6030 Silane		8.65	.01/5μ	--	--	--
C. Z-6020 Silane		6.35	.0075/5μ	--	--	--
D. DC® 1204 Primer		5.40	.004/5μ	--	--	--
E. DC® 3-6060 Primer		NA	--	--	--	--
ADHESIVES						
A. X1-2561*		10.00	.06	--	9	Medium
B. RTV 3140		11.19	.06	--	--	Low

*The cost of this experimental product is based on estimates assuming large scale production and use.

I_{sc} and V_{oc} Versus Days of Outdoor Exposure For Candidate Encapsulation Materials

Days Exposure	RTV-3140		Sylgard 184		DC 840/B-4oN		Q1-2577		DC-808		X1-2561	
	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}
0	487	573	489	577	473	572	469	583	505	577	458	549
11	499	559	474	569	466	557	451	570	453	561	478	559
26	430	569	448	576	453	568	441	580	426	567	412	567
37	457	578	463	584	439	576	450	589	383	570	396	570
44	452	577	464	581	450	576	452	588	416	576	396	571
53	449	587	469	590	416	581	434	596	413	578	378	579
60	438	577	515	584	445	574	494	590	424	576	406	570
66	464	574	500	576	441	569	484	587	425	572	349	568
81	403	580	425	585	342	576	423	590	392	577	315	567
96	423	586	451	588	413	582	445	598	396	582	396	574
108	357	578	458	584	413	575	429	590	430	577	364	575
124	420	579	359	581	419	579	388	590	397	577	330	571
134	417	576	469	582	434	576	461	589	410	574	413	569
150	409	580	468	587	413	560	460	593	488	576	329	569

TABLE IV

SUPER DORLUX SUBSTRATE MODULE DESIGN
TEMPERATURE CYCLING TEST

AT 95% RELATIVE HUMIDITY
ROOM TEMPERATURE TO 40.5°C

	Q1-2577				X1-2561				DC-840/B-48N				DC-808				RTV-3140			
	CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2	
CYCLES	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc
0	551	376	573	460	561	399	569	403	586	408	575	472	574	339	576	380	567	472	570	430
5	580	378	596	492	581	515	588	506	590	401	581	470	595	470	584	382	0	0	574	453
15	567	378	595	492	567	393	574	415	592	401	577	436	582	315	591	380	-	-	587	517
25	573	370	591	478	567	391	571	393	586	303	577	459	587	341	577	353	-	-	577	427
34	568	316	589	427	567	381	572	381	588	335	571	292	575	236	575	270	-	-	575	333
44	573	389	590	515	577	550	570	427	589	340	574	488	571	351	569	395	-	-	574	474
54	577	392	593	495	571	405	574	428	591	424	576	485	580	344	579	389	-	-	581	464

GLASS SUPERSTRATE MODULE DESIGN
TEMPERATURE CYCLING TEST

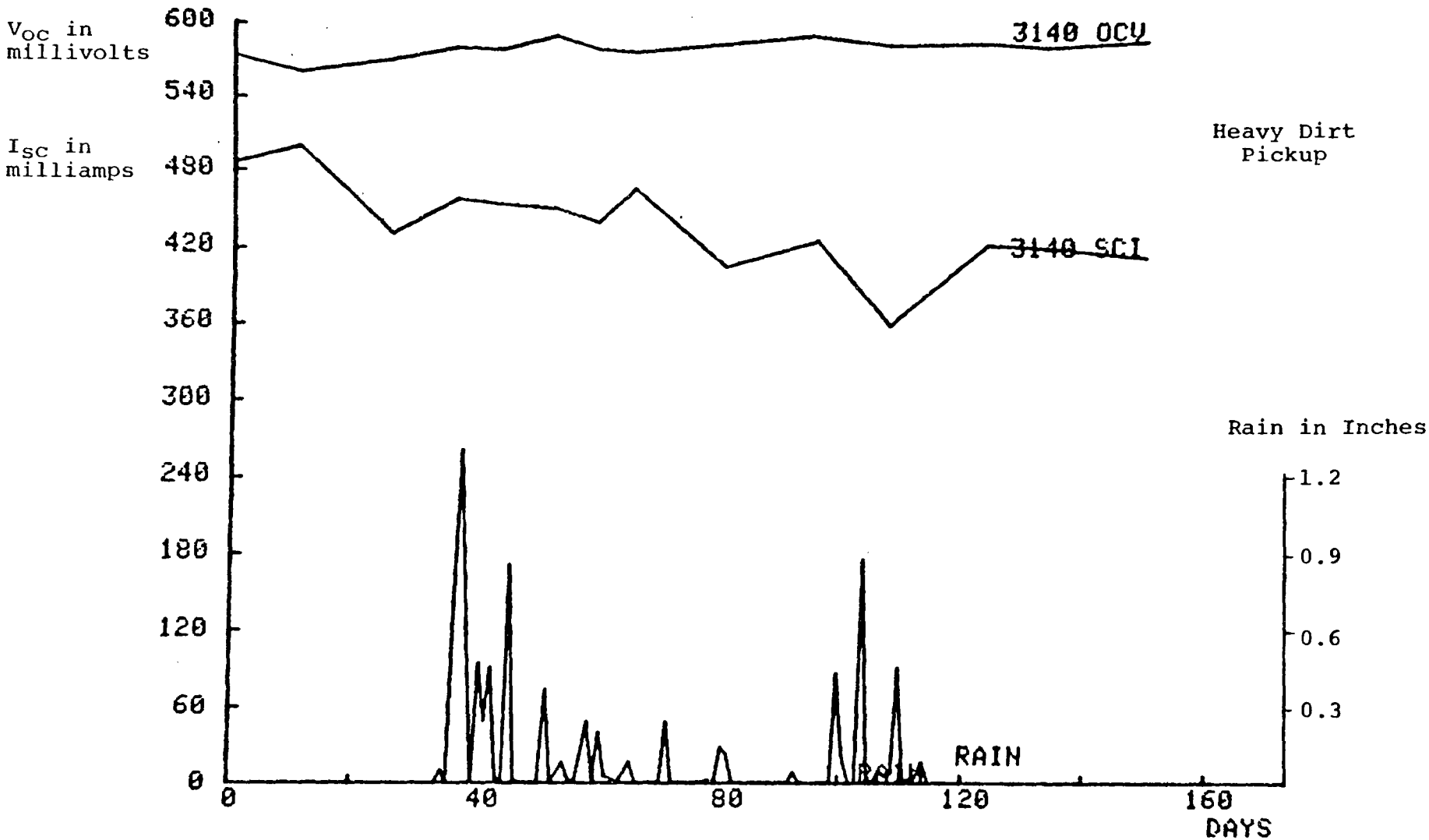
AT 95% RELATIVE HUMIDITY
ROOM TEMPERATURE TO 40.5°C

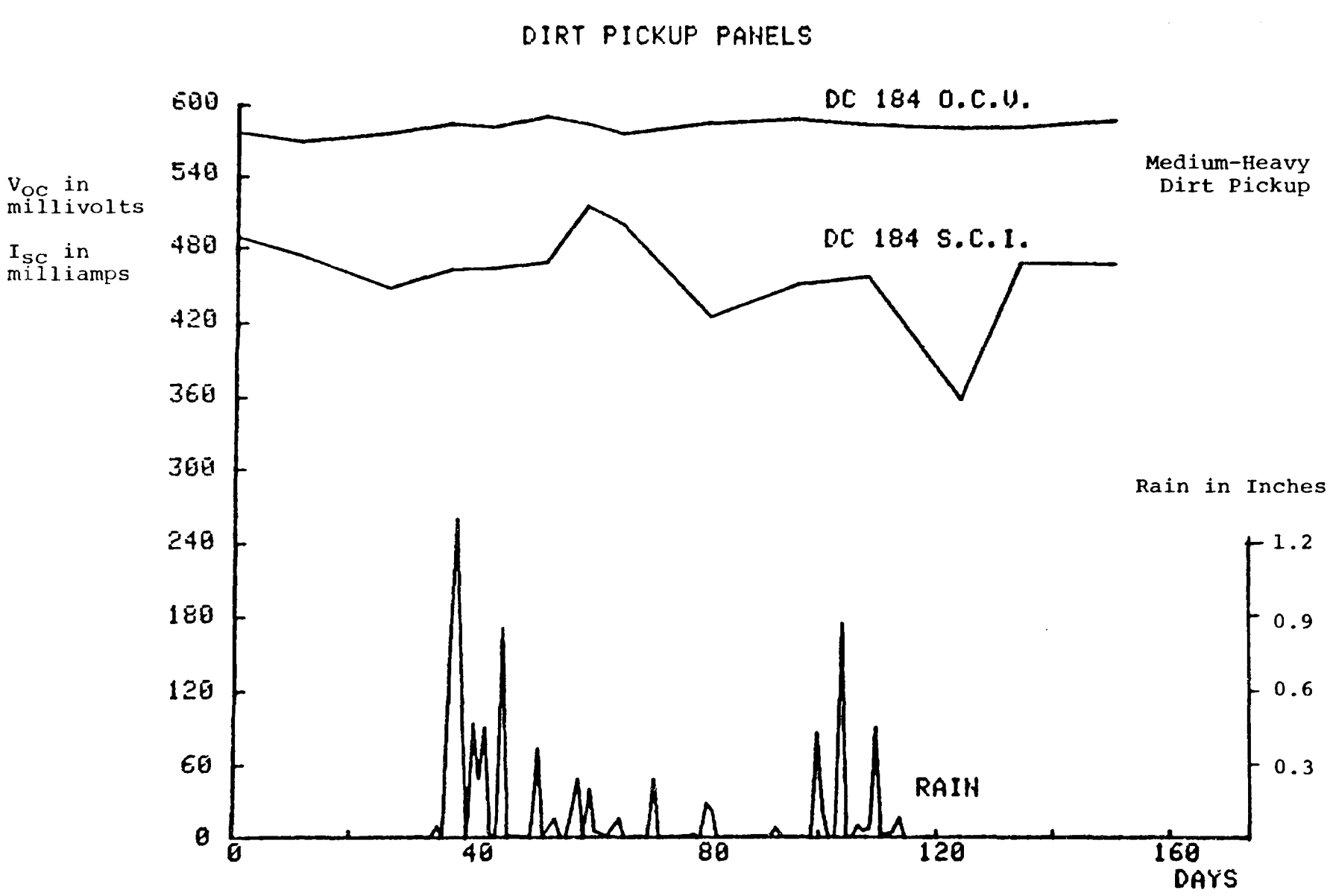
	Q1-2577				X1-2561				DC-840/B-48N				DC-808				RTV-3140			
	CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2	
CYCLES	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc
0	582	423	575	386	589	474	580	504	584	466	585	394	590	466	590	472	579	438	584	463
5	587	421	592	484	596	460	584	489	588	427	585	377	595	406	591	459	586	430	591	459
15	584	428	587	499	593	473	580	501	586	440	582	381	592	416	588	426	584	443	588	470
25	580	401	586	445	590	450	579	491	579	401	581	365	587	383	589	423	582	453	586	441
34	578	413	582	475	582	411	575	455	580	411	580	379	588	411	585	429	580	433	584	460
44	580	332	568	264	588	454	575	479	578	420	579	389	587	427	584	450	580	451	583	501
54	584	441	575	367	577	314	577	460	585	368	582	381	592	380	571	270	583	44[illegible]	573	347

