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Final Technical Report for:

HERMETIC EDGE SEALING OF PHOTOVOLTAIC MODULES

Contract No. DOE/JPL 956352

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ABSTRACT

This final report covers work done from November, 1982, through June, 1983, on a program entitled "Hermetic Edge Sealing of Photovoltaic Modules."

The program objective was to investigate the feasibility of using an electrostatic bonding (ESB) and ultrasonic welding process to produce hermetic edge seals on terrestrial solar cell modules. The fabrication sequence is to attach an aluminum foil "gasket" to the perimeter of a glass sheet. A cell circuit is next encapsulated inside the gasket, and its aluminum foil back cover is seam welded ultrasonically to the gasket.

An ESB process for sealing aluminum to glass was developed in an ambient air atmosphere, which eliminates the requirement for a vacuum or pressure vessel. An ultrasonic seam welding process was also developed which did not degrade the quality of the ESB seal. Good quality welds with minimal deformation were produced.

The effectiveness of the above described sealing techniques was tested by constructing 20 x 20 cm^2 (8 x 8 in^2) sample modules, and then subjecting them to nondestructive fine and gross leak tests. The gross leak tests identified several different causes of leaks which were then eliminated by modifying the assembly process.

This program has been successful in demonstrating the technical feasibility of producing hermetically sealed edges on photovoltaic modules using a combination of ESB and ultrasonic welding.

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SECTION 1
INTRODUCTION

The DOE Photovoltaic Energy Technology Division's "Five Year Research Plan" has set as one of its technical objectives to "develop methods for improving (flat plate module) life expectancy beyond 10 years to approximately 30 years."(1) A promising approach for increasing module lifetime is to provide a hermetic package for the module components. Such a package would prevent corrosive agents in the atmosphere (especially water vapor and oxygen) from infiltrating the module. Module damage and subsequent degradation due to such infiltration could then be prevented.

Current module designs which are least permeable include glass superstrate/metal foil back cover designs and glass superstrate/glass back cover designs. None of these designs, however, are hermetic at the edges where the superstrate meets the back cover.

Spire Corporation has proposed and investigated (under this DOE/JPL contract) an innovative method for producing truly hermetic photovoltaic module edge seals. This method is summarized by the following process steps:

1. Bond an aluminum foil gasket to the perimeter of a glass sheet by electrostatic bonding. This glass sheet will become the module superstrate.
2. Encapsulate a solar cell circuit behind the glass using a standard lamination or casting process.
3. Bond the back cover, made of aluminum foil, to the foil gasket by ultrasonic seam welding.

The three tasks of this program are:

1. Experimentally develop an electrostatic bonding technique for bonding aluminum foil to glass sheet in air at atmospheric pressure.
2. Experimentally develop an ultrasonic bonding technique to bond aluminum foil to aluminum foil to complete the hermetic edge seal of a photovoltaic module.
3. Demonstrate the effectiveness of the above stated techniques by fabricating a small number of dummy modules and testing them for hermeticity using helium leak testing methods. Methods for non-destructive testing shall be investigated.

SECTION 2
TECHNICAL DISCUSSION

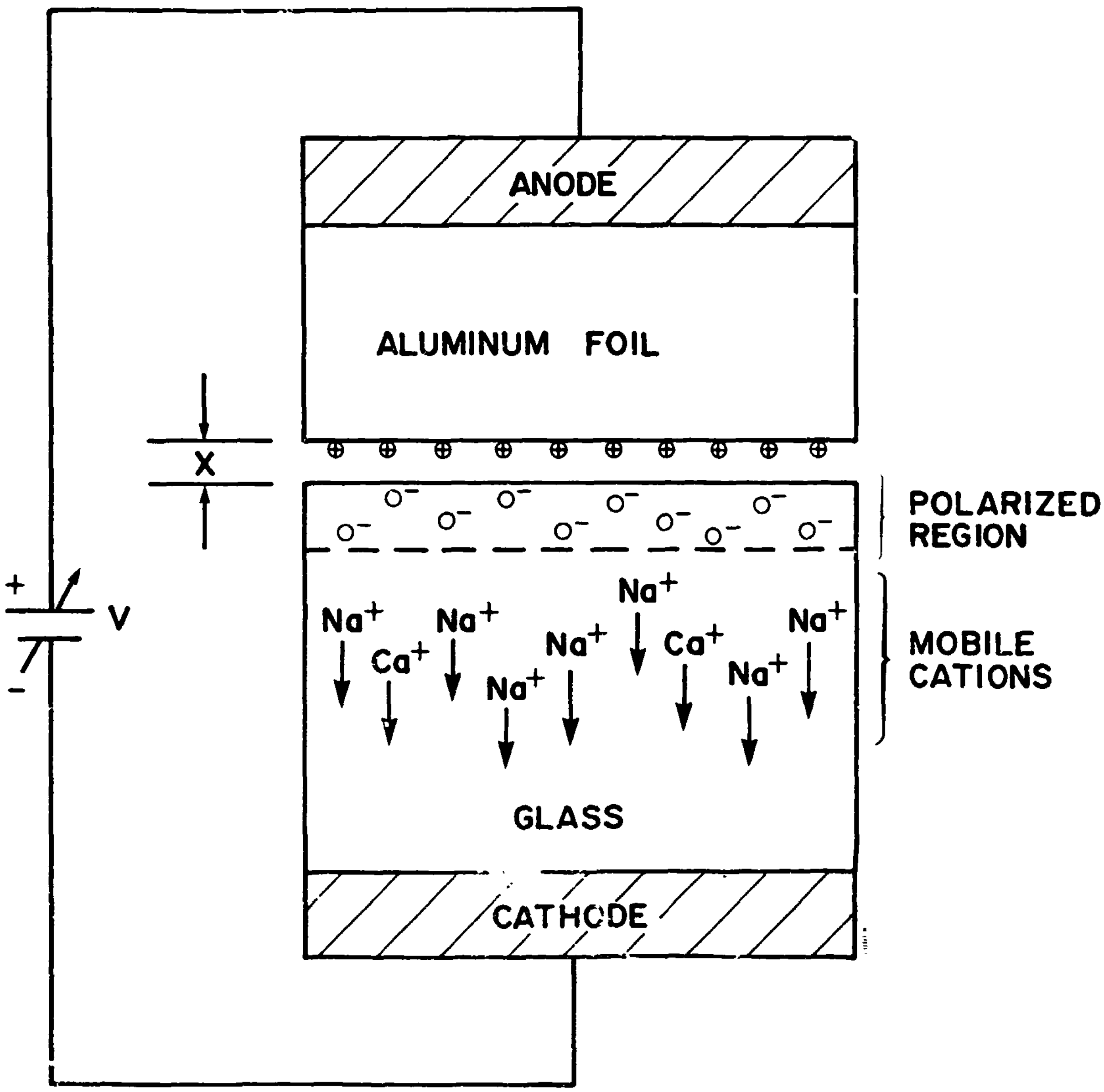
2.1 ELECTROSTATIC BONDING TECHNIQUE

2.1.1 Background

Electrostatic Bonding (ESB) is a field-assisted sealing technique with general applicability to joining glass to conductors, semiconductors and insulators.[2,3] This process permits sealing at temperatures well below the softening point of glass. As an example, a sodium borosilicate glass (Corning 7052) has been sealed to an iron-nickel-cobolt alloy at 480°C, while the conventional sealing temperature for this pair is 1100°C.[4]

To visualize the process sequence and requirements, consider the bonding of a soda-lime-silicate (window) glass plate to an aluminum foil, as shown in Figure 1. The pair is heated to a temperature at which alkali oxides (Na_2O, CaO, etc.) thermally dissociate. A high voltage, V, is applied such that the metal is positive with respect to the glass. Positively charged alkali ions, which are fairly mobile, are moved away from the glass-metal interface. This leaves a thin polarized region of less mobile negatively charged oxygen ions.

