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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE
PRODUCTION

MASTER

Task 4: Automated Array Assembly
Quarterly Report No. 1

By
John J. Hagerty

October 15, 1980

Work Performed Under Contract No. NAS-7-100-955699

MBAssociates
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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE PRODUCTION

TASK 4: AUTOMATED ARRAY ASSEMBLY

Quarterly Report No. 1

JPL Contract No. 955699

PREPARED BY: JOHN J. HAGERTY

15 October 1980

MB-R-80/23

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ABSTRACT

In the first quarter of this new program we have made substantial progress in several areas. The robot's end effector has been re-constructed using a new process that insures even coil depth. Solder paste dispensing has been improved by means of a manifold-type dispenser. Several new robot programming techniques have been employed to improve both positional laydown (cell-to-cell spacing) accuracy and rotational (lead alignment) accuracy. A new heating technique has been employed that eliminates solder and flux smear and also eliminates the cooling wait.

Also, we have concentrated on the design and initial construction of the Automated Lamination Station. This has resulted in the design, construction and initial testing of the vacuum platen, the design and a proof-of-principle mockup of the Lamination Preparation Station; and a design for the Automated Lamination Chamber.

1.0 INTRODUCTION

This is the first quarterly report under JPL contract No. 955699. It is a direct follow-on to JPL contract No. 954882 and therefore makes continuous reference to it. It is assumed that the reader is familiar with both the goals of and the hardware developed during that project.

The scope of work under this contract includes making improvements to the existing hardware (in order to reduce cycle time and improve the system capability) and developing new hardware to allow the robot to carry out the next steps in module manufacture.

Work has been broken into five phases. The first phase is to modify existing hardware and controlling computer software to:

- 1) improve cell-to-cell placement accuracy, 2) improve the solder joint while reducing the amount of solder and flux "smear" on the cell's surface, and 3) reduce the system cycle time to 10 seconds.

The second phase involves expanding the existing system's capabilities to be able to reject broken cells and make post-solder electrical tests.

Phase 3 involves developing new hardware to allow for the automated encapsulation of solar modules. This involves three discrete pieces of hardware: 1) a vacuum platen end effector for the robot which allows it to pick up the 1'x4' array of 35 inter-connected cells. With this, it can also pick up the cover glass and completed module. 2) a lamination preparation station which cuts the various encapsulation components from roll storage and positions them for encapsulation, and 3) an automated encapsulation chamber which interfaces with the above two and applies the heat and vacuum to cure the encapsulants.

Phase 4 involves the final assembly of the encapsulated array into a framed, edge-sealed module completed for installation. For this we are using MBA's Glass Reinforced Concrete (GRC) in panels such as those developed by MBA for JPL under contract No.955281. The GRC panel plays the multiple role of edge frame, substrate and mounting structure. An automated method of applying the edge seal will also be developed.

The final phase (5) is the fabrication of six 1'x4' electrically active solar modules using the above developed equipment.

2.0 TECHNICAL DISCUSSION

The following are discussions of the progress made on the various areas of the project in the last quarter. They are arranged by project phase.

2.1 Phase One: Improvements to Existing System

There are three goals in this phase as stated in the introduction: 1) improve placement accuracy, 2) improve solder bond and reduce flux "smear" and 3) reduce system cycle time to 10 sec/cell. Progress has been made towards each of these goals which are discussed separately.

2.1.1 Improve Placement Accuracy

This is strictly a robot programming problem since the robot does all of the cell handling and transport operations.

The Unimate 2000 was designed for use in medium to heavy industry (such as automobile chassis welding) where accuracy on the order of a tenth of an inch is acceptable. Its selection for use in the previous contract was based on factors such as reliability, ease of programming, cost and large work area.