TABLE VI: TRANSMISSION OF X1-2561 SOLVENTLESS RESIN AND DC-840/B48N BLEND CONTAINING UV SCREENING AGENTS

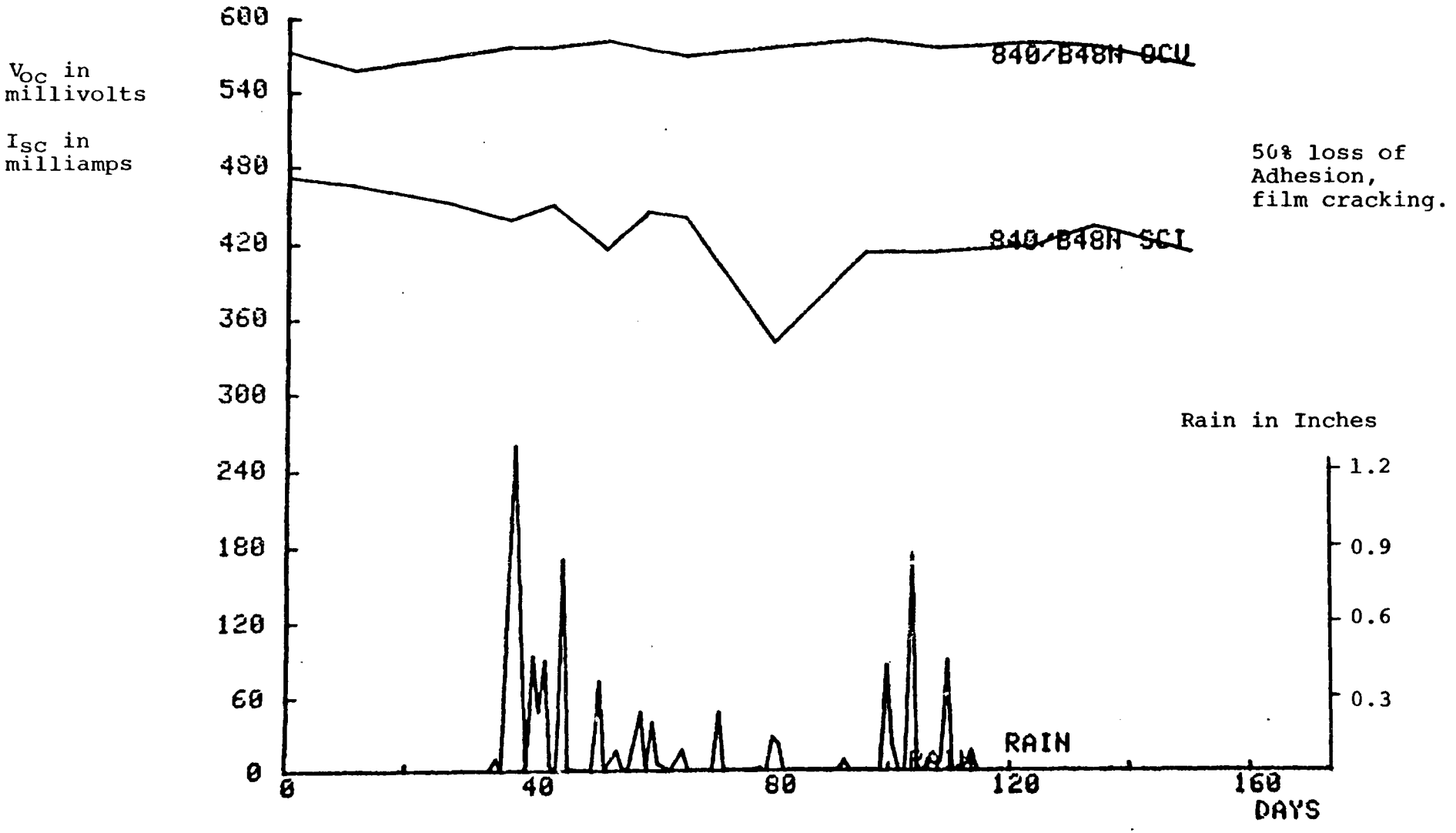
	% Transmission Change Vs. Control	
X1-2561 Solventless Resin	200 - 400 nm	200 - 1800 nm
250 ppm 1,4-DHN	- 1%	- 2%
1,000 ppm 1,4-DHN	-10%	- 5%
10,000 ppm 1,4-DHN	-No film, stabilizer cured resin	
DC-840/B48N Blend		
250 ppm 1,4-DHN	- 4%	+ 4%
1,000 ppm 1,4-DHN	-23%	-23%
250 ppm 1,4-NQ	-18%	- 6.7%
1,000 ppm 1,4-NQ	-22%	-21.6%
250 ppm 2,4-DHBP	-10.5%	+ 4%
1,000 ppm 2,4-DHBP	-28%	0

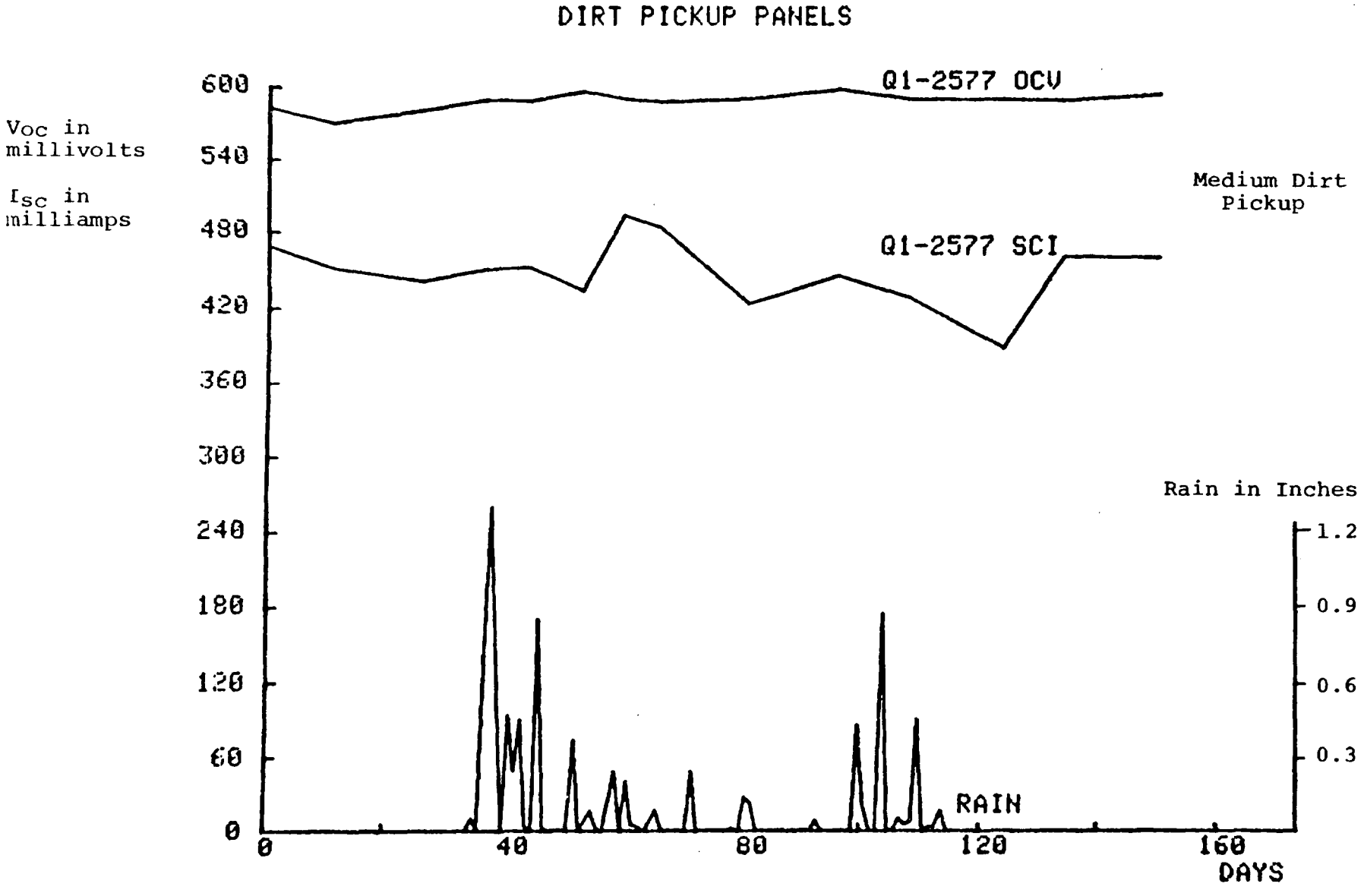
DIRT PICKUP PANELS



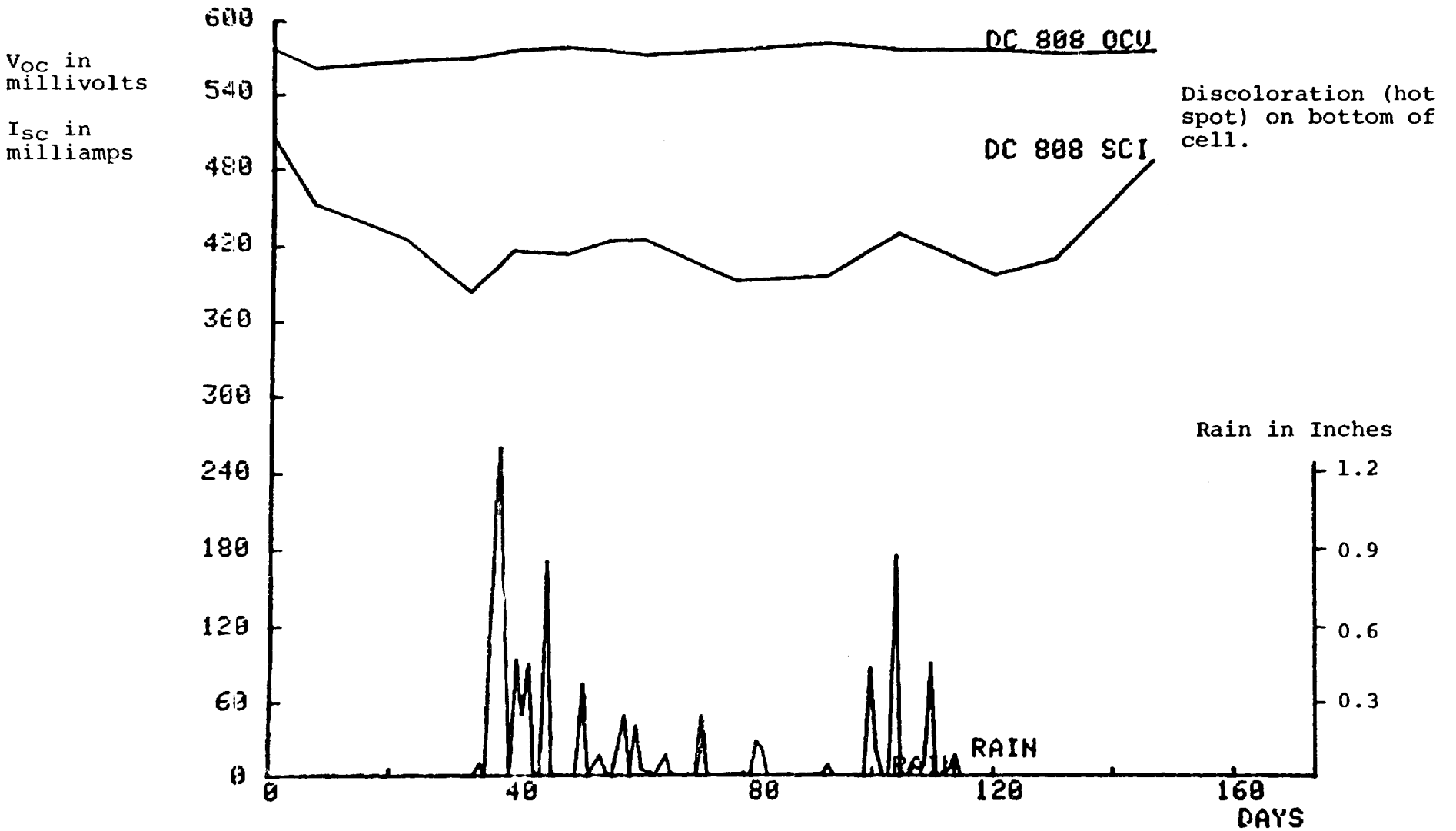

DIRT PICKUP PANELS
DC 184 O.C.V.
DC 184 S.C.I.
Medium-Heavy
Dirt Pickup
V_{OC} in
millivolts
I_{SC} in
milliamps
600
540
480
420
360
300
240
180
120
60
0
Rain in Inches
1.2
0.9
0.6
0.3
RAIN
0
40
80
120
160
DAYS