Initially, contact between the glass and metal occurs at only a few locations due to the surface roughness of the materials. Adjacent to points of contact the applied voltage appears across the gap, x, between the glass and metal. The electrostatic force in the gap is proportional to V^2/x^2. Thus, for small gaps, a strong electrostatic force will close the gap, starting at points of contact and spreading across the interface. As contact area increases, the polarized region spreads. The region is approximately a few micrometers deep, and when the gap is zero, the electrostatic field may be as high as 10^6 V/cm. Free oxygen ions in the polarized region are believed to chemically bond to the metal, forming a thin metal oxide at the interface. This assumption is supported by the observation that the strength of the seal assembly as well as its failure mode are similar to those of conventional fusion seals.[3]



- BONDING FORCE $\sim \frac{V^2}{X^2}$
- CHEMICAL BOND: Al_2O_3

FIGURE 1. ELECTROSTATIC BONDING PROCESS
(Aluminum and soda-lime-silicate glass used as an example.)

2.1.2 Investigations

The first part of the ESB investigation was to choose the proper materials for bonding an aluminum foil gasket to a glass superstrate. Annealed soda-lime-silicate float (common window) glass was chosen for a variety of reasons, including its availability, high degree of surface smoothness and high alkali ion content. A pure aluminum alloy, 1100-0, was chosen for its soft temper and low yield strength, factors which minimize residual stress at the post-bond glass-aluminum interface. More information concerning these materials choices is given in a previous report.(5)

Suitable graphite electrodes were fabricated for bonding aluminum foil gaskets to the perimeter of 20.3 cm x 20.3 cm (8.0 in. x 8.0 in.) glass. The aluminum was cut in a picture frame geometry, with a 20.0 cm outside dimension and a 19.4 cm inside dimension. The aluminum thickness was chosen to be 51 micrometer (2 mil) because it is rugged enough to survive ultrasonic welding, yet not so thick as to generate excessive stress at the ESB interface. A glass thickness of 3.2 mm (1/8 inch) was selected since it is the most commonly used thickness for photovoltaic module superstrates.

A range of ESB experiments was conducted, aimed at developing a bonding process in air at atmospheric pressure. Similar aluminum foil-glass bonding had been carried out at Spire in a program to develop hermetically sealed thermal pane windows(6), but these bonds were done in a vacuum environment. The development of this process in air is important because it allows for a great simplification of bonding apparatus. The baseline bonding cycle, showing the applied pressure and voltage and the resulting induced ionic current flow, is shown in Figure 2. The bonds produced under these conditions had excellent adhesion, but a large number of small air pockets, on the order of 1 mm diameter, were trapped between the aluminum and the glass.

A series of experiments was undertaken to eliminate the air entrapment problem. Process parameters such as pressure, applied voltage, temperature and time were varied but with no significant improvement. At this time, it was realized that the aluminum had a "shiny" side and a "dull" side, and that the difference in its reflective property was probably due to a variation in surface roughness. This was verified by measurement with a surface profilometer. As shown in Figure 3, the smooth (shiny) side has peak to peak heights less than .15 μm, while the rough side has features as large as 1.35 μm, peak