However, with this robot, there has always been a problem in laying down cells with a high degree of accuracy. This is mainly because the cells are 4" in diameter and the end effector has a 5" diameter. This means that the cell is completely hidden during the critical final positioning maneuvers. During the previous contract, positioning was achieved by means of fiducial marks scribed on the end effector. These marks were lined up with corresponding marks on the vacuum chuck and with the centerlines on the layup pattern during final positioning. This sort of "dry" programming (without using a cell to check final position) requires that 1) the fiducial marks on the end effector be accurately placed, 2) the end effector be accurately positioned on vacuum chuck during pickup, 3) the cell be well centered on the vacuum chuck and 4) that the end effector be correctly lined up with the pattern centerlines during final positioning. All of these tolerances multiply cumulatively which can severely impact accuracy. Even so, this technique worked well enough to produce an accuracy of $\pm 1/4$ " which was sufficient for the previous contract's requirements.

Current industry standards, however, require a minimum tolerance (i.e. maximum edge-to-edge spacing) of 0.060" between cells. The Unimate 2000, however, has an accuracy limit of only ± 0.050 ". Since we are working up against this limit, a more accurate programming technique is required. A simple (in hindsight) yet very effective solution to this problem is the use of a dummy indicator cell. This is a 4" diameter disc with four accurately positioned pointers spaced at 90° along the disc's centerlines. These pointers are long enough to protrude beyond the edge of the end effector and allow alignment along the layup pattern's centerlines. Three of the four problems mentioned above are eliminated since the cell's actual centerlines are used for alignment. The only one that must be considered is keeping the indicator cell centered on the chuck. This is slightly more difficult

than with a standard cell since the pointers prevent the cell from falling into the chuck's central locating indentation.

Another important, though less dramatic, accuracy improvement has to do with rotational positioning. In any series-connected string of cells, the leads reverse direction as you go from row to row. This requires a nearly 180° wrist rotation by the robot. Unfortunately, the robot's wrist rotation limit is only 150° each way from center. With the use of the indicator cell we no longer have to line up the end effector's fiducial marks with the vacuum chuck during pickup. Therefore, we can now "pre-rotate" the wrist 30° before pickup to give us the extra rotational travel needed.

2.1.2 Improve Solder Bond

We are approaching this task three ways: 1) improving the robot hardware by refining the bonding head (end effector), 2) improving the robot software by incorporating a new soldering technique and 3) using a new method of solder paste dispensing at the preparation station.

2.1.2.1 Robot End Effector

For even cell heating, it is critical that the cell-to-coil distance be constant over the entire cell area. In previous end effectors, difficulties in holding the coil level during potting prevented this, and even post-potting machining did not fully correct the problem. A new potting technique was used in which the coil was first glued directly to a piece of 1/16" thick silicone rubber sheet. After the glue (a one-part silicone RTV) had set, the coil-and-rubber-sheet assembly was inserted into the plexiglas end effector housing. The outer edge was sealed and the pottant (G.E.RTV 11) was poured through the top. This step also permanently affixed the coil assembly to the housing thus saving two more construction steps (trimming and inserting) that could cause alignment errors. After the pottant had set, the vacuum pickup holes were drilled through the rubber sheet at pre-marked locations.

This new end effector (Figure 1) has proven very successful in early tests. These tests included a new soldering technique that is described next.

FIGURE 1
ROBOT END EFFECTOR SHOWING LAYERED CONSTRUCTION

2.1.2.2

Induction Heat Soldering

There are three problems associated with soldering the leads while the cell is held tightly against the end effector. One is that due to the capillary action from this close proximity the melted flux tends to flow in a thin sheet over a large area of the cell. This "smearing" can be detrimental to cell performance and requires that a cleaning step be added to the manufacturing sequence. Another problem is that the melted flux is quite sticky and causes the cell to adhere to the end effector when the robot tries to release it. The third problem is that the robot must wait for the reflowed solder to cool before releasing the cell to avoid dislocating the leads and causing a "cold" solder joint. We are experimenting with a new soldering technique that eliminates all three problems.