DIRT PICKUP PANELS

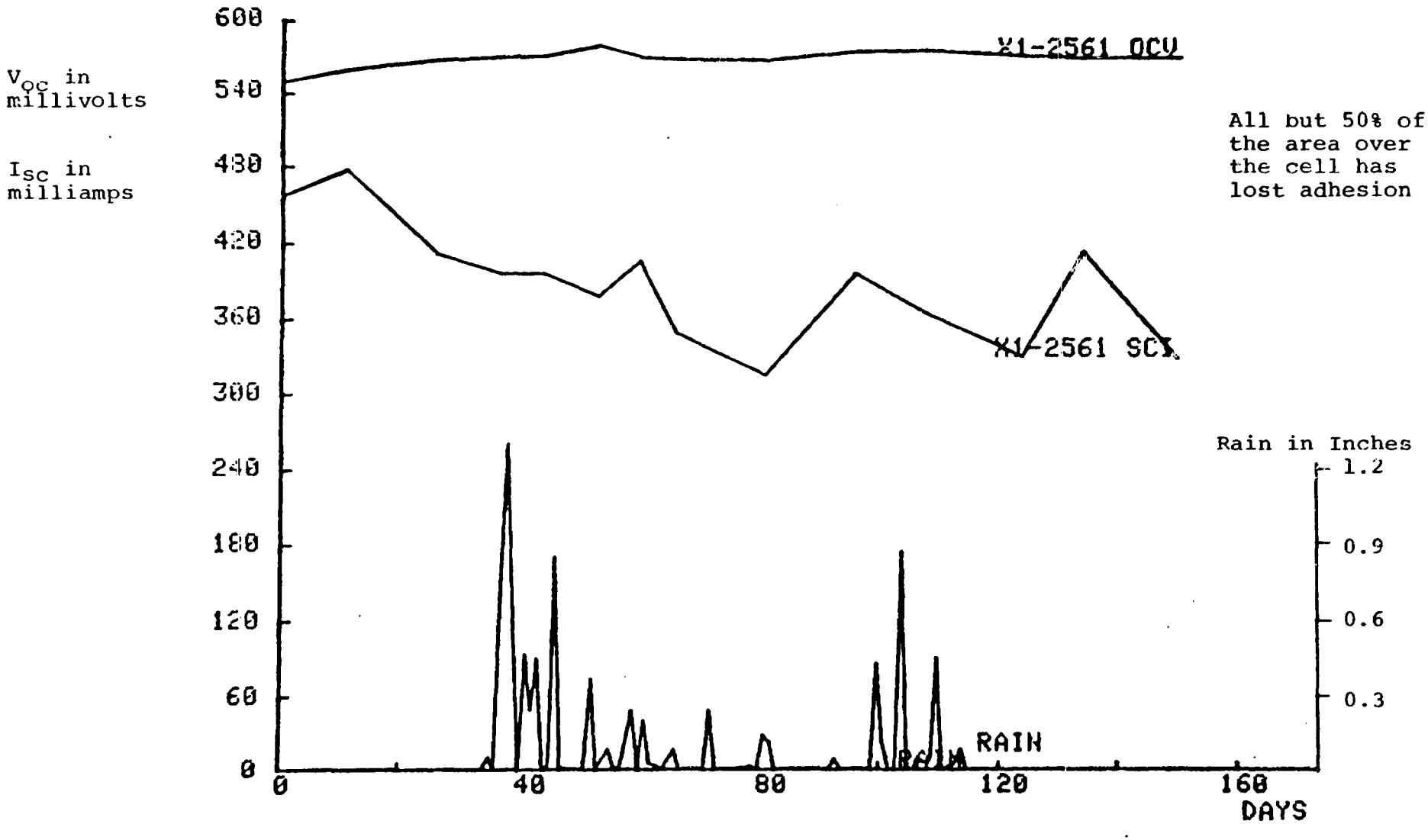


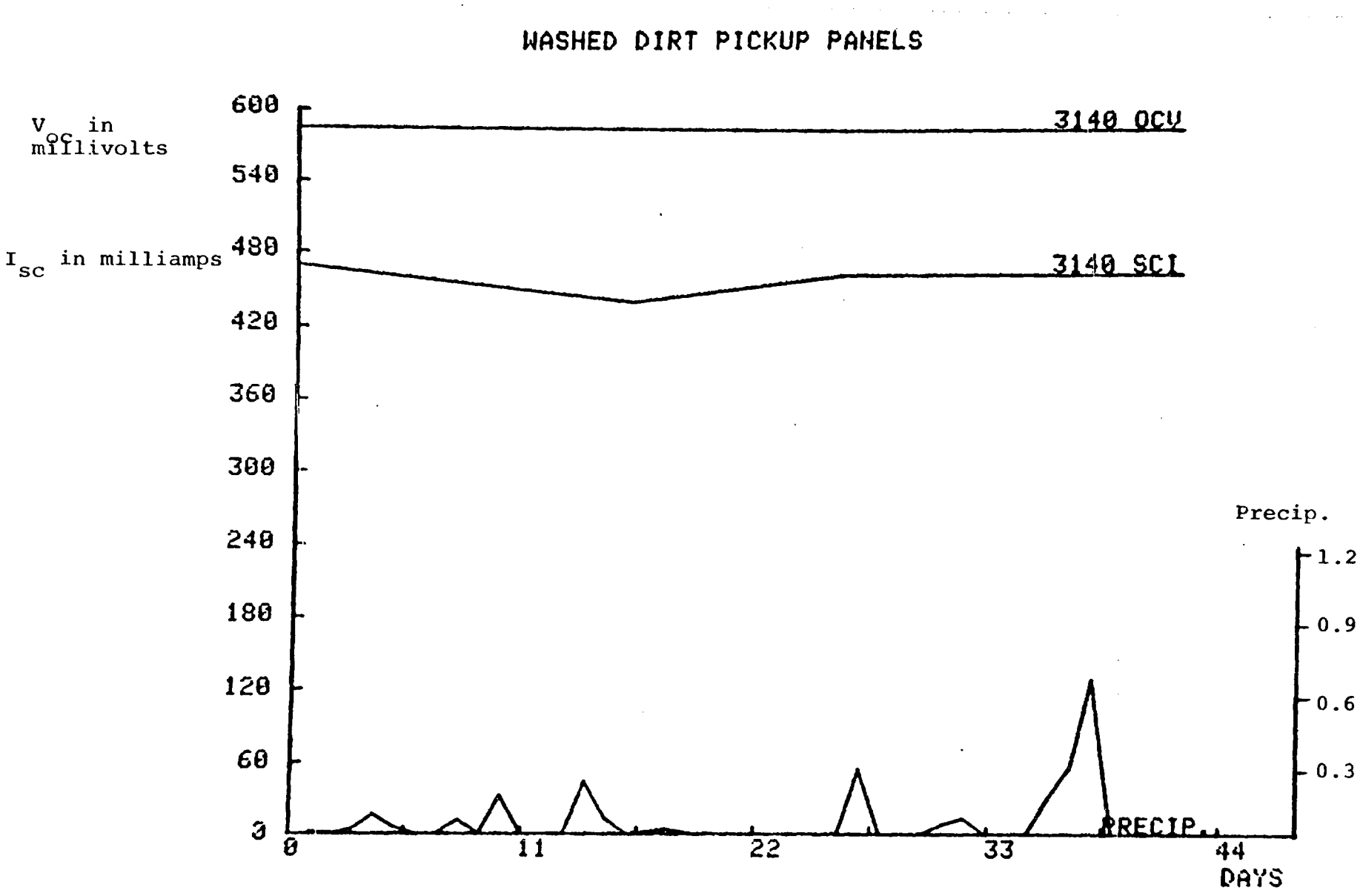

DIRT PICKUP PANELS
Voc in millivolts
Isc in milliamps
600
540
480
420
360
300
240
180
120
60
0
Q1-2577 OCV
Q1-2577 SCI
Medium Dirt Pickup
Rain in Inches
1.2
0.9
0.6
0.3
RAIN
0
40
80
120
160
DAYS