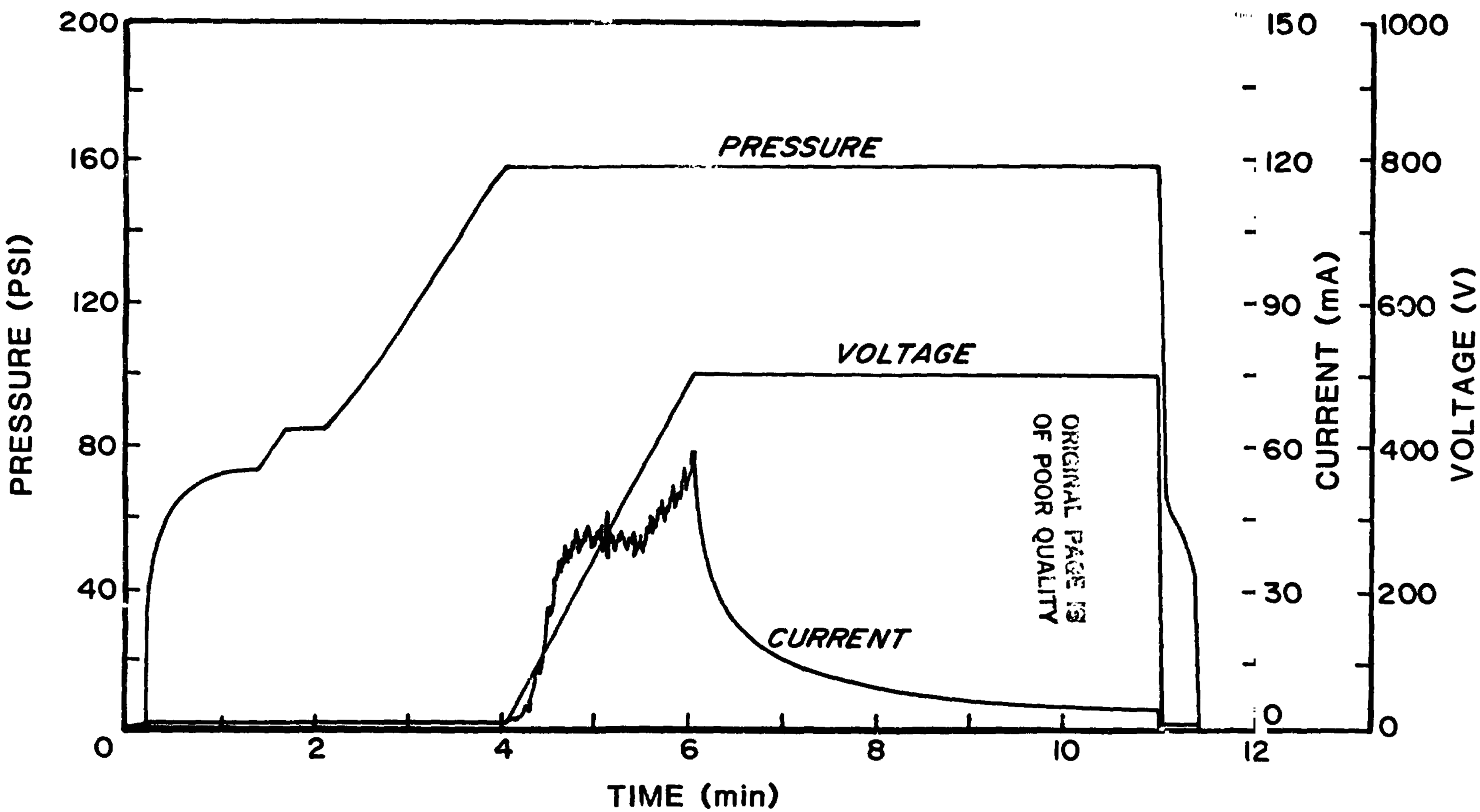


FIGURE 2. BASELINE ESB CYCLE. T=350°C

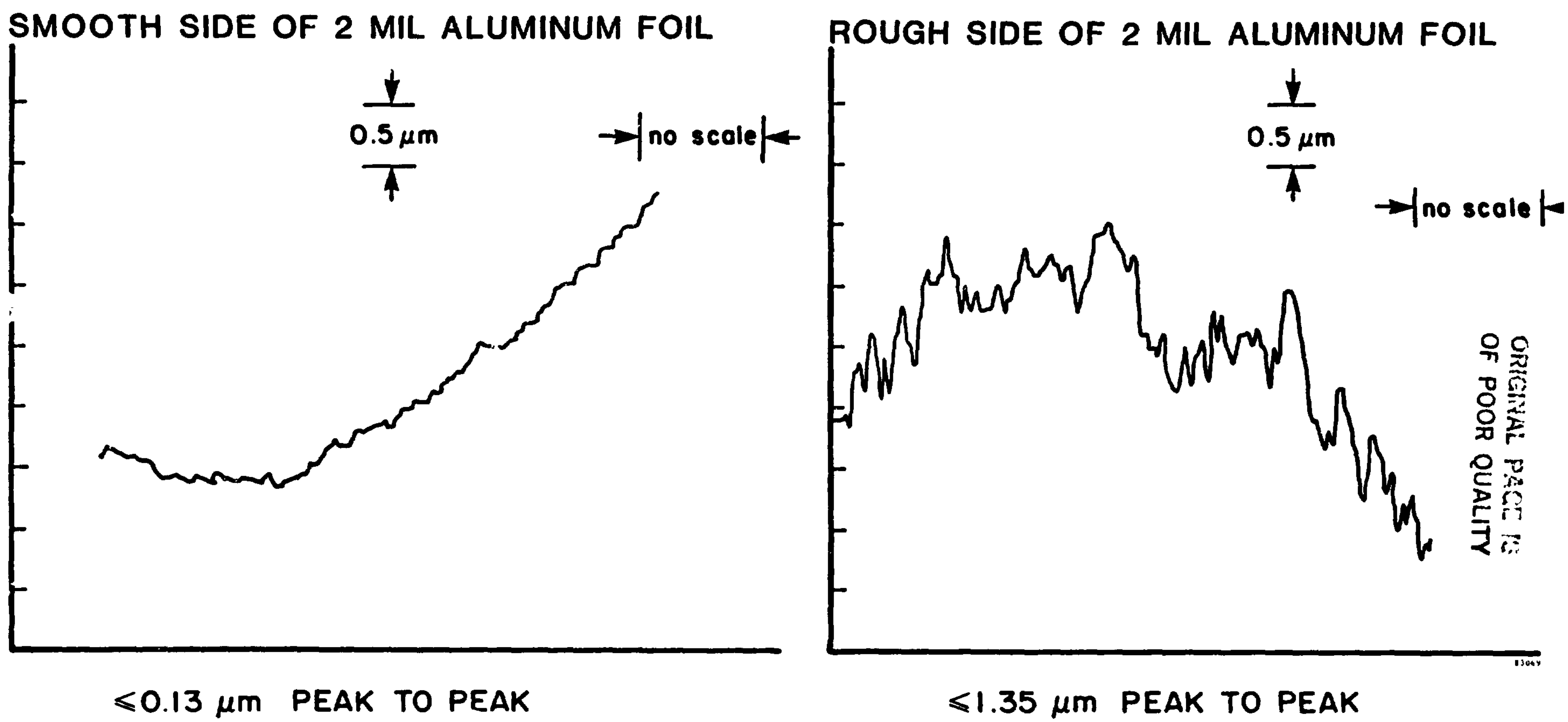


FIGURE 3. ALUMINUM FOIL SURFACE SMOOTHNESS

to peak. Inspection of the bonding experiments up to that time revealed that the more reflective, smooth side had been bonded to the glass, in all cases. The first experiment in bonding the rough side resulted in complete elimination of all trapped air pockets. The adhesion of the bond was qualitatively good, but not as strong as the bonded regions of the smooth aluminum foil bonds.

An explanation for the reduction in bond adhesion of the air pocket-free bonds was deduced from examination of the bonds under moderate (52X) magnification. Figure 4 shows two photomicrographs of aluminum foil-glass interfaces, as seen through the glass. The top picture shows a typical interface created by bonding the 0.1 micrometer smooth foil to glass in air. Although there are a number of air pockets present, the region between pockets is extremely well bonded. In contrast, the bottom picture in Figure 4 shows a post-bond interface between 1 micrometer smooth foil and glass. The light areas are regions of good bonding, while the dark areas are unbonded. Although there are no air pockets, it is seen that the rougher surface foil has less percentage of total area bonded than the inter-bubble regions of the smooth foil, which results in the observed reduction in foil adhesion to glass. There is probably an optimum surface roughness, between 1.0 and 0.1 micrometers peak to peak, at which a maximum bonded area is achieved without leading to the entrapment of air in pockets.