This new technique starts the same as the old one with the induction heater being turned on just before final positioning to preheat the cell. However, rather than waiting for the solder to reflow and then cool before release, the robot releases the cell immediately and backs off approximately 1/8". Since the cell is released before the solder and flux have melted, there is no capillary action to smear the flux and it stays in a very localized area around the joint (Figure 2). The surface tension of the liquid solder pulls the leads down to form an excellent bond. Finally, since the end effector is not in contact with the cell during heating, the robot can leave as soon as the heater turns off allowing the cell to cool on its own. Of course, this 1/8" increase in the coupling (coil-to-cell distance) reduces the RF flux thus increasing the heating time. However, this increase has been found to be less than the old cooling wait time resulting in a net decrease in cycle time. An unexpected side benefit is that the increased coupling also results in a more even heat distribution over the cell.

2.1.2.3

Solder Paste Dispensing Manifold

One area of the preparation station that required upgrading was the mechanism that applied solder paste to the cell's metalization pattern.

FIGURE 2
COMPARISON OF OLD AND NEW SOLDERING TECHNIQUES

In the previous system the paste was dispensed through an 18 gauge needle while the tube was moved in a controlled manner across the cell. The difficulty with this technique lies in producing uniform, continuous beads of solder paste of small diameter (approx. 0.015") using the air-and-piston system.

None of the leading pneumatic dispenser system manufacturers (Tridak, EFD, ASI, etc.) have systems that will produce a bead of high viscosity material using this technique and instead opt for a series of small dots. Following this example, we have built a manifold-type solder paste dispenser of novel design (Figure 3). The dispenser consists of two manifolds, one for each lead. Each manifold consists of a hollow, aluminum box in which the solder paste is injected from a single supply cylinder on the top and out through six Tridak low restriction nozzles along the bottom (Figure 4). The solder paste cylinder is attached by a leur lock fitting on the manifold lid and supported by a clip holder.

The novelty of this approach has to do with the way it is used in our system. This will be discussed next since it deals with cycle time reduction.

2.1.3 Cycle Time Reduction

The cycle time goal for layup and interconnect on this program is 10 sec/cell. It was determined during the previous program that the preparation station would require only minor modifications to achieve this. Significant gains can be made simply by changing the controlling computer program.

Our preparation station is essentially a serial processing machine (i.e. one cell at a time is run through the complete preparation cycle) as compared with a parallel processor (such as the K&S machine) where several cells at a time move down an assembly line with each work station doing a small part of the preparation. As a serial processor, a certain amount of dead time can exist for each mechanism on the station. This dead time can be minimized by overlapping operations. Two of the operations that are being overlapped are ribbon feed and cell solder dispensing. To accomodate this, the front end of the manifold tapers down

FIGURE 3
MANIFOLD-TYPE SOLDER PASTE DISPENSER (Shown Extended)

FIGURE 4
UNDERSIDE OF PASTE DISPENSING MANIFOLD SHOWING NOZZLES

to a sharp leading edge, forming a ramp where it meets the ribbon at the edge of the vacuum chuck. After the dispenser is in position over the cell, the ribbon is fed up this ramp and over the top of the dispenser. There is a groove cut into the ramp and top of the dispenser to act as a guide. When the dispenser retracts, the lead simply lays down on top of the cell. In addition to reducing cycle time and improving in ribbon positioning accuracy, this technique eliminates the problem of the lead "plowing" into the solder paste during ribbon feed.

The big unknown in reducing cycle time involved the robot. In our first full size program, the robot laid up a 35 cell (1'x4') panel in 345 seconds for an average of 9.86 sec/cell. This was only pick-and-place (P&P) time and did not include a heating wait which would add approximately 3 sec/cell. However, this first program was done with a non-optimized floor arrangement which included a 5 ft. transverse motion for the robot back and forth between the prep station and table. Rearranging the equipment to the final floor plan (which eliminates this motion) should reduce the P&P time enough to meet program goals.

2.1.4 General Phase One Improvements

Although it does nothing to improve the accuracy or reduce cycle time, there is one more improvement that should be mentioned. This is the purchase and installation of a custom enclosure to house the entire cell preparation system. This enclosure (built by Crystal Mark in Glendale, Calif.) performs far more than just a cosmetic function, however. It consolidates the system into a single unit while protecting the electrical and mechanical components from contamination. The enclosure is actually two units joined on a 30° angle. The operator's section (Figure 5) contains a lockable console for storage of the computer and some manuals. It also has sufficient desk space for efficient operation. The equipment section (Figure 6) is a completely enclosed cabinet with only the flush mounted preparation station and Siltec cassette unloader protruding. All of the pneumatic plumbing and valving as well as the computer interface electronics are located inside. There is also ample room to accommodate the additional electronics necessary for the Automated Lamination Station (described in 2.3).