DIRT PICKUP PANELS

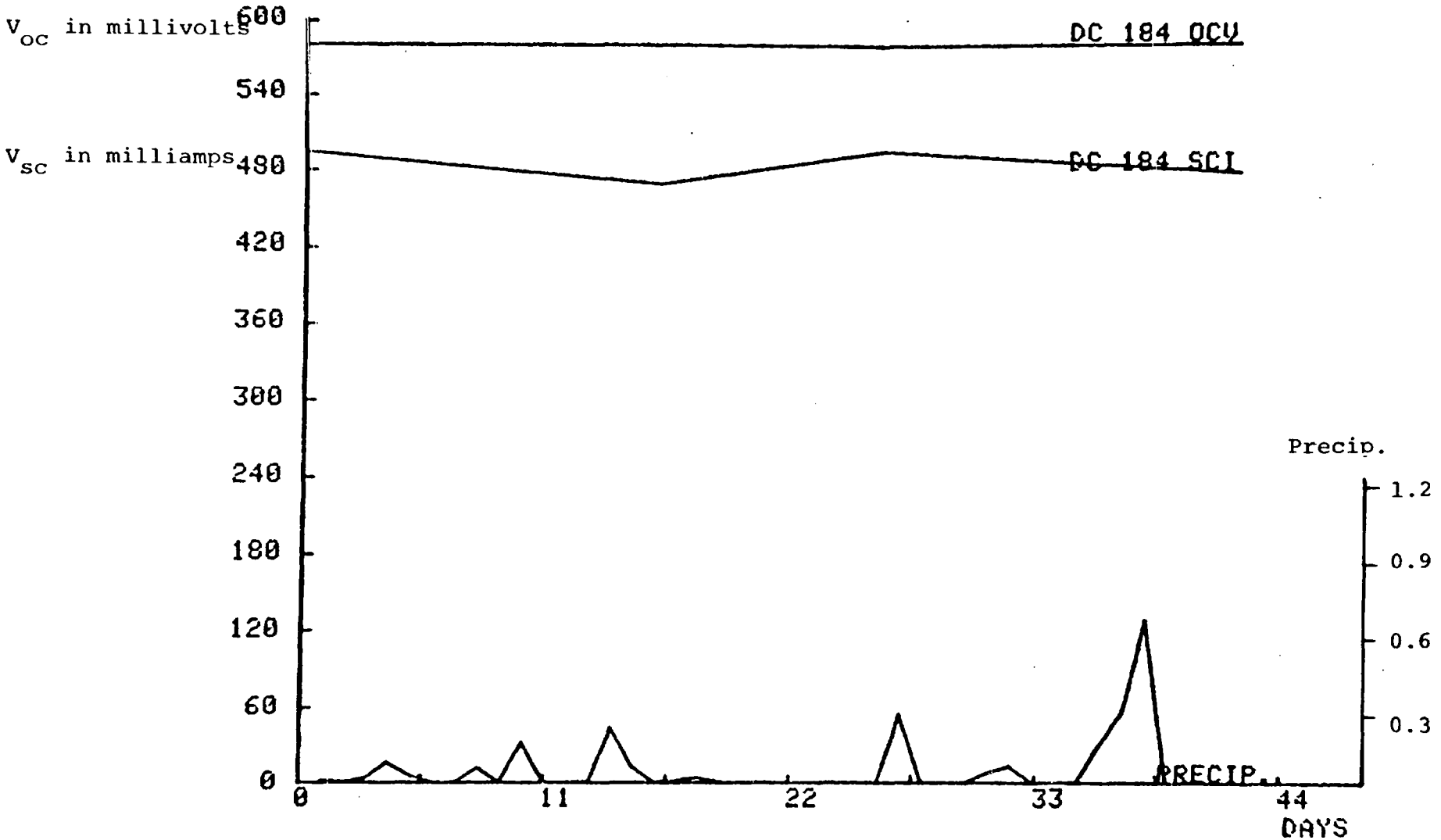


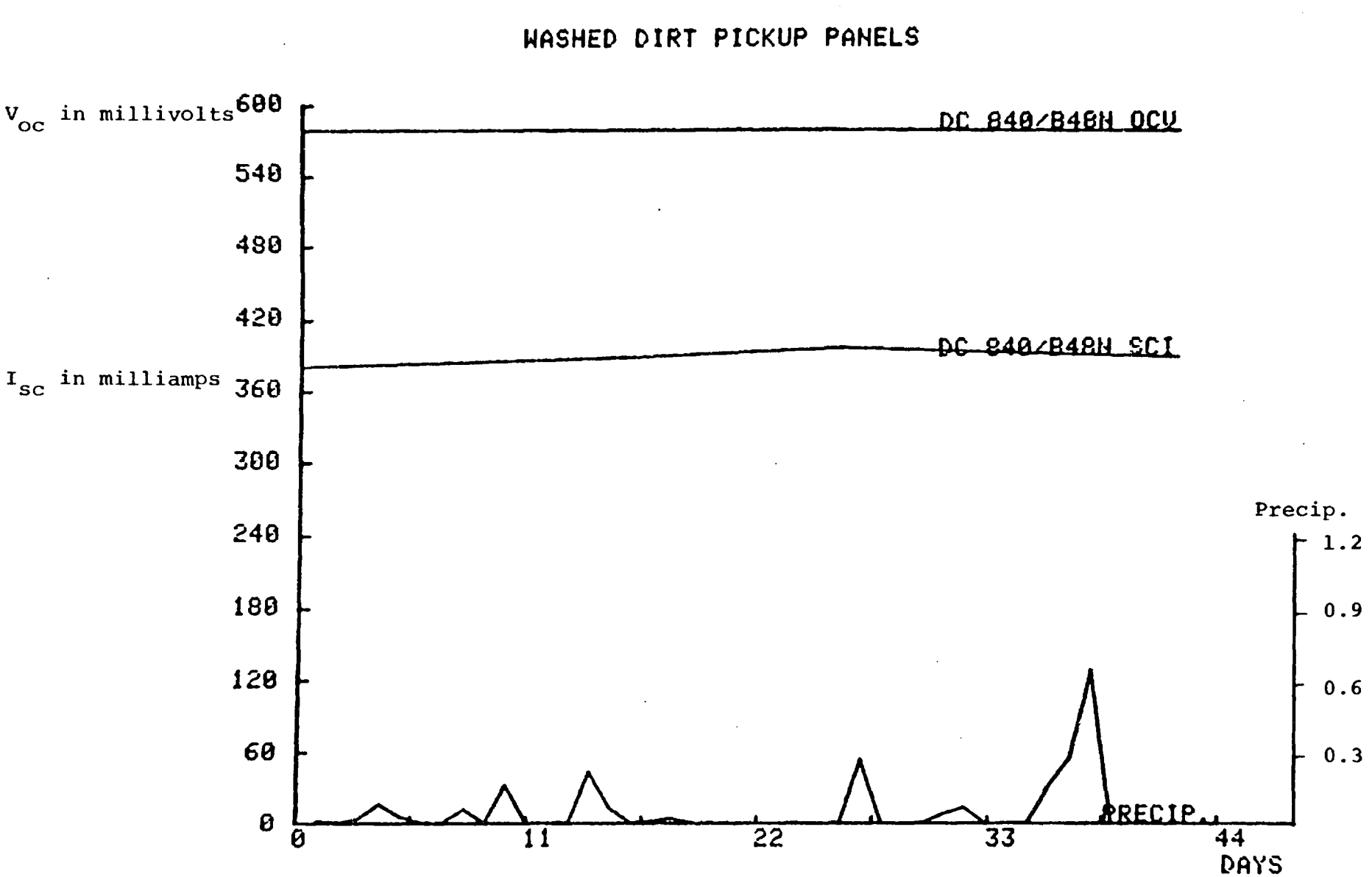
DIRT PICKUP PANELS



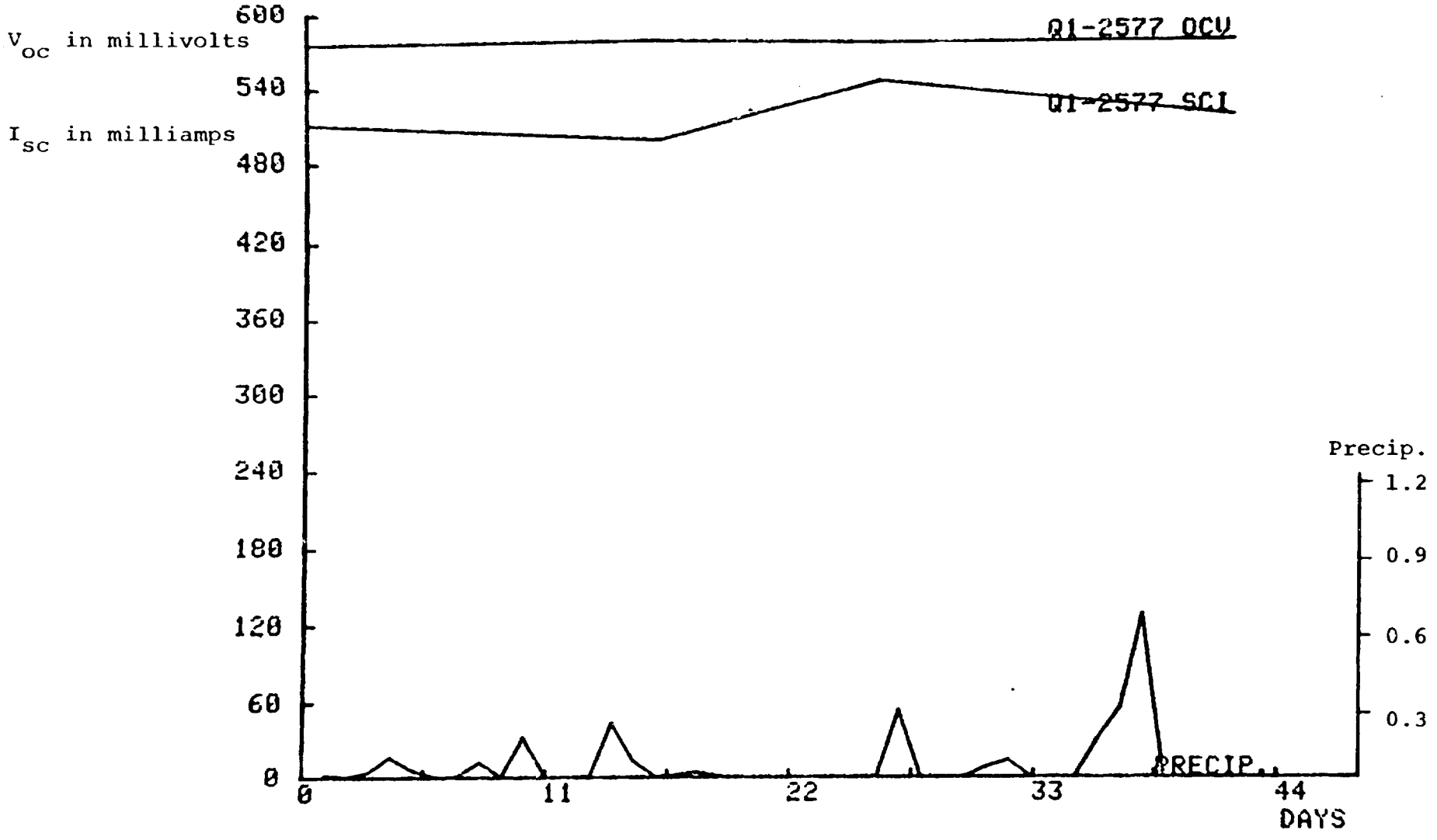

WASHED DIRT PICKUP PANELS
V_{oc} in millivolts
I_{sc} in milliamps
600
540
480
420
360
300
240
180
120
60
0
3140 OCV
3140 SCI
Precip.
1.2
0.9
0.6
0.3
PRECIP.
0
11
22
33
44
DAYS

WASHED DIRT PICKUP PANELS




WASHED DIRT PICKUP PANELS
V_{oc} in millivolts
600
540
480
420
I_{sc} in milliamps
360
300
240
180
120
60
0
DC 840/B48N OCV
DC 840/B48N SCI
Precip.
1.2
0.9
0.6
0.3
PRECIP.
0
11
22
33
44
DAYS

WASHED DIRT PICKUP PANELS



WASHED DIRT PICKUP PANELS

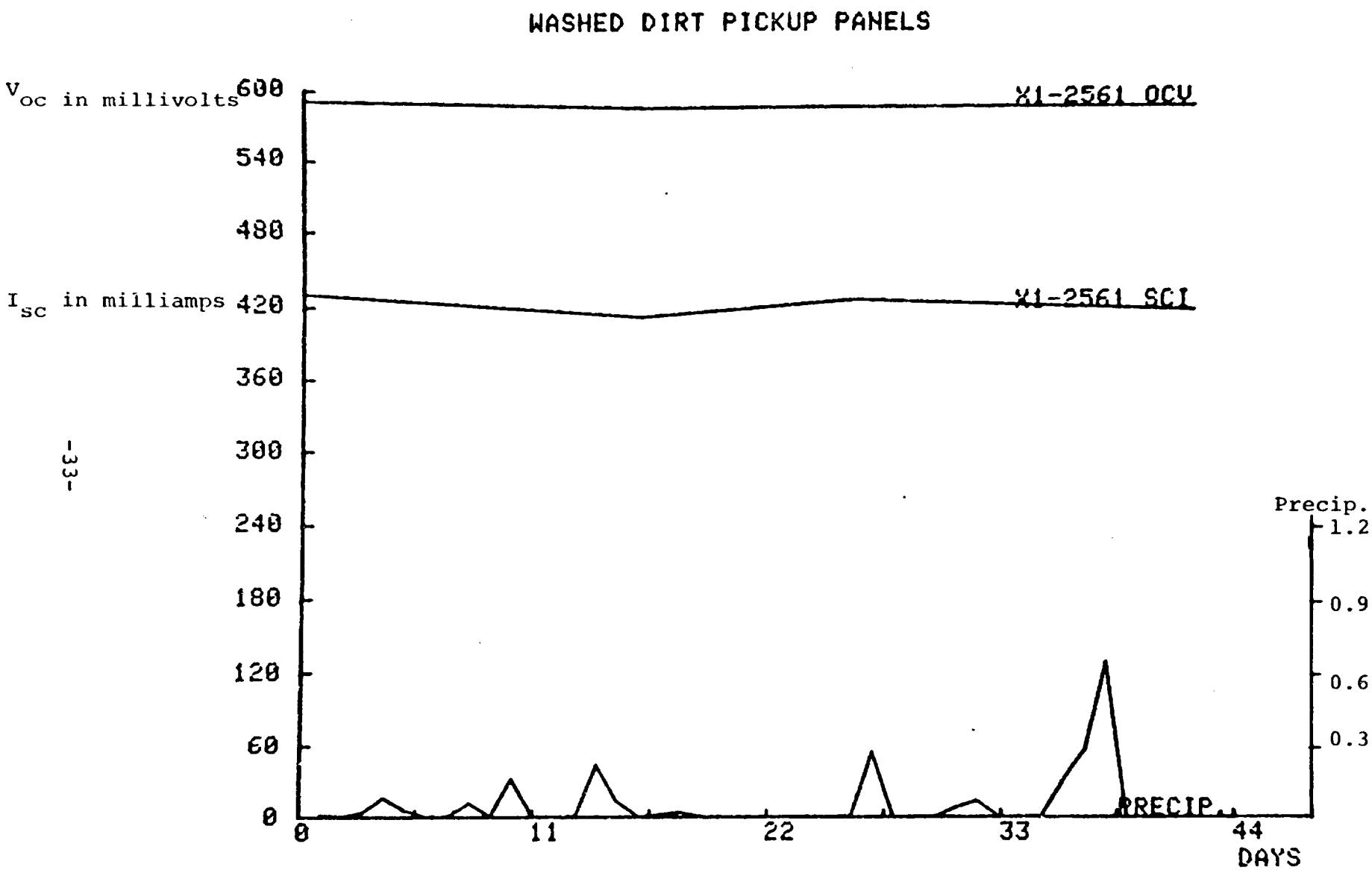


FIGURE 12

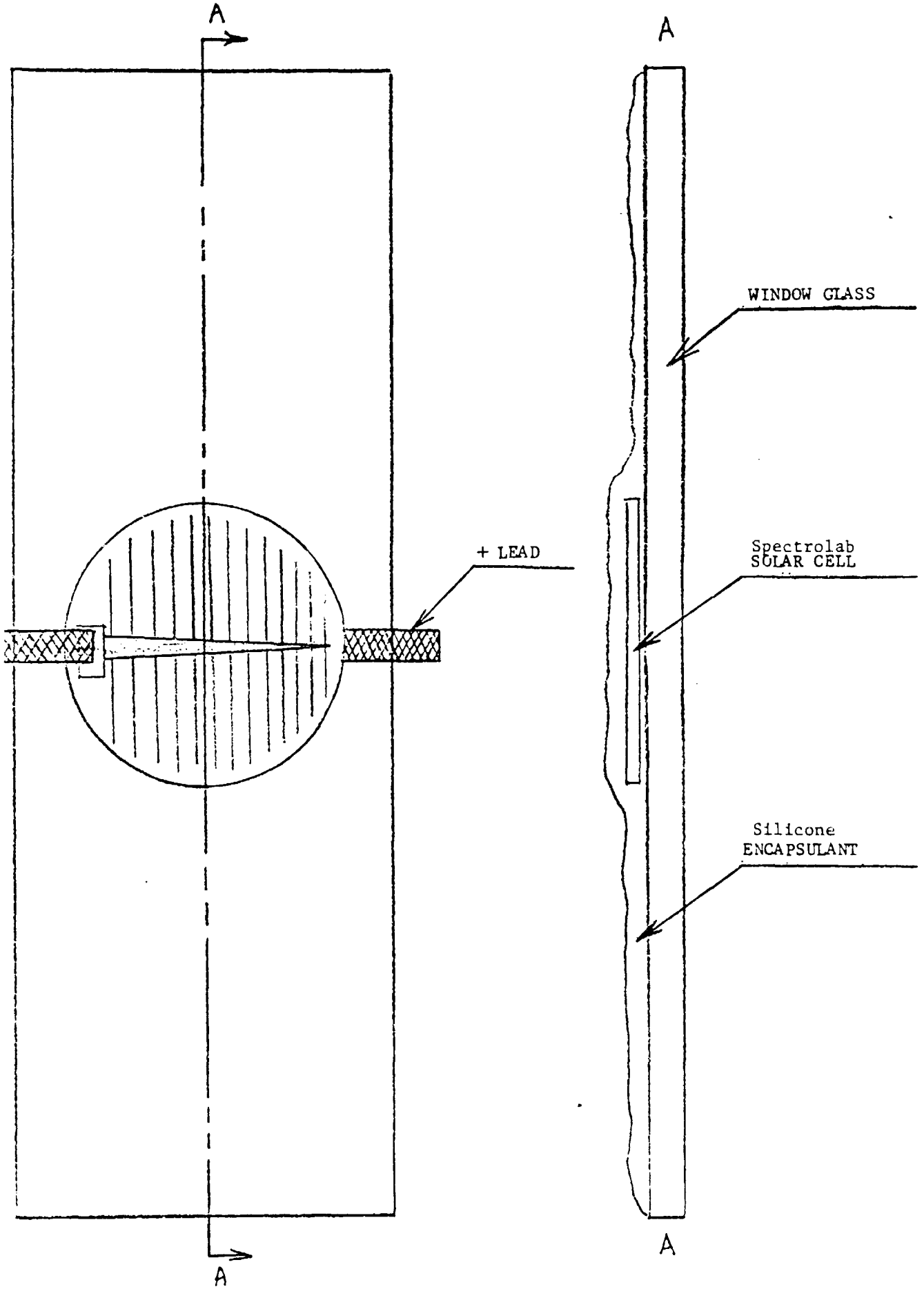
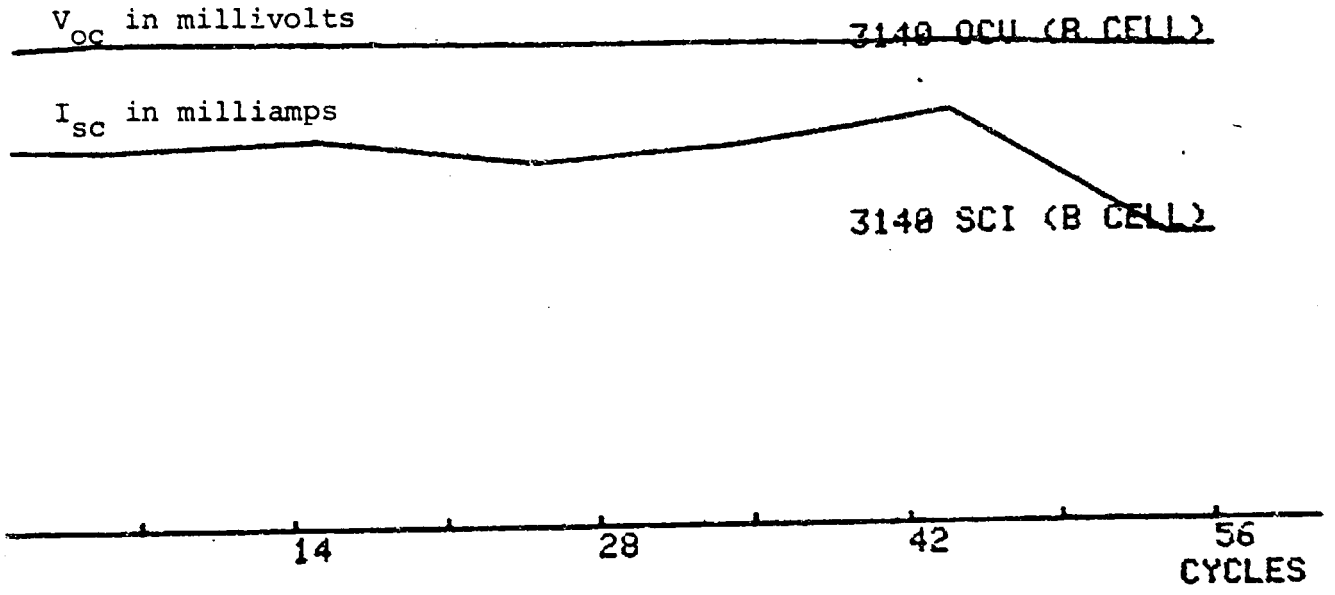
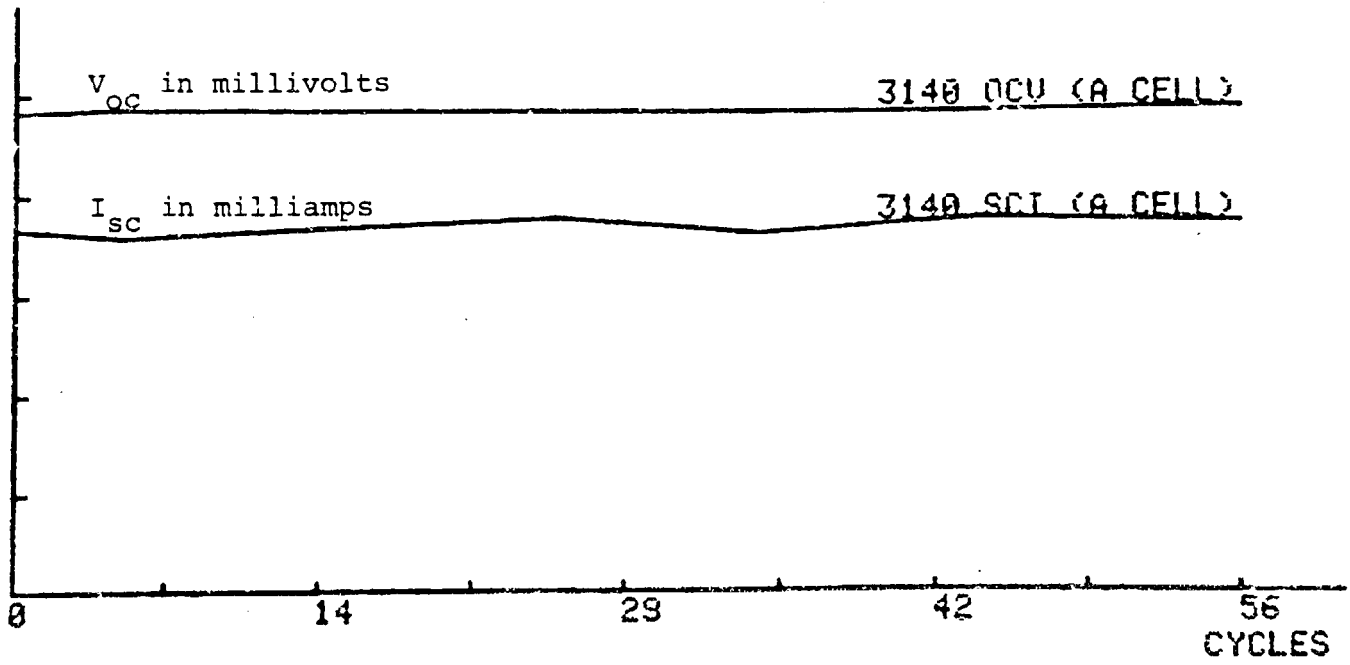