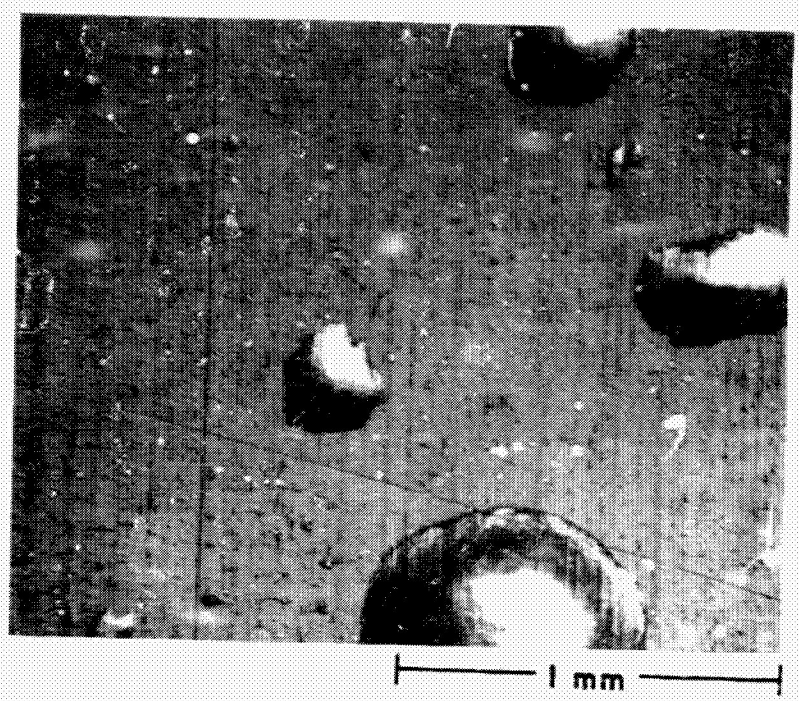
As mentioned briefly above, there was no significant improvement to the bond quality by varying the process parameters. Consequently, the parameters have not been modified substantially from the baseline cycle illustrated in Figure 2.

The applied hydraulic ram pressure has been increased from 150 psi to 250 psi better bond uniformity. These ram pressures translate to electrode contact pressure . the bond of 27.8 psi and 60.4 psi, respectively.

Voltages higher than 500 V were found to cause arcing across the edge of the glass due to the geometry of the process, and the ambient air environment. Thus 500 V is a good peak voltage level.

Several methods which reduce bonding time have been incorporated into the process sequence. The five minute dwell time that peak voltage was applied in the baseline (Figure 2) case was determined to be conservative, since the induced current flow decays sharply once the peak voltage is obtained. The peak voltage dwell time has therefore been reduced to one minute. Similarly, the rate of the applied voltage (dV/dt) has been increased from 250 V/minute to 500 V/minute. These changes have led to a total reduction in cycle time of 5 minutes. A plot of the new, optimized ESB cycle is shown in Figure 5.

Smooth Surface, 2 mil Aluminum Foil



Rough Surface, 2 mil Aluminum Foil

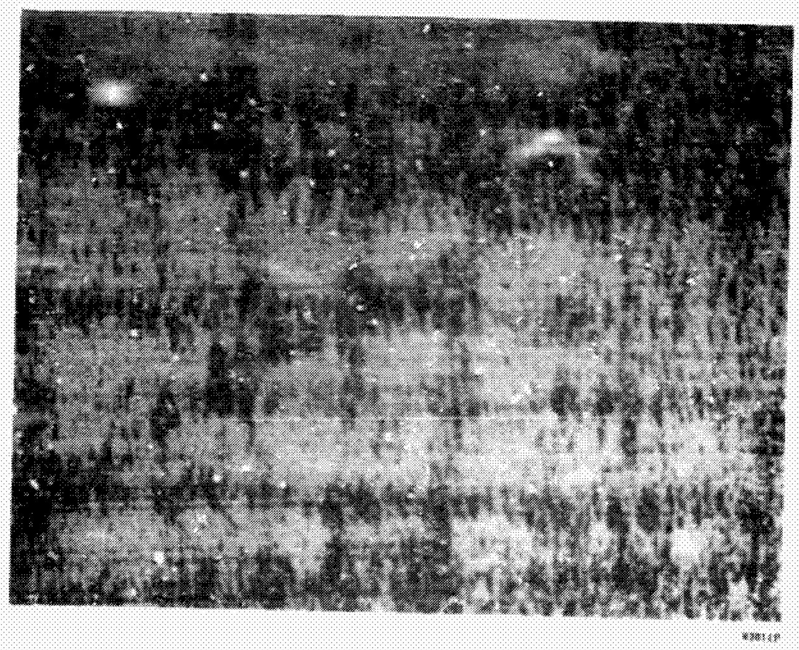


FIGURE 4. PHOTOMICROGRAPHS OF ALUMINUM FOIL BONDED TO GLASS BY ESB. Views are of the foil-glass interface as seen through the glass. Magnification is 52X for both views.

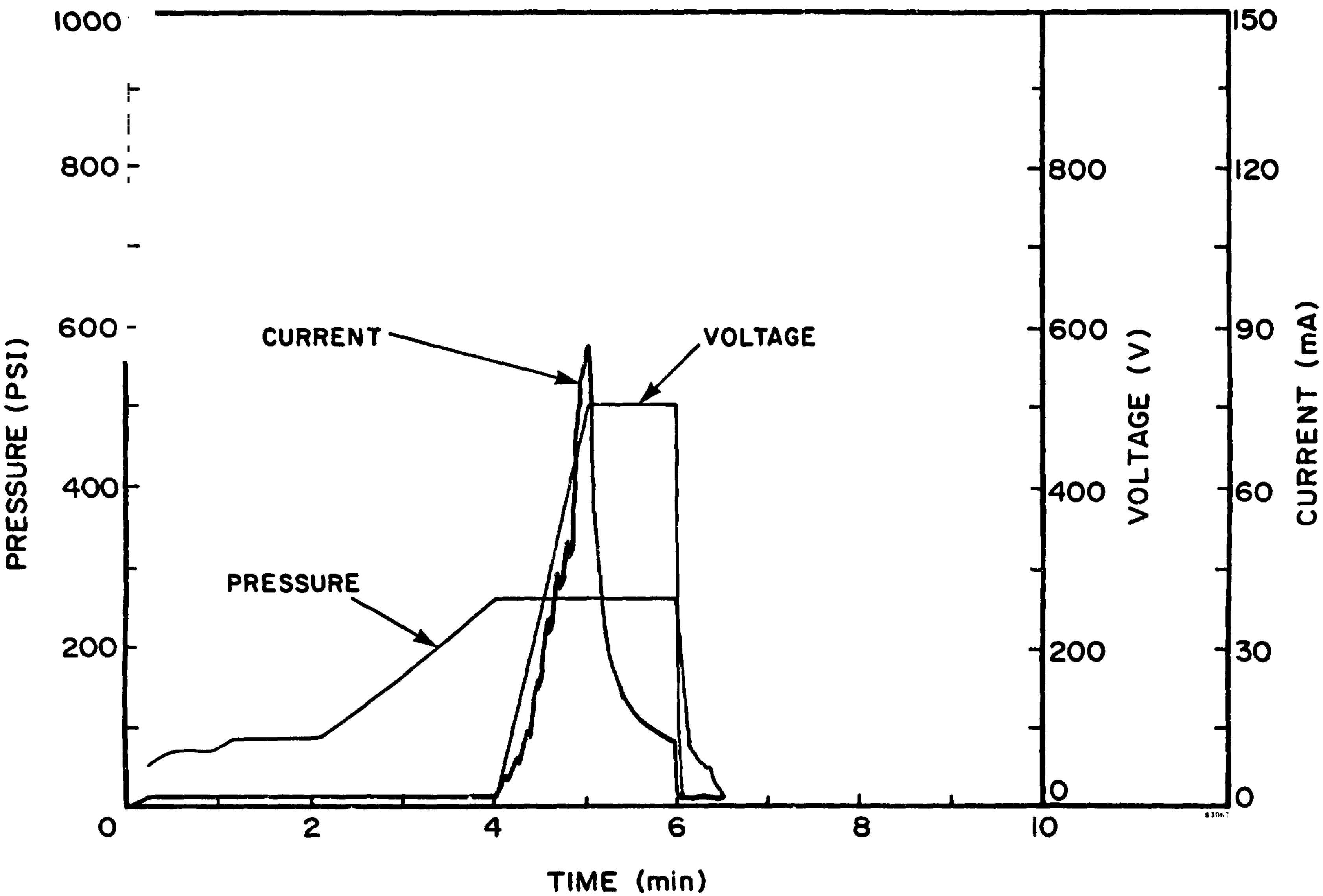


FIGURE 5. OPTIMIZED ESB CYCLE. T=350oC.