FIGURE 5
OPERATOR'S SECTION OF NEW ENCLOSURE

FIGURE 6
EQUIPMENT SECTION OF NEW ENCLOSURE

In this way, all of the interface electronics can be located in close proximity to the computer, which aids in reducing random signals that could produce errors. Additionally, all of the sensitive, low voltage information cables run in protected cableways to further reduce outside interference.

2.2 Phase Two: Expand Capability of Existing System

This phase of the project involves adding capabilities to the existing layup and interconnect system to make it more adaptable to a real life production situation. This involves the detection of both broken cells or cells with bad metalization patterns during preparation, and poor bonds after soldering.

Implicit in both of these is correction, i.e., once the problem has been detected, action will be taken to correct it. Since the robot is our only cell handling device, it was assumed that it would be the one to remove or repair the bad cell. As we investigated deeper into the problem, however, we came up against a serious obstacle.

In order to take corrective action, the robot must be able to do conditional branching, that is the robot would have to deviate from its pick-place-and-solder routine to a pick-and-dispose or resolder-and-retest or unsolder-and-dispose routine on command from the controlling computer. Although conditional branching is a trivial task for all general purpose computers (it is, in fact, the basis for all machine intelligence) it is beyond the capability of the Unimate 2000. Although it would be possible to modify the robot to do conditional branching, it would be a very major modification (in essence a "brain transplant") and is beyond the scope of this contract.

The robot aside, there are still ways to perform the stated tasks and fulfill the spirit of the contract.

2.2.1 Broken Cell Detection and Disposal

Detecting a broken cell, or one with a substandard metalization pattern, is a fairly straightforward expansion of our cell orient-

ation routine.

The normal cell preparation cycle starts with the cell being ejected from the Siltec unloader. It glides off the belts onto the vacuum chuck (turntable) which is where all of the preparation takes place. The surface of the chuck has a matrix of holes through which air is exhausted making the chuck into an air table. It is tilted approximately 5° from the horizontal with four locating pins on the "downhill" edge. Once the cell has glided off the belts and settled against the pins, the airflow is reversed clamping the cell to the chuck. The chuck then rotates 360° while an optical sensor aimed at the cell's edge measures the reflected light. The computer then plots (internally) the light level for each of the discrete cell positions (there are 800 steps per revolution or approximately $\frac{1}{2}^{\circ}$ per step). This plot is known as the cell's signature and its shape is very distinctive for a good, on-center cell. A simple pattern recognition program examines the signature's peaks and valleys to determine the location of the contact pads and the chuck is then rotated to the correct alignment. In order to detect broken cells, we need only teach the program to recognize a few more signatures. The signature of a broken cell would contain a high flat plateau representing the place where the piece of the cell is missing and the sensor is looking directly at the shiny aluminum surface. An off-center metalization pattern (or a cell not centered on the chuck) would produce a signature with skewed peaks and valleys. A substandard or missing metalization pattern would produce low peaks or none at all.

Once a cell has been determined to be bad, its disposal (other than using the robot) is actually quite simple. Since the chuck is already at an angle, we need only rotate the chuck so that the locating pins are "uphill" and turn on the air. The cell will then glide off the chuck and fall into a disposal container.

2.2.2

Solder Bond Testing

This section of Phase Two has only been superficially investigated so far. A method of contacting the lead has been developed

(Figure 7) that allows contact with the robot standing off 1/8" as described in 2.1.2.2. For actual electrical testing, two brush contacts would have to be used, of course.

The only approach tested so far is a simple resistance test. This test would measure the resistance from one lead, through the solder joint, across the metalization pattern, through the other solder joint and out the other lead. (This test would work only for cells with parallel interconnect leads). A second set of contacts would be measuring the back solder bonds.