A
A
WINDOW GLASS
+ LEAD
Spectrolab
SOLAR CELL
Silicone
ENCAPSULANT
A
A

FIGURE 13

TEMP/ HUMIDITY PANELS (GLASS SUPERSTRATE)

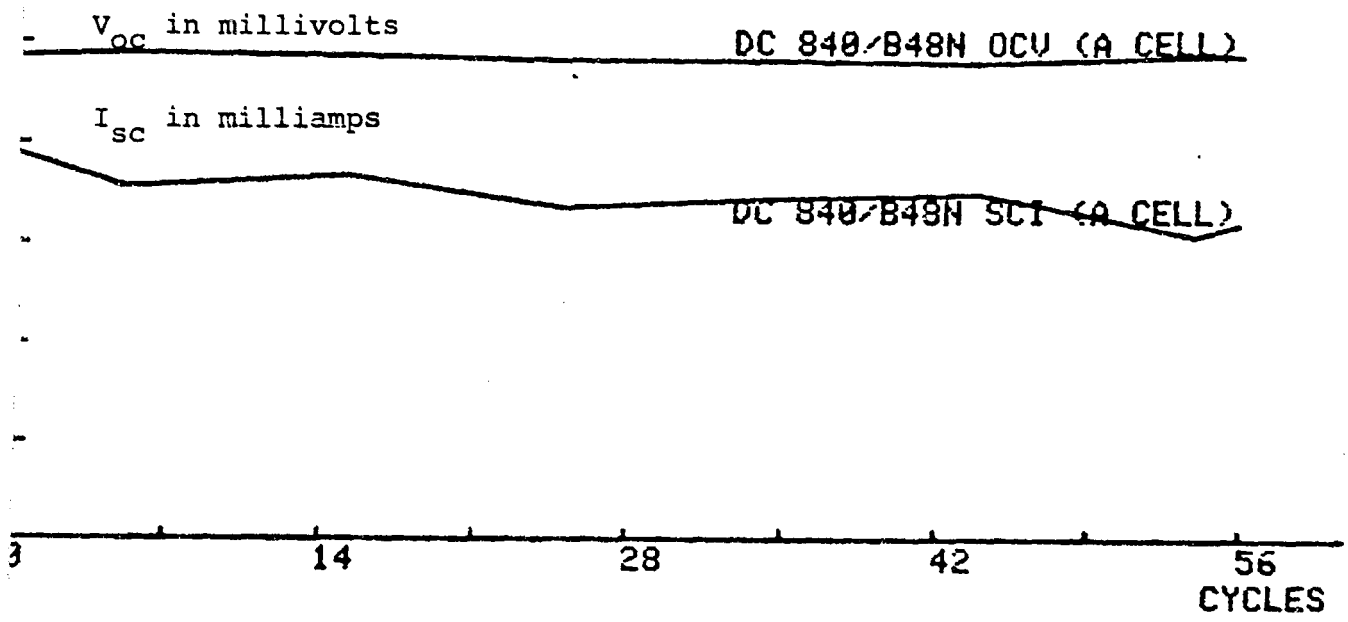




ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 14

TEMP/HUMIDITY PANELS (GLASS SUPERSTRATE)



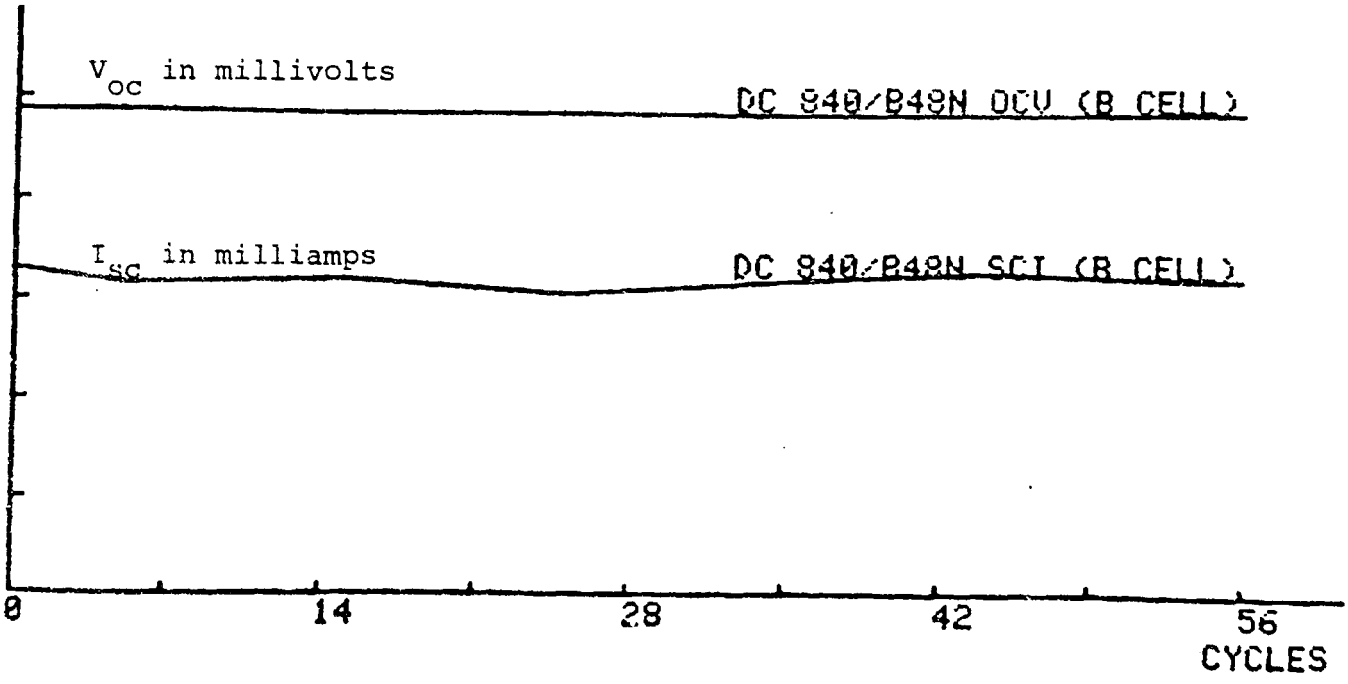
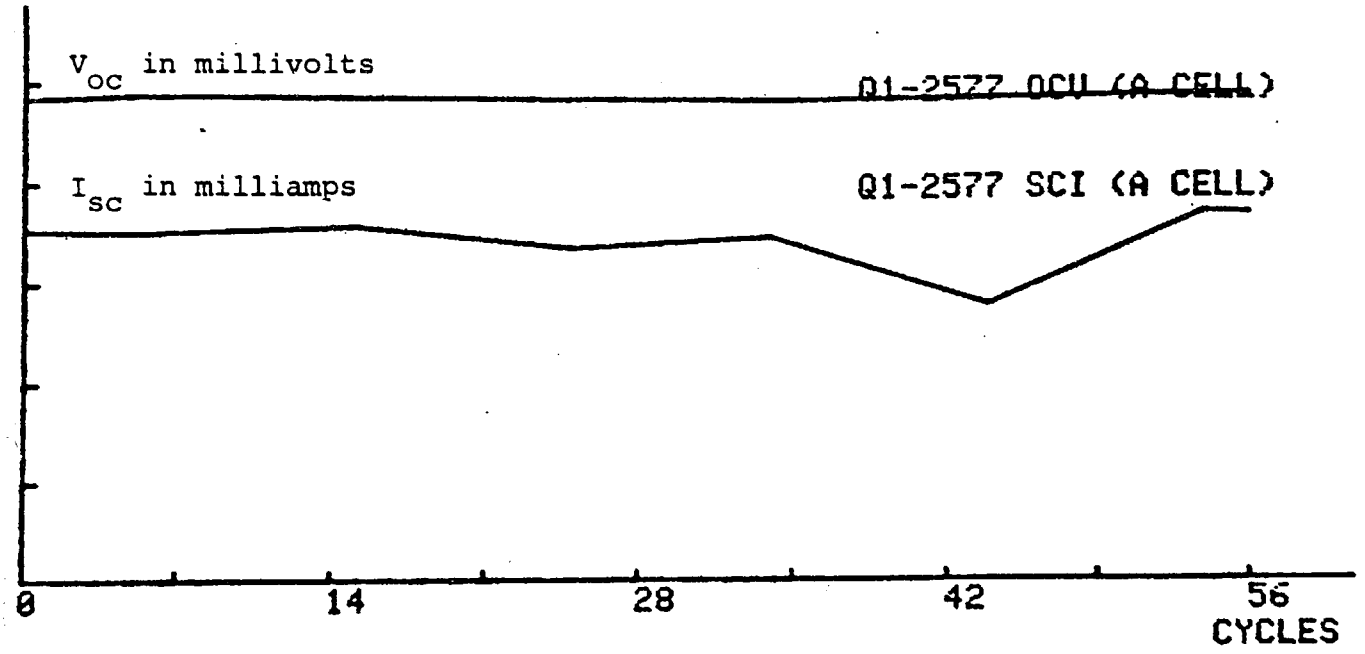


FIGURE 15

TEMP/HUMIDITY PANELS (GLASS SUPERSTRATE)