2.1.3 Roller Bonding Experiments

The ESB experiments discussed in section 2.1.2 were done using Spire's research electrostatic bonder. This equipment uses fixed parallel plate electrodes for doing bonds up to 20.3 cm (8.0 inch) square. It is recognized that such an arrangement is not economically scalable for large area (e.g. meter square) modules. An alternate, simpler technique is to bond with a rotating disk electrode. Such an arrangement can be used to bond aluminum ribbons to glass edges independently of glass size. A properly designed disk mounting system could also accommodate glass waves and variations in glass thickness. A further advantage is that bonding with a rotating electrode should prevent air pocket formation when bonding smooth surfaces, since bonding should occur along a progressive front.

A crude experimental version of such a bonder was assembled to determine if such a technique is feasible. Adherent electrostatic bonds were achieved on both the rough and smooth sides of the 51 micrometer thick foils. The bonded interfaces were essentially similar to those shown in the photomicrographs in Figure 4. Results were, however, less reproducible than the fixed electrode results for several reasons, including, the lack of control of the roller's traversing speed, the lack of a roller electrode of the proper geometry, poor alignment and poor vertical force control between the roller electrode and the aluminum ribbon. Despite these equipment limitations, the experiment did prove the feasibility of bonding using the rolling electrode approach.

2.2 ULTRASONIC BONDING TECHNIQUE

This technique is used for welding a module back cover, made of aluminum foil, to the aluminum foil gasket which is electrostatically bonded to the glass superstrate. The two foils are joined by high-frequency (50 KHz) mechanical vibration which causes local plastic deformation at the weld interface. Moisture, organic and oxide films are dispersed and an area of nascent metal contact is formed without temperatures required for melting.

The welding head assembly was mounted on linear bearing pillow blocks on shafts and is driven by a rack and pinion assembly which simultaneously translates and rotates the disk shaped welding tip. The pinion pitch diameter is matched to the welding tip diameter to prevent slippage between the tip and the work. A motor drives the weld tip and pinion rotation, and a variac is used for speed control. Vertical force is provided by an air cylinder which is also used to lift the weld tip away from the work. Ultrasonic power is adjusted with a 10 turn potentiometer on the power supply.

The first welding experiments were done at the maximum translational speed of 284 cm/minute and a vertical force of 3.6 kg. Weld power (rated at 100 watts into an 8 ohm load) was varied from 20% up to 100%. Even full power was found to be insufficient for adherent welds between 2 layers of 51 μm thick aluminum foil. The speed was then reduced to 208 cm/minute. The foils were found to be separable but beginning to adhere at 50% power. At 70% power the weld quality was excellent at the center of the weld, but occasionally burned through the foil at the weld edge. At 65% power the welds were still of excellent quality — the foils could not be separated at the weld, and the foils were not being damaged. Thus the conditions of 208 cm/minute traversing speed, 3.6 kg vertical force and 65% weld power were used for fabricating the first dummy modules.

It was later found necessary to reduce the weld power when gross leak tests indicated the welds had occasional microscopic pinholes on the inside edge of the weld. The frequency of pinholes was on the order of 2 per module, or about 1 pinhole per 40 cm. When the weld power was reduced from 65% to 50% the pinholes were eliminated.

Unlike the pre-module experiments, 50% power seems to be high enough for good welds. The pre-module experiments were done with foils taped to glass, rather than electrostatically bonded and laminated foils. Thus there is less damping of the ultrasonic frequencies and more efficient energy transfer.

2.3 DEMONSTRATION OF DEVELOPED TECHNIQUES

The effectiveness of the electrostatic bonding and ultrasonic welding techniques in providing a hermetic seal was investigated by fabricating a number of 20.3 cm (8 inch) square dummy modules and subjecting them to leak tests.

2.3.1 Dummy Module Fabrication

The dummy modules made for this task are of the glass superstrate, aluminum back cover design, as shown in Figure 6. The fabrication sequence was as follows:

1. Electrostatically bond an aluminum gasket to the glass superstrate. This is done first since encapsulants and solders used in modules cannot survive the ESB process temperature of 350°C.
2. Prime the glass inside the gasket to promote ethylene vinyl acetate (EVA) adhesion.
3. Lay up a stack of EVA sheet / solar cell / fiberglass scrim / EVA sheet / aluminum foil on top of the primed side of the glass. The EVA sheets and scrim were cut to the inside dimensions of the gasket (19.4 cm, 7-5/8 inch square), while the foil was cut to the glass dimensions (20.3 cm, 8 inch square).
4. Laminate the stack.
5. Weld the foil back cover to the foil gasket using the ultrasonic seam welder.

Figure 7 shows a dummy module glass superstrate before (top left) and after (top right) attaching the aluminum foil gasket by ESB. Also shown are the front view (bottom left) and back view (bottom right) of completed modules.

2.3.2 Leak Testing

MIL-STD-883B, Method 1014.4, Seal is a non-destructive test method for leak testing hermetically sealed packages. This standard was adopted to investigate the effectiveness of the edge sealing techniques developed during this program. The tracer gas (He) fine leak test (test condition A1) was used to measure fine leak rates, while the fluorocarbon gross leak test (test condition C) was used to detect the presence of gross leaks.

The helium fine leak test was done by pressurizing the module at 60 psig in 95%-100% He for 2 hours. The module was then placed in a vacuum chamber connected to a mass spectrometer leak detector. The reject limit for packages with volumes V ≥ 0.40 cc is 2×10^{-7} atm cc/sec He.