Early measurements were very encouraging. The resistance of a fully soldered lead was approximately 50 m Ω . The resistance through a lead with completely unmelted solder paste is approximately 500 m Ω . This order-of-magnitured difference seemed a good basis for a test until we made further tests. These revealed that 1) the resistance of a partially soldered lead falls logarithmically, or at least very non-linearly, between the two extremes mentioned (e.g. a lead soldered along only 10% of its length has a resistance of <100 m Ω) and 2) the brush-to-lead resistance alone is approximately 100 m Ω . This test, therefore, would only be reliable in detecting a totally unsoldered lead. Another form of testing would be required to determine a partially soldered condition. The standard IV output test is probably impractical since the cell is completely covered (i.e., in the dark) by the end effector.

There is another, unavoidable problem associated with post-solder testing. No matter what test scheme is adopted, the robot must wait until the solder joint has cooled before testing it. This eliminates the time advantage gained by our new soldering technique. For this reason, this portion of Phase Two has been given a low priority on the program.

Here too we have a method of avoiding the inflexible-robot-program problem, albeit not as elegantly as before. After each cell is tested (in whatever method is chosen) the results can be recorded on the computer's printer producing a "report card" on each module. If there are any problems, they would be noted and repaired off-line by a (human) repair specialist. This is exactly the technique used by automobile

FIGURE 7
SPRING LOADED BRUSH CONTACT ON END EFFECTOR

corporations who want to repair defects noted during assembly yet have to keep the assembly line moving.

2.3 Phase Three: Automated Lamination Station

This is the largest part of the program as it deal with the development of the Automated Lamination Station. This station consists of three major components: 1) the vacuum platen end effector for the Unimate robot, 2) the Lamination Preparation Station and 3) an Automated Lamination Chamber. Of these the vacuum platen and Lamination Preparation Station have received the most attention. The vacuum platen has been built and currently undergoing tests. A proof-of-principle mockup of the Lamination Preparation Station has been built and tested. The lessons learned from this mockup are being applied to the final design of the station.

2.3.1 Vacuum Platen

In the design of the vacuum platen (Figure 8), it was first decided that it should be able to pick up sheets of cover glass and finished laminated modules, as well as circuits of interconnected but unlaminated cells. This is required since only one robot will be handling all three types of materials and it would be too cumbersome to change end effectors during this robot's routine.

The limiting factor in the design was the pickup of the 35 interconnected cells. Each cell must be individually supported because the interconnect leads cannot be relied upon to hold the cells in registration.

For actually picking up the cells, we use 35 discrete vacuum cups. To insure a good seal to the cell, we chose a vacuum cup which fits between the two leads on the cell surface. Additionally, they are a bellows type design which allows approximately 1/2" of compliance in the vertical direction when contacting the cells. Each vacuum cup is attached to its own small eductor in which air goes in one end and a low grade, high flow rate vacuum is created at the other. The 35 eductors are attached to a manifold which is in turn supported by a trusswork. Figure 9 is a close-up of the underside of the platen showing the eductors and bellows type vacuum cups. The trusswork is then bolted to the robot which supplies air

FIGURE 9
UNDERSIDE OF VACUUM PLATEN SHOWING EDUCTORS
AND BELLOWS VACUUM CUPS

for operation through its internal plumbing normally used to operate a pneumatic clamp,

In testing the vacuum platen only one significant problem was encountered. This was a large pressure drop in the air lines due to the high air flow rate through the vacuum platen (resulting from the large number of eductors used). It requires a minimum of a 20 psi drop across each eductor to insure a tight seal with the cells. To eliminate this problem we streamlined the plumbing by removing some of the restrictive elements.*

The tests consisted of picking up 35 discrete cells as well as picking up the 8 lb finished laminate (as shown in Figure 10). Even a 1'x4' piece of MBA Glass Reinforced Concrete (our proposed substrate, see Section 2.4) weighted to simulate a finished panel (approximately 21 lbs) was handled without problems.

In its current configuration, the vacuum platen is able to hold these materials while the robot goes through some rather violent acrobatics, far more severe than would be encountered during normal handling.