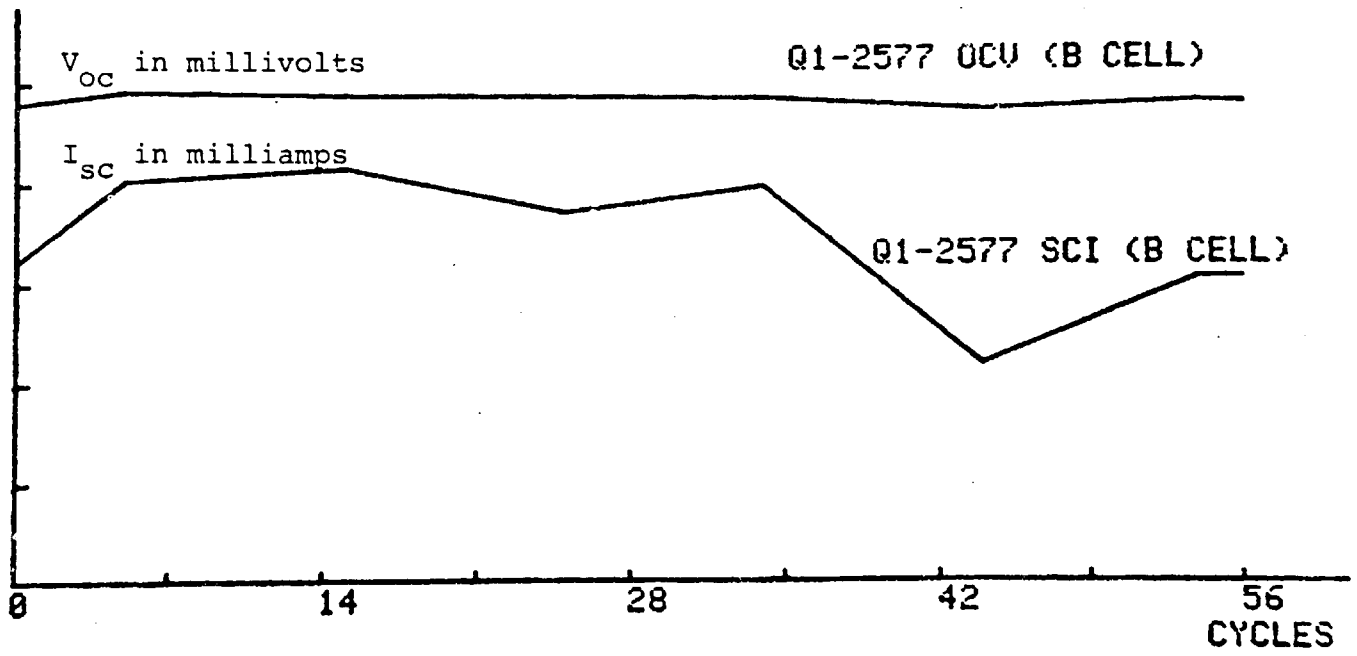
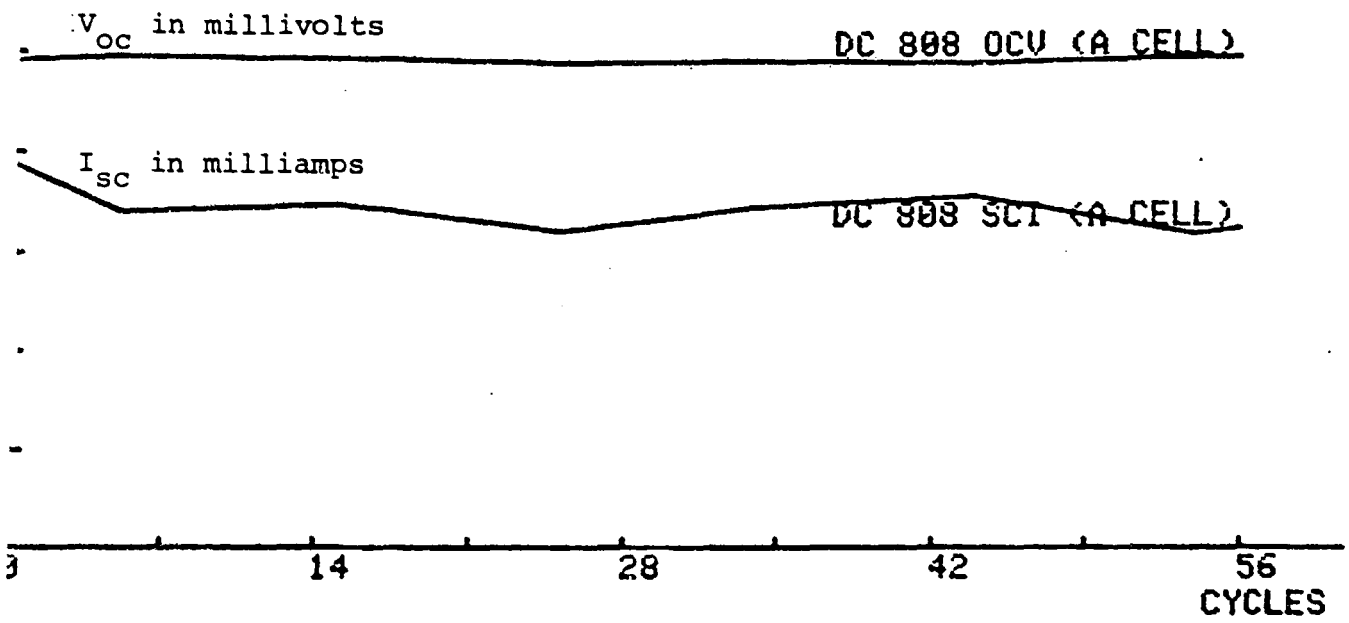


FIGURE 16

TEMP/HUMIDITY PANELS (GLASS SUPERSTRATE)



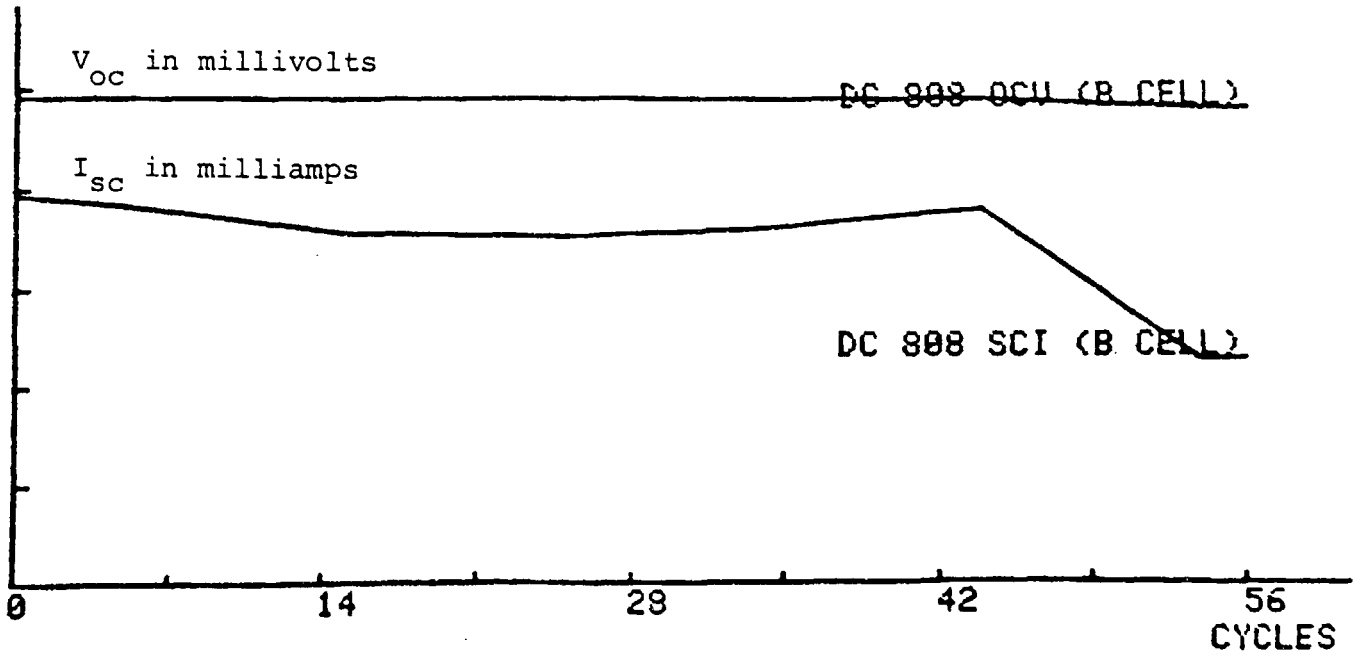
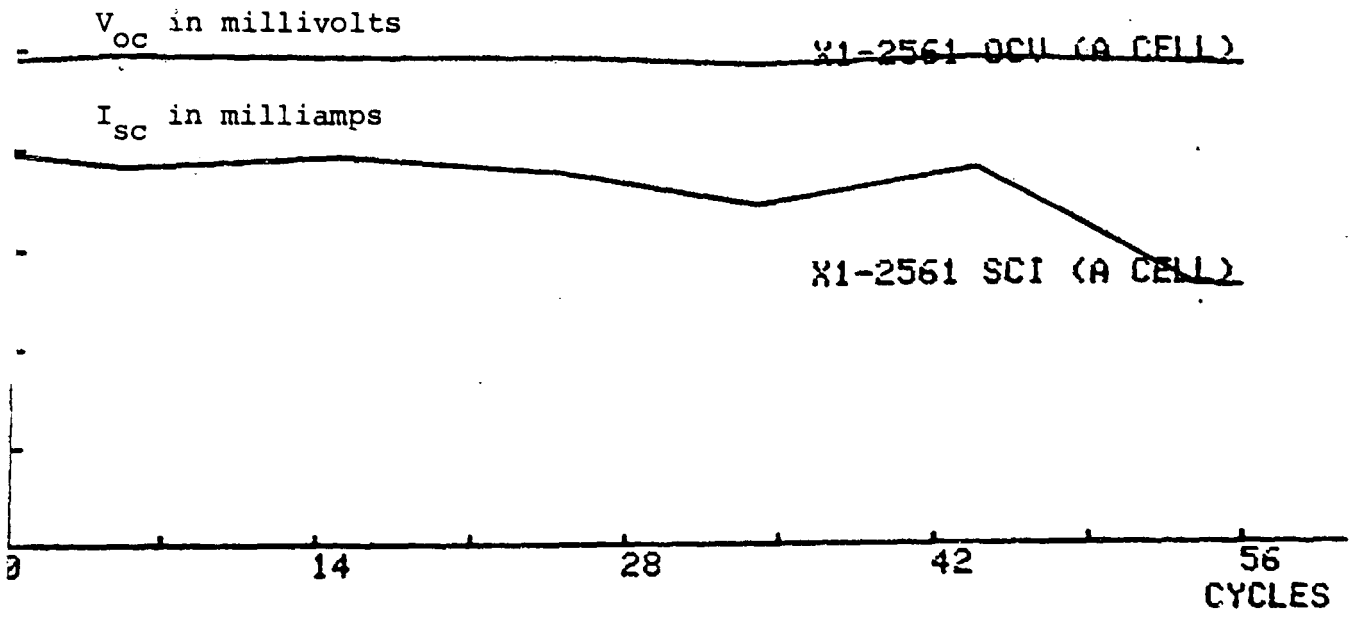


FIGURE 17

TEMP/ HUMIDITY PANELS (GLASS SUPERSTRATE)



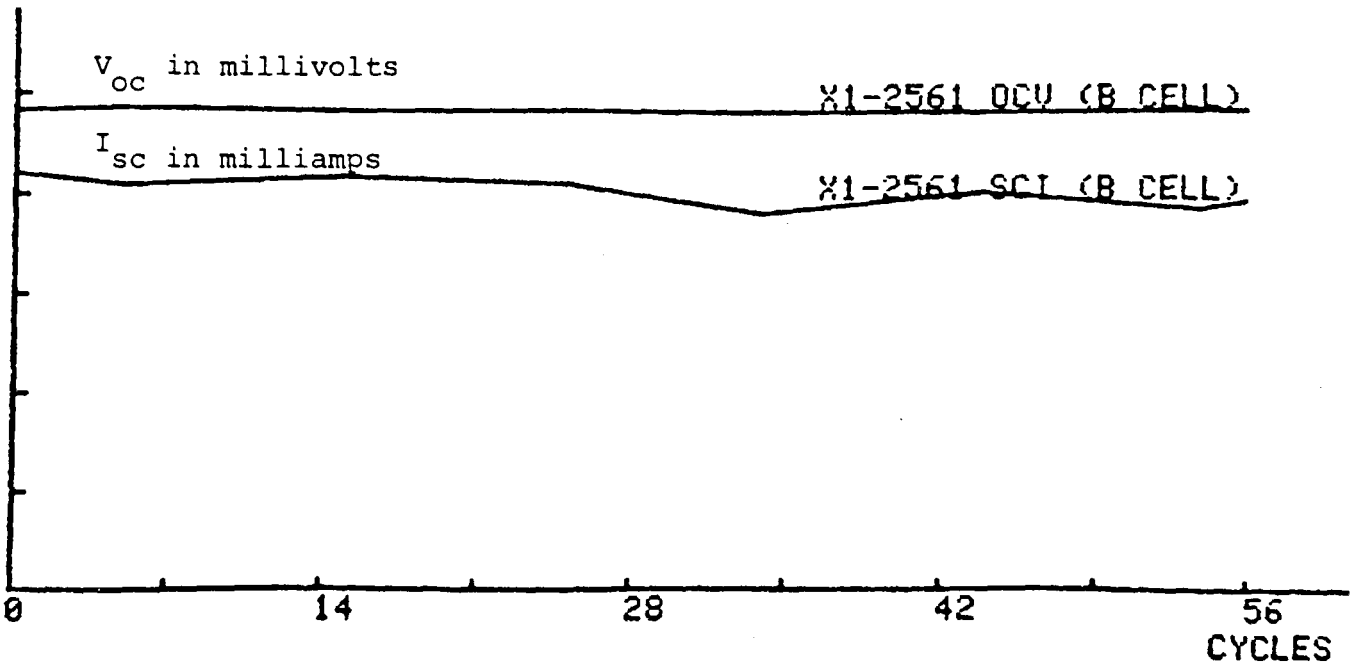
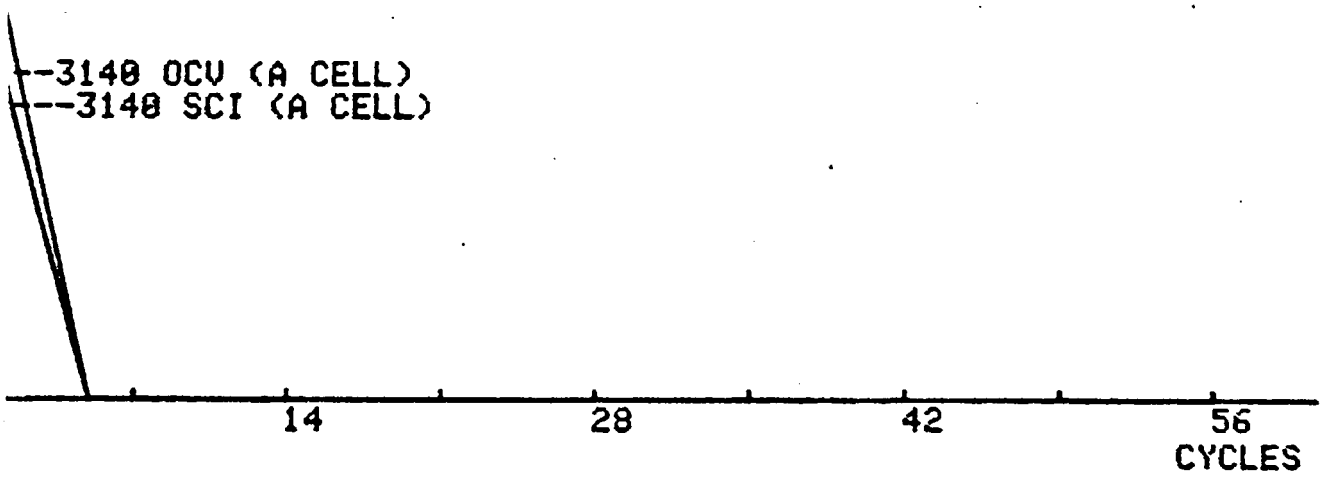