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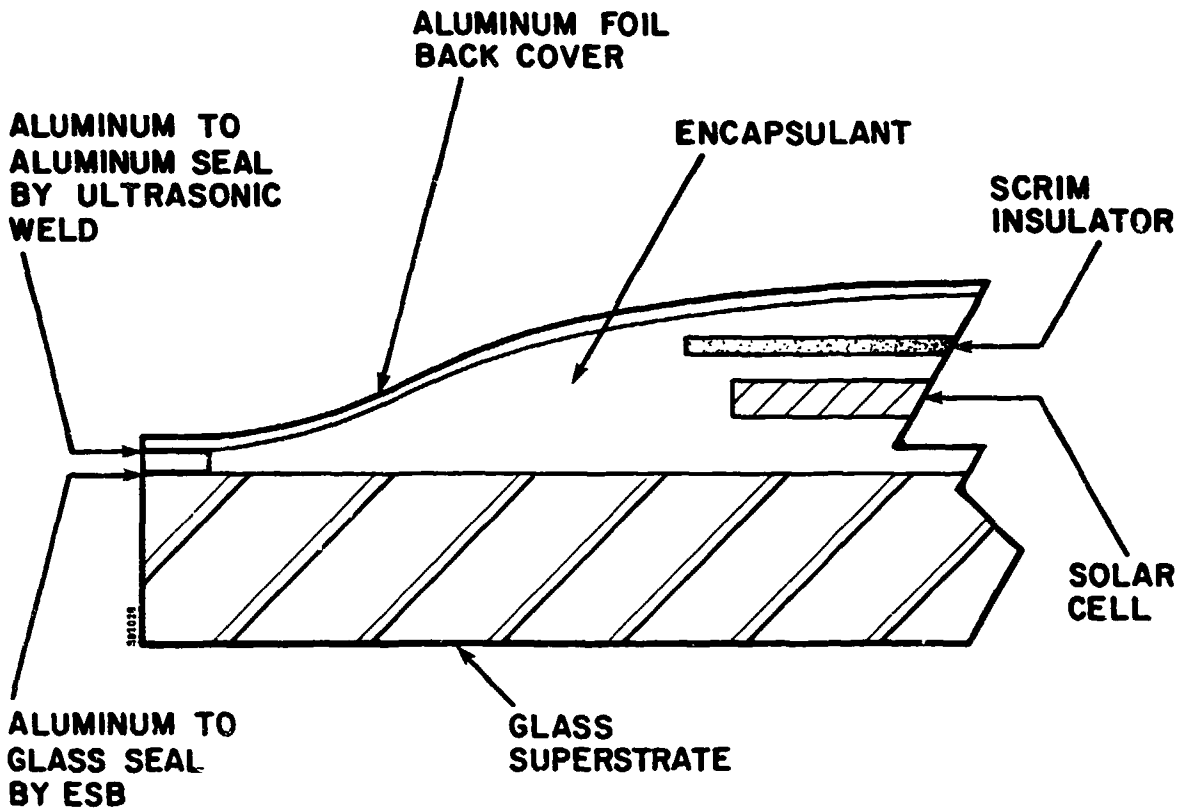

FIGURE 6. GLASS SUPERSTRATE DESIGN MODULE WITH ALUMINUM FOIL BACK COVER AND HERMETIC EDGE SEAL

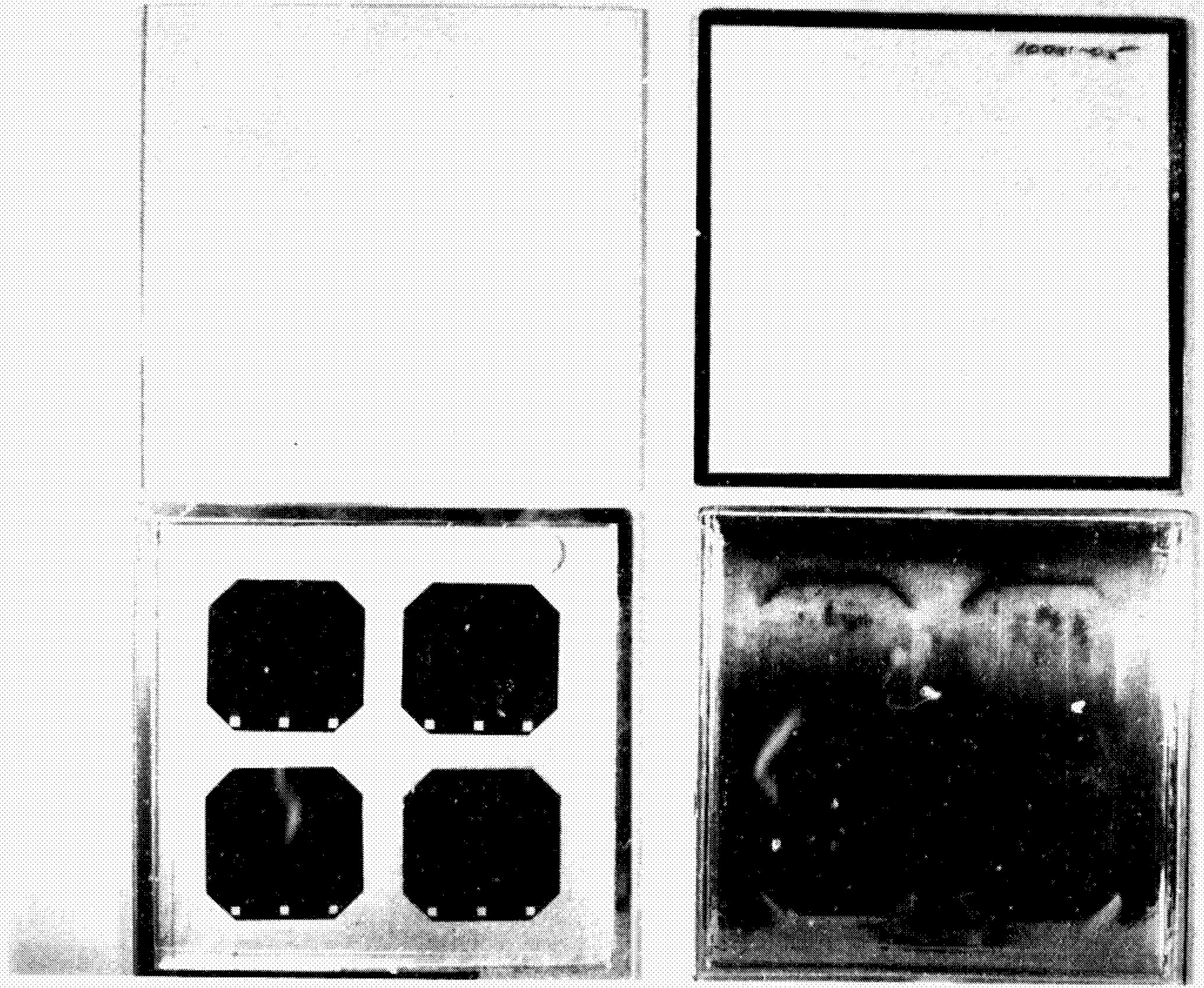

FIGURE 7. HERMETIC SEALING OF DUMMY PHOTOVOLTAIC MODULES

The fluorocarbon gross leak test was done by submerging the module under FC-72 detector fluid and pressurizing to 60 psig for 2 hours. The module was then removed from the detector fluid, allowed to dry for 2 minutes in air, immersed in FC-40 indicator fluid heated to 125°C, and observed for at least 30 seconds. The failure criterion is a definite stream of bubbles (gaseous detector fluid) or two or more large bubbles originating from the same point.