The only problem that might arise is one of inaccuracy in putting the cells down (i.e. a small cell shift in one direction or another). This will be investigated further.

2.3.2 Lamination Station

The function of the Lamination Preparation Station is to cut the various laminate materials and place them into the lamination chamber. The laminate will consist of a bottom lamina sheet made from several layers of materials, the circuit of 35 interconnected cells, a top lamina sheet consisting of one or more layers of materials, and a sheet of cover glass. The modules we will make will be nominally 1'x4'.

To simplify the handling of the lamination materials, we have specified that the materials forming bottom lamina sheet be supplied

* These elements were some pressure regulators and solenoid valves. This rendered the operation totally manual and was done only short term to expedite testing.

FIGURE 10
VACUUM PLATEN PICKING UP FINISHED MODULE

rolled together in rolls 1 ft. wide. If the top lamina sheet consists of more than one material, those materials must also come rolled together in a 1 ft. width. It is not uncommon for materials to be supplied in such a fashion and our investigation into the subject shows that this is how similar materials are handled in industry.

Because the cycle time of this station is limited by the pick and place time of the robot, we decided to have one station perform these tasks serially, rather than having many lamination chambers moving from station to station where only one task is performed by a station. This is the same design philosophy as used for the cell preparation station and we feel is best suited to this task also.

The general sequence of operations that must be performed by this station is as follows:

- 1) Place the bottom lamination materials in the lamination chamber.
- 2) Place interconnected circuit of cells in chamber (done by robot).
- 3) Place the top laminate.
- 4) Place cover glass (done by robot).
- 5) Release chamber to begin vacuum/thermal cycling and wait for a new chamber to come into place.

Figure 11 illustrates our conceptual design of the lamination station. At each end of the station is a feeding and shearing mechanism. One end handles the bottom laminate, and the other the top laminate. The lamination chamber lies in the middle. Running back and forth between the ends is a shuttle which clamps onto the edge of the materials and reels them out across the chamber.

The cycle for the Lamination Preparation Station is as follows:

- 1) The bottom lamina sheet is fed through the shear into the shuttle which is parked at the end near the robot.

- 2) The shuttle clamps onto the end of the material.
- 3) The feed rollers disengage.
- 4) The shuttle pulls the bottom layer out over the chamber.
- 5) The feed rollers re-engage to apply tension to the material.
- 6) The shear cuts the material off.
- 7) The shuttle pulls the material into its final position.
- 8) The shuttle releases the material and parks at the far end.
- 9) The interconnected cells are placed into the chamber by the robot.
- 10) The top laminate is placed on top of the cells in the same manner as the bottom laminate.
- 11) The robot places the cover glass into the chamber.
- 12) The chamber is ejected for vacuum/thermal cycling and a new chamber comes into place.

To test this design, the shearing and placement of laminates in particular, we built a mockup station (Figure 12) with only one feeder-shearing mechanism and a shuttle. Although all the functions of the mockup were controlled manually, it was automated enough so that hands never actually touched the materials. The feed rollers were old conveyor rollers operated with a hand crank, The shear was a converted paper cutter operated by an air cylinder. The shuttle had closet door rollers running in tracks. The shuttle clamp was a flat plate which was activated by an air cylinder.

The mockup functioned amazingly well. There was no problem positioning the material in a simulated chamber or with cutting the materials.

The mockup has been very useful in bringing to light many of

FIGURE 12
MOCKUP OF AUTOMATED LAMINATION STATION

the subtleties involved in this kind of operation. One of the potential problems we have been able to foresee is that after the top lamina is cut off, it cannot be dragged into position over the cells without disturbing them. This can be taken care of by having the feeder-shearing mechanism pivot forward slightly before the material is cut so that it will drop directly into place without further positioning.

At this point, we are drawing up designs for the actual station based on the lessons learned from the mockup station.

2.3.3 Lamination Chamber

Figure 13 illustrates our design concept for the Automated Lamination Chamber. As most of our activities during the quarter have concentrated on the vacuum platen and Lamination Preparation Station, no actual hardware has been built. The various chamber components are described separately.