FIGURE 18

TEMP/ HUMIDITY PANELS (DORLUX SUBSTRATE)



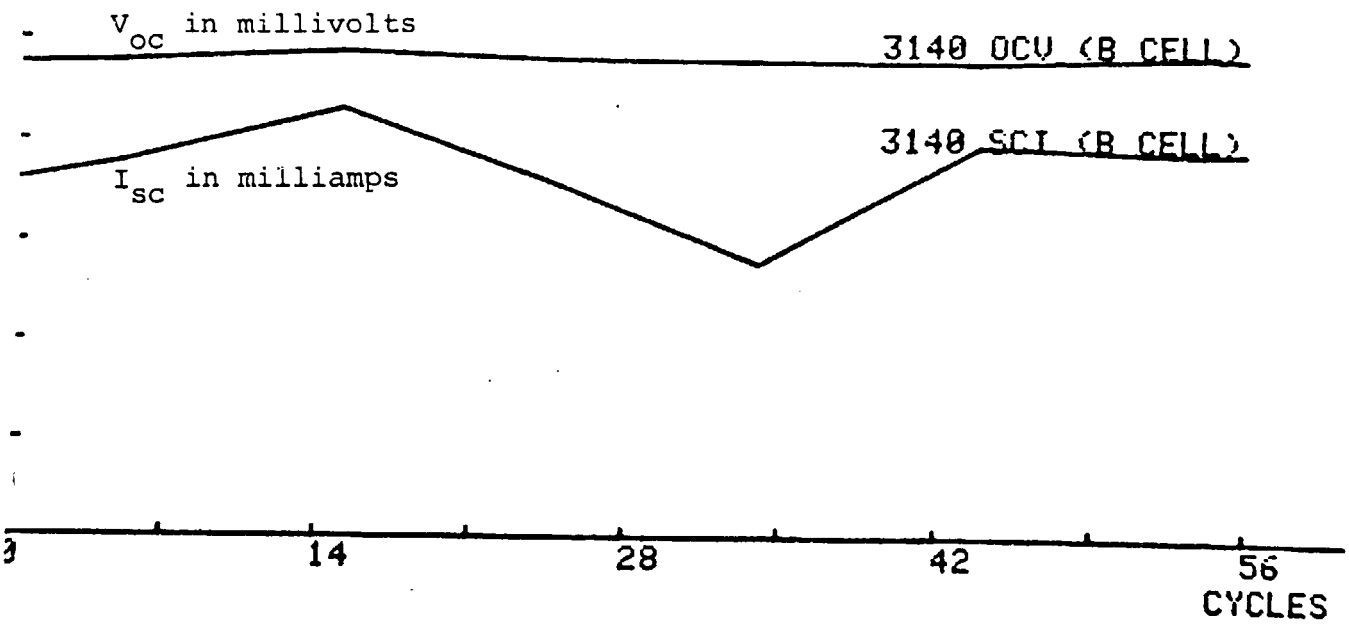
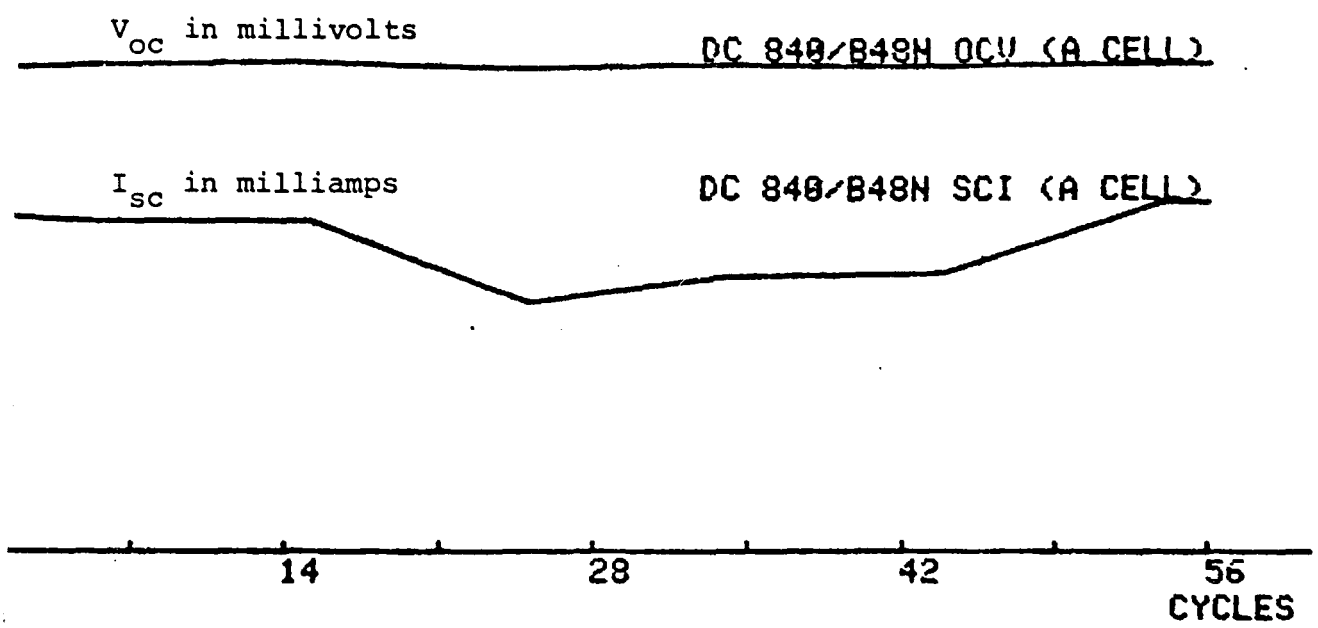


FIGURE 19

TEMP./ HUMIDITY PANELS (DORLUX SUBSTRATE)



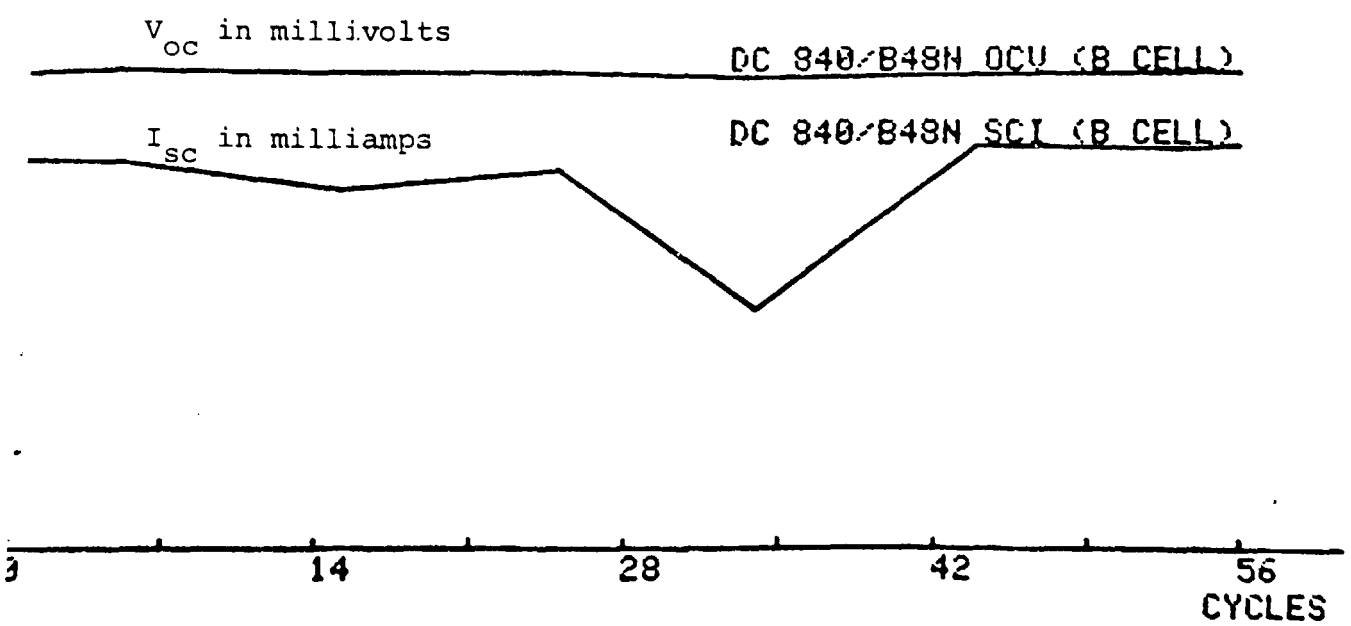
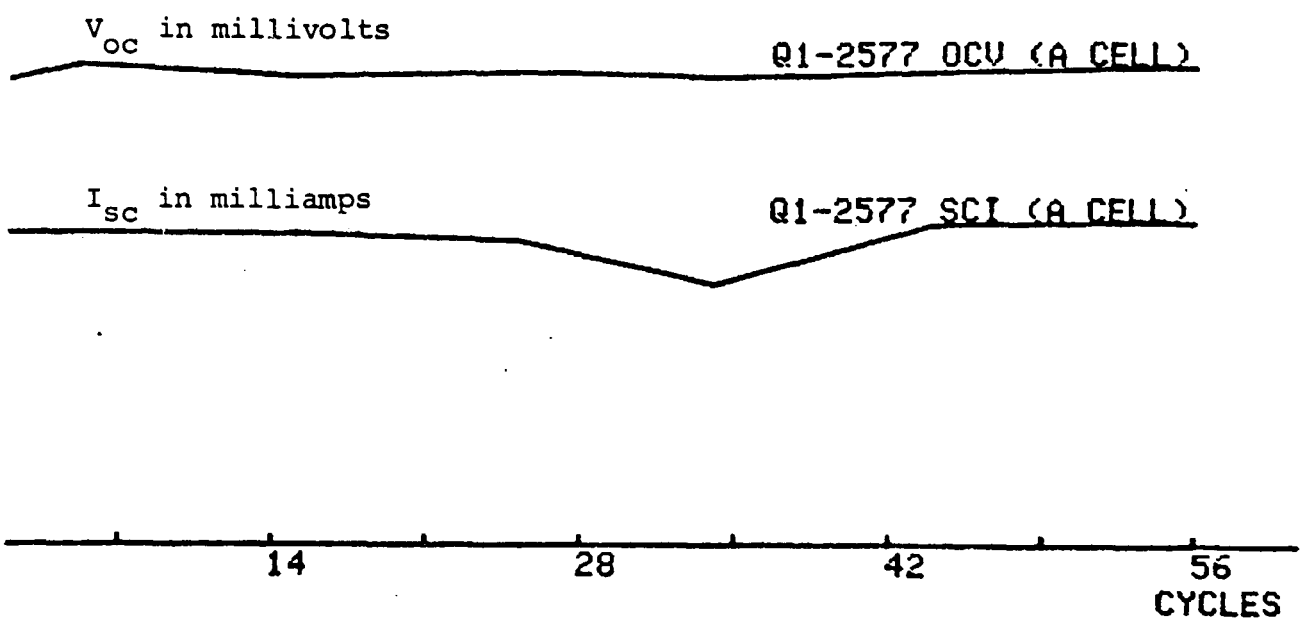


FIGURE 20

TEMP/ HUMIDITY PANELS (DORLUX SUBSTRATE)