2.3.3 Results

The first group of dummy modules was layed up with the foil back cover folded back at the perimeter. This was done to prevent the EVA from squeezing between the back cover foil and the gasket foil, which would prevent the foil-to-foil seam weld in step 5 of the fabrication sequence. After lamination, the folded edges could then be unfolded back to the original, flat condition for welding. During gross leak testing it was discovered that the edge folding method caused pinholes in the foil at a large percentage (~50%) of the module corners, where two fold lines intersect. Thus the folding method was abandoned.

An improved method for preventing unwanted EVA flow over the foil gasket which worked successfully was suggested by Dale Burger (JPL Technical Manager for this contract). A reusable aluminum frame was fabricated with a similar shape as the foil gasket and a thickness (0.8 mm, .032 inch) about the same as the total EVA thickness (0.9 mm, .036 inch). This frame was placed over the unfolded aluminum foil back cover during lamination, as shown in Figure 8.

Not only does the frame solve the pinhole problem caused by intersecting folds, but there are other advantages as well. The fabrication sequence is simplified as the folding and unfolding operations are eliminated. Foil distortion due to unfolding is also eliminated, which makes the ultrasonic welding operation more uniform.

The second group of dummy modules was thus layed up with an unfolded aluminum foil back cover and the reusable frame, as in Figure 8. The first modules made in this manner also failed the fluorocarbon gross leak test. Pinhole leaks were discovered at a rate of about 2 per module, located on the inside edges of the ultrasonic seam welds. The weld power was then reduced from 65% to 50% of full power.

A third type of module was then fabricated, using the lay-up scheme of Figure 8 and a reduced ultrasonic welding power. This module successfully passed the fluorocarbon gross leak test.

Results of the helium fine leak tests are given in Table 1. All of the dummy modules (01 through 11) had gross leaks except number 26. Number 26 is also an order of magnitude less leaky to helium than the modules with gross leaks.

The helium leak rate of module 26, at 2.8 x 10^{-7} atm cc/sec, is slightly higher than the MIL-STD acceptance level of 2.0 x 10^{-7} atm cc/sec for packages with a volume greater than or equal to 0.40 cc. One should note, however, that the specification is written for integrated circuit packages whose volumes (or seal lengths) do not approach the volumes (or seal lengths) of the dummy modules tested. The dummy module volume is approximately .091 cm x 19 cm x 19 cm = 33 cc, or 82 times the minimum package volume with this leak rate acceptance level. A meaningful helium le . rate acceptance criterion can best come from a correlation of leak rates with module degradation observed as a result of environmental testing.

Table 1. Helium Fine Leak Test Results (MIL-STD 883B, Method 1014.4, Test Condition A1)

Serial Number	Leak Rate, R_1 (10^{-7} atm cc/sec He)
01	21
02	27
04	55
05	49
07	22
08	32
09	51
10	23
11	27
26	2.8

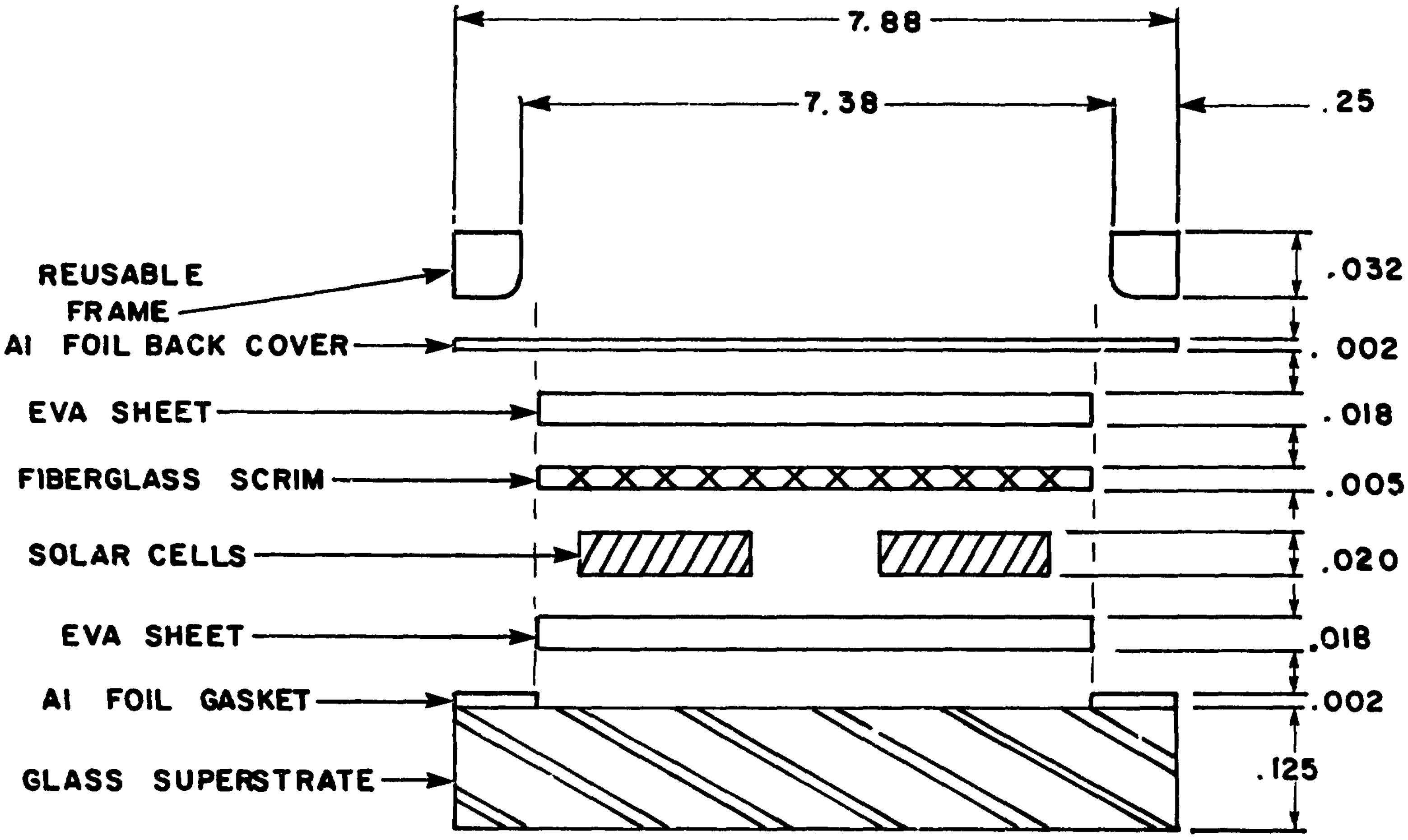

FIGURE 8. EXPLODED VIEW OF MODULE LAYUP WITH FRAME. Vertical dimensions exaggerated. Drawing not to scale. Dimensions in inches.