2.3.3.1 Chamber Body

The design is based on the chamber developed by MBA under JPL contract 955281. The internal dimensions are 13"x49"x1/2" deep which allows 1/2" clearance around all sides of the 1'x4' panel. This gap around the floor of the chamber is occupied by vacuum slots which lead to the external vacuum source via a manifold. The floor and walls are Teflon coated to prevent the finished panel from sticking after laminating. The tops of the chamber walls are approximately 1" wide to allow room for the vacuum seal.

Beneath the floor of the chamber are the vacuum and heating components. Vacuum components consist of manifolds around the edge under the slots which lead to a single external vacuum connector. The heating components consist of lengths of flexible ribbon heaters interleaved across the underside of the chamber floor. These ribbon heaters (also known as "heat tape") consist of resistance heating elements wrapped in fiberglass cloth. This makes them extremely flexible and they are commonly used in industry to provide localized heating for various processes by wrapping them around pipes and vessels or across flat surfaces (such as our chamber).

FIGURE 13
AUTOMATED VACUUM CHAMBER CONCEPT

2.3.3.2 Chamber Cover

Although it appears solid in the illustration, the chamber cover is based on the "vacuum bag" principle as was the cover of the prototype chamber mentioned above. For that chamber, the cover was simply a 1/4" thick sheet of silicone rubber that reached to the outer edge of the chamber walls. Pieces of angle were placed along the edge of the sheet and clamped in place with spring clips. A film of vacuum sealing grease served as the seal. This arrangement was able to sustain the minimum 27 in Hg required for lamination.

In order to automate this arrangement, the design was changed somewhat. The cover now consists of a metal framework surrounding the rubber sheet. This both supports the sheet and provides the mating surface for the vacuum seal. This seal is a permanent O-ring or soft rubber type mounted on the vacuum chamber walls. The majority of the cover area is still the flexible rubber sheet as is required by the "vacuum bag" concept.*

2.3.3.3 Hinge Design

Connecting the chamber body to the cover is a hinge upon which were placed several design constraints resulting in the chosen configuration as shown in the figure.

The main constraint is that, in the open position, the cover must lie flat and the top of the cover be at least level with the top of the chamber body and preferably lower. This is to allow clearance for the chamber to pass under the Lamination Preparation Station.

The most straightforward way of doing this is to attach the cover by means of a continuous or "piano" hinge along the back such as with a tool chest. There are several drawbacks to this design, however. First, a large vertical clearance is required to allow the cover to swing open. Second, it is difficult to actuate in an automated manner since the center of gravity of the cover follows a similar large arc. This means that the moment reactions at the hinge (where the actuators would have to be attached) would be very large to start opening the cover, drop to zero

* In this concept, the rubber sheet acts as a diaphragm allowing atmospheric pressure to press down on the laminate inside helping to force out air trapped between the layers of the laminate.

at mid travel, and be very large the opposite direction to stop the cover. A third problem is that until the last instant of closing, the cover is not parallel to the chamber body. This means that the sealing distances and forces are uneven being heavy along the back and light along the front. A final drawback is that the cover inverts every time it is opened. This would have an unknown effect on the rubber diaphragm flexing back and forth.

To avoid these problems, it was obvious that the cover should be opened vertically a short distance, moved away horizontally and dropped back down once it is clear of the chamber. One possible way to do this is with a non-linear slide such as used on the side doors of helicopters and delivery vans. However, investigations into these devices showed them to be rather intricate precision mechanisms not really in keeping with the design philosophy of the project.

A more elegant solution is a simple 4-bar linkage with the chamber cover and body forming two of the links as shown in the Figure. It is mechanically much simpler than a slide while retaining the advantages of low maximum height and keeping the cover parallel to the body at all times. Additionally, it has the further advantage of allowing the cover to be dropped as low as desired when opened. Finally, it is very easy to actuate with either rotary actuators at the pivot points or linear actuators acting on the links. Torsional springs installed at the pivots would support the cover when open and preload it when closed to ensure a good vacuum seal.