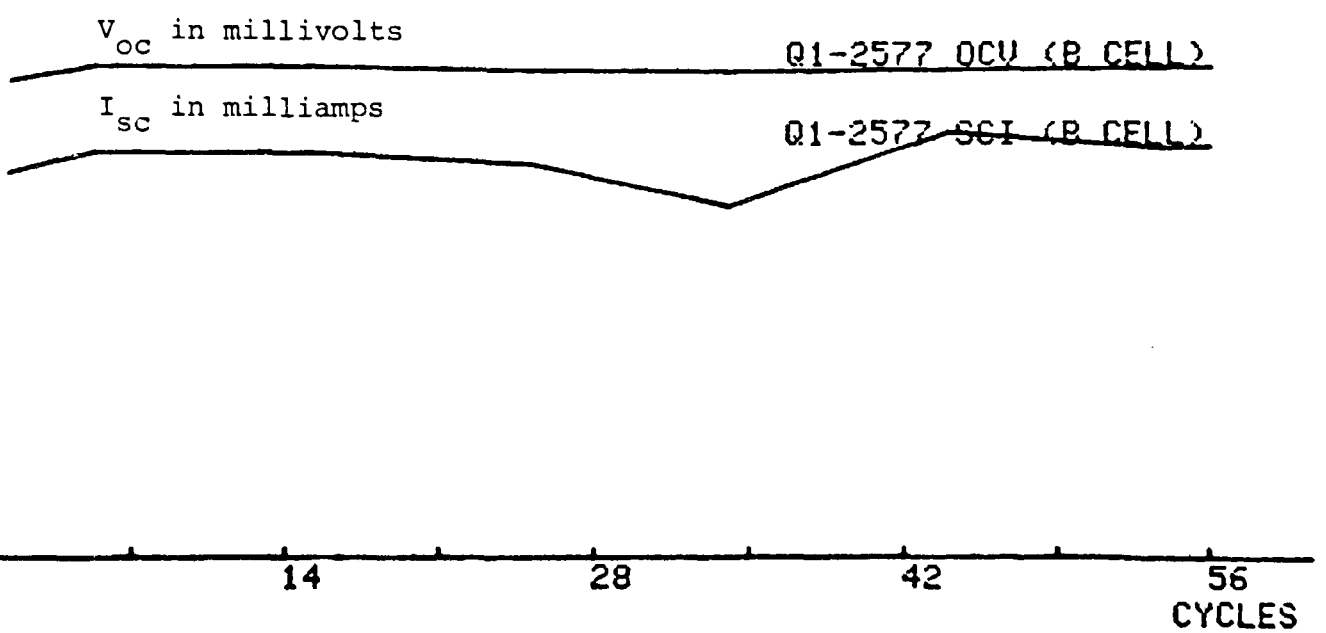
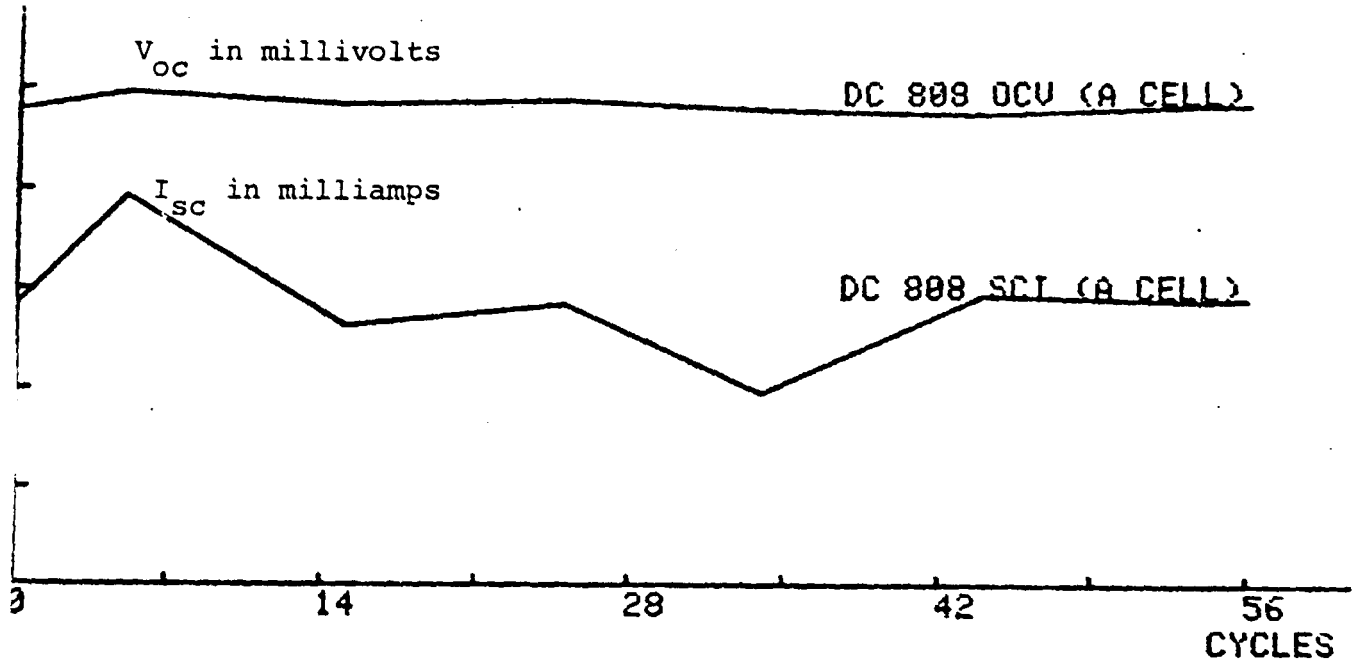


FIGURE 21

TEMP/ HUMIDITY PANELS (DORLUX SUBSTRATE)



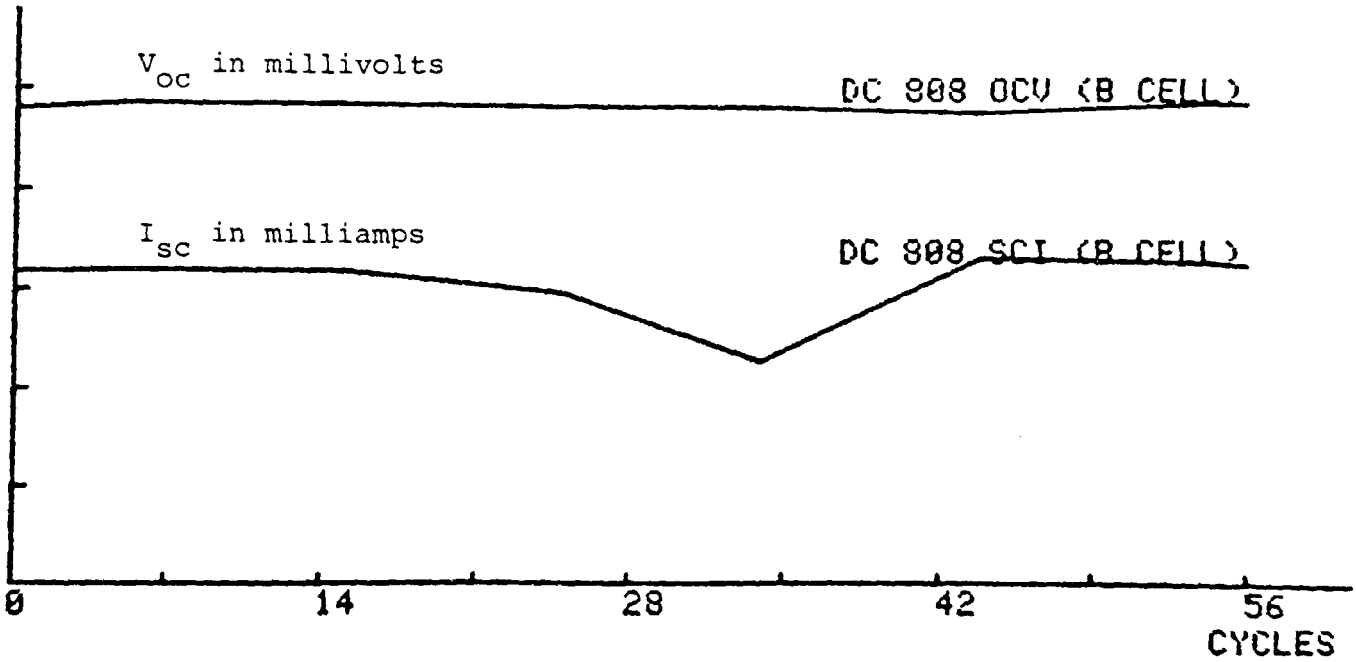
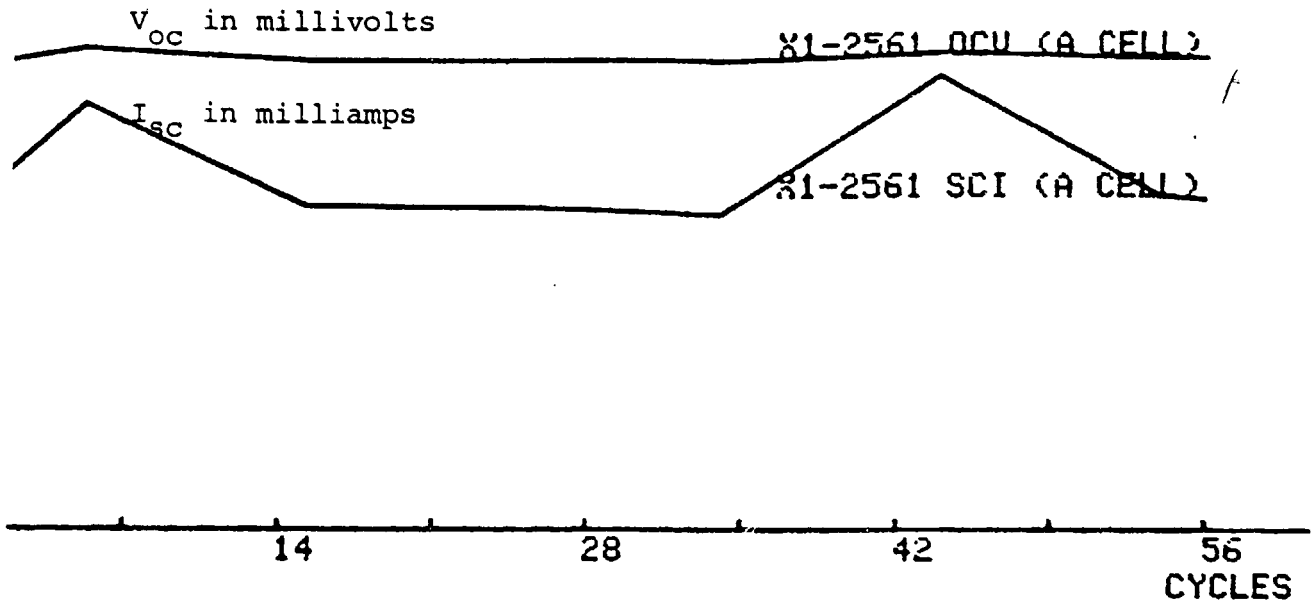
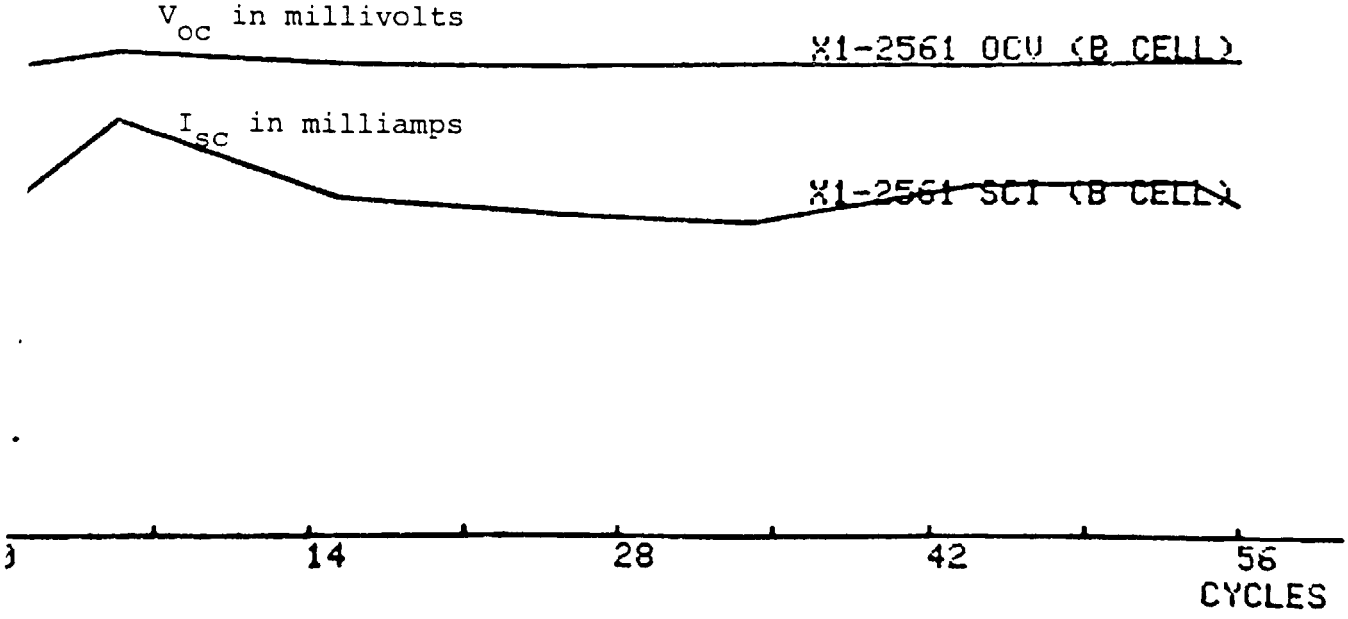


FIGURE 22

TEMP/ HUMIDITY PANELS (DORLUX SUBSTRATE)