SECTION 3
CONCLUSIONS

The three tasks of this program have been completed. An aluminum foil to window glass electrostatic bonding technique has been developed in air at atmospheric pressure, which allows for simplification of the bonding apparatus. An ultrasonic seam welding technique for joining two aluminum foils has also been developed. The welding process does not damage the electrostatic bond which is prefabricated between one of the foils and the window glass. Sample modules were fabricated and tested for hermeticity using non-destructive helium (fine) and fluorocarbon (gross) leak test methods.

A number of iterations in the sample module assembly process was required to eliminate the causes of leaks in the module. A module has been assembled which passed the gross leak test. Although this module did not quite meet the acceptance limit of the fine leak test, the test criterion is designed for packages with much smaller volumes and seal lengths.

The program has demonstrated that it is technically feasible to produce hermetically sealed edges on photovoltaic modules using a combination of an electrostatic bond and an ultrasonic weld.

SECTION 4
RECOMMENDATIONS

Although this program has demonstrated the technical feasibility of an electrostatically bonded - ultrasonically welded hermetic edge seal, it is recognized that production quantities of large area photovoltaic modules cannot be economically manufactured by simply scaling the specific techniques used in this program. The major obstacle is the normal variation in glass thickness and flatness over long distances, which makes bonding with fixed parallel plate electrodes impractical. It is therefore recommended that research be conducted into more advanced bonding processes. A research plan with two main objectives is described below.

1. Rotating Electrode ESB

A technique which is insensitive to glass thickness variations is an electrostatic bonding method using a rotating disk electrode, described in Section 2.1.3. A system could be designed where glass and a ribbon of aluminum foil are fed under the rotating disk. Such a bonder would attach foils to glass edges independently of glass size.

Since material waste must be avoided, the aluminum foil must be supplied in ribbon form, rather than as picture frames cut from sheets. One must then solve the potential problem of leaks from a lap joint, as depicted in Figure 9. Since the aluminum is a ductile metal, in a soft annealed condition, and the bonding electrode contact area is very small under the disk, high pressures can easily be applied which may deform the aluminum sufficiently to create a continuous ESB seal. Process parameters such as vertical force, glass-aluminum feed rate, temperature, voltage and electrode geometry require investigation.

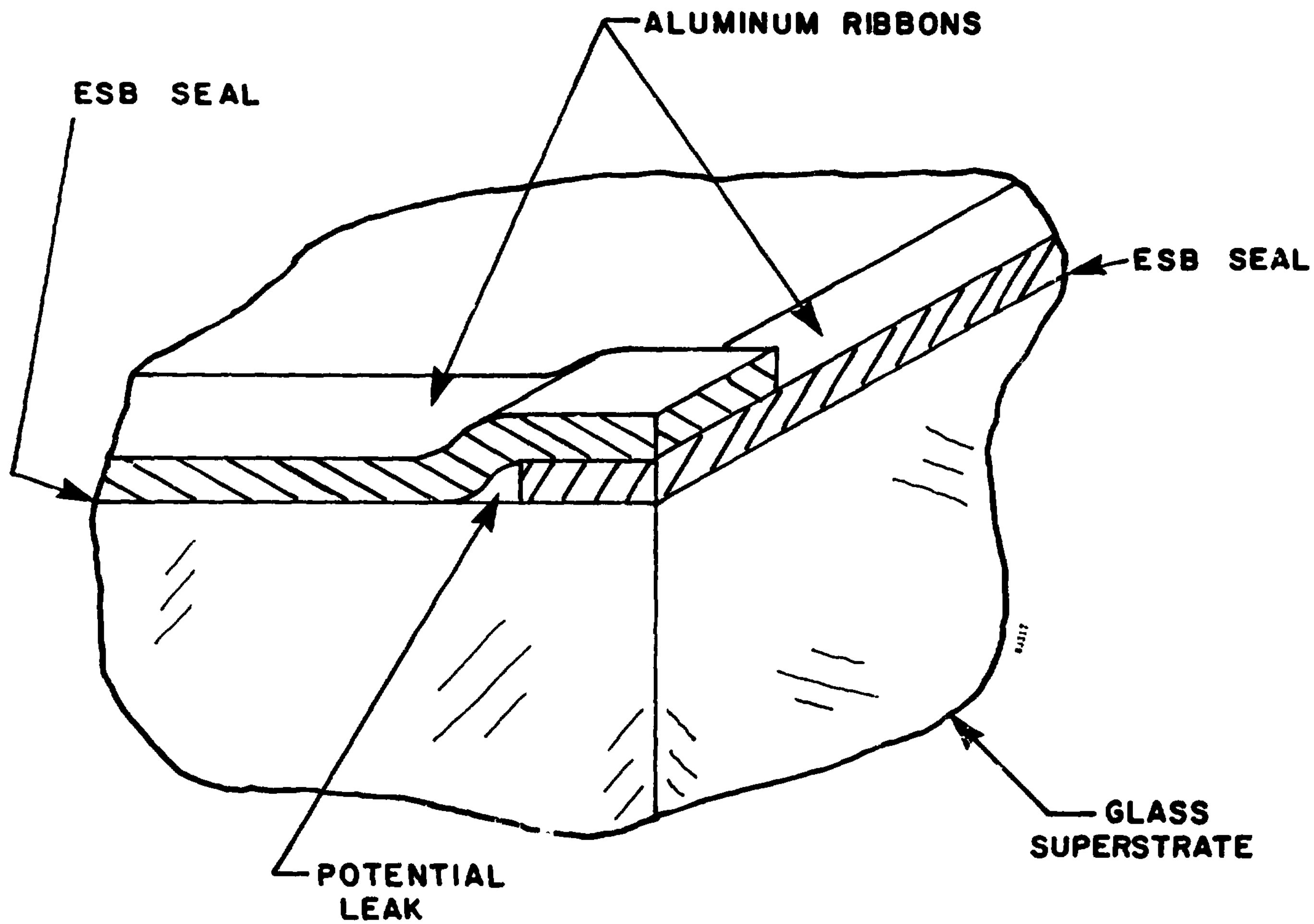

FIGURE 9. LAP JOINT BETWEEN TWO ALUMINUM

2. Shallow Zone Heating Applied to Rotating Electrode

Further improvements in regards to rotating disk electrostatic bonding would occur if a shallow, locally heated zone could be created at the bond site without damage to the glass. The glass bulk would remain at ambient temperature, resulting in simplified equipment design and reduced energy consumption. Of even greater importance is that the module's back cover foil could be bonded directly to the glass superstrate after module fabrication, eliminating the need for the aluminum foil ribbon, the ultrasonic welding step and the lap joint at the intersection of the ribbons. Process research concerning methods of creating shallow hot zones on the surface of a moving glass superstrate is required.

SECTION 5
ACKNOWLEDGMENT

The author is grateful for the many helpful comments and suggestions offered by Dale R. Burger, the JPL Technical Manager for this contract.

SECTION 6

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