2.3.3.4 Control and Instrumentation

Since the chamber is of automated design, a certain amount of feedback instrumentation is required. However, due to the very flexible nature of our control system, this can be kept to a minimum. Feedback instrumentation consists of a vacuum transducer mounted on the manifold to monitor chamber pressure and a small number of thermistors (the prototype chamber required only three) to monitor temperature. Control equipment involves only a solenoid valve to regulate chamber pressure and some high output power transistors to supply power to the ribbon heaters.

Phase Four: Edge Seal and Final Assembly

The details of the deliverables of this phase are still under discussion so very little work has been done. However, the requirements are very clear and are as follows.

The goal of this phase is to take the encapsulated modules, such as would be removed from the lamination chamber at the end of its cycle, and turn them into field-installable solar panels.

This requires, at the minimum, edge sealing, framing and the attachment of (or installment into) a field support structure.

Figure 14 is not an illustration of any piece of equipment currently under development, but rather illustrates the above requirements.

Our approach is to use MBA's Glass Reinforced Concrete (GRC) as a combination substrate, edge frame and support structure. The 4'x8' panel shown in the figure is based on a similar panel developed by MBA for JPL under contract #955281.

The GRC panel has a 1/2" deep indentation on the surface which acts as an edge frame and allows the module's glass surface to be flush with the panel's concrete edge.

The edge seal (probably a hot melt Butyl or EPDM) is applied by a machine that has controlled rectilinear motion.

One of the details still under discussion is whether the GRC panel will be large and accommodate several modules such as shown in the figure, or be able to accommodate only one module each. This latter form would be for feasibility demonstration only since such a configuration would have very poor array packing densities.

The general sequence of operations for a machine as shown in the figure (which has eight 1'x4' modules per GRC panel) is:

- 1) The edge sealant is applied along the three sides of the GRC panel where the edges of module #1 (the one closest to the viewer in the illustration) will make contact.

FIGURE 14
AUTOMATED EDGE SEAL APPLICATION CONCEPT

- 2) Module #1 is placed into the GRC panel by the robot.
- 3) Edge sealant is applied to the panel where the two short sides of module #2 will make contact and along the fourth side of module #1 where the two modules join.
- 4) Module #2 is placed into the GRC panel by the robot.
- 5) Steps 3 and 4 are repeated five times for modules 3 thru 7.
- 6) Edge sealant is applied to all four sides of the remaining opening in the GRC panel.
- 7) Module #8 is placed into the GRC panel by the robot.
- 8) The panel is removed for attachment of electrical hardware followed by packing and shipping to the installation site.
- 9) New (empty) GRC panel is put in place and the cycle starts over.

The cycle time of such a machine would be tied to that of the encapsulation station, i.e., approximately one minute per module or eight minutes for a 4'x8' panel.

2.5 Phase Five: Fabrication

This phase is fairly self explanatory. It requires the fabrication of six 1'x4' modules ready to be installed in the field. The cells are to be layed-up and interconnected using the equipment developed during the previous contract (and improved during this one). The interconnected cells are to be encapsulated, edge sealed and framed using equipment developed during this contract.

Whether these will be six separate modules each on its own small GRC panel or six modules and two blank spaces on a more standard size 4'x8' panel is still to be determined.

3.0 CONCLUSIONS

This program is progressing very well. The vacuum platen passed its initial tests flawlessly.

The Lamination Preparation Station has been built in mockup and many valuable lessons have been learned which are being incorporated into the final design.

The design concept for the Lamination Chamber has been detailed so that construction can begin.

In addition, the existing system has been modified in a way that both reduces soldering time and vastly improves the quality of the solder bond.

Finally, concepts have been developed for both the detection of broken cells and poor solder bonds and the automated application of edge seal and final assembly.

Over the next period we will continue with final design and start construction of both the Lamination Preparation Station and Lamination chamber.

4.0 PROGRAM PLAN

Included is a program plan that shows progress-to-date on the various phases as well as their projected completion dates.

ATTACHMENT A

*U.S. GOVERNMENT PRINTING OFFICE: 1980-740-145/987

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PROGRAM PLAN