5101-226
Flat-Plate Solar
Array Project

JPL/DOE-1012-83
Distribution Category UC-63b

(NASA-CR-172652) DEVELOPMENT OF A LARGE LOW-COST DOUBLE-CHAMBER VACUUM LAMINATOR (Jet Propulsion Lab.) 32 p HC A03/MF A01 CSCL 10A

N83-26254

Unclas
G3/44 03860

Development of a Large Low-Cost Double-Chamber Vacuum Laminator

D.R. Burger

January 15, 1983

Prepared for
U.S. Department of Energy
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The JPL Flat Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost competitive solar arrays.

This publication reports on work done under NASA Task RD 152, Amendment 66, DOE NASA IAA No. DE A101 76ET20356.

ACKNOWLEDGMENTS

The author wishes to thank Donald Bickler for his support during the development of this laminator. Credit should also be given to Leland Gee, Edward Fortier, John Knox, Gerald Stebbins and Scott Leland for their many helpful suggestions and enthusiastic participation in this effort. Significant cost savings were achieved as a result of their contributions.

ABSTRACT

A double-chamber vacuum laminator was required to investigate the processing and control of the fabrication of large terrestrial photovoltaic modules, and economic problems arising therefrom. Major design considerations were low cost, process flexibility and the exploration of novel equipment approaches. Spherical end caps for industrial tanks were used for the vacuum chambers. A stepping programmer and adjustable timers were used for process flexibility. New processing options were obtained by use of vacuum sensors. The upper vacuum chamber was provided with a diaphragm support to reduce diaphragm stress. A counterweight was used for handling ease and safety. Heat was supplied by a large electrical strip heater. Thermal isolation and mechanical support were provided inexpensively by a bed of industrial marbles. Operational testing disclosed the need for a differential vacuum gauge and proportional valve. Reprogramming of the process control system was simple and quick.

CONTENTS

SECTION I

INTRODUCTION

Double-chamber vacuum lamination is a process used for encapsulating terrestrial photovoltaic (PV) modules. The initial equipment developed specifically for this use (Reference 1) was capable of handling modules up to 1 x 4 ft. With expansion of the PV industry, larger modules are sought. In order to investigate processing problems unique to larger modules, a 4 x 4-ft research laminator capability was desired. The design, fabrication and operation of the Flat-Plate Solar Array Project (FSA) 4 x 4-ft laminator (Figures 1 and 2) is described in this document.

Design of any piece of processing equipment must be guided by the needs of the product, the state of the art and the needs of the user. Even though this was a research effort, these guidelines were followed to enable transfer of any technological benefits disclosed during the research effort to the terrestrial PV industry.

Lamination for protective packaging has been used for many years. The most familiar examples are drivers' licenses and military service records. These items are laminated using heated rolls or heated platens and mechanical pressure. Many epoxy-fiberglass laminates are fabricated by use of an autoclave for application of pressure. Other laminated structures use a single vacuum chamber to furnish lamination pressure. A variation on this method is vacuum bagging. A third technique makes use of double-chamber vacuum lamination.

Use of lamination in the PV industry is, as usual, governed by economic considerations (Reference 2). Lamination has superseded earlier cast-silicone-rubber encapsulation technology because of its lower labor requirements, and the reduced cost and amount of materials used.

At present, one major lamination cost is that of equipment. A 15-megawatt PV plant would produce about 1800 cells per hour. If 144 of these cells are laminated into each 4-ft-square module, about 11 laminators would be required, assuming a 45-minute cycle time; the cost of the laminators could become a major capital investment (Reference 3).

Double-chamber vacuum lamination (see Figure 2) allows the laminant materials to outgas before application of pressure, by evacuating both vacuum chambers at the start of the process. After trapped or absorbed gases have escaped, pressure is applied to the laminant stack by venting the top chamber to atmosphere.

Removal of trapped gases solves one visual-appearance requirement for successful PV module lamination. Some other requirements are: (1) application of heat to provide lower viscosity for thermoplastic bonding or crosslinking of thermosetting polymers; (2) rapid, even application of heat for fast process cycling; (3) application of pressure to inhibit formation of bubbles from adsorbed or reactant gases and to encourage encapsulant flow into voids; (4) capability of handling transparent superstrate and opaque substrate

Figure 1. 4 x 4-ft Laminator and Module

module designs; (5) minimal differential lateral pressure to reduce cell movement. Each of these product-related requirements imposes design constraints upon the lamination equipment.

Another laminator requirement is process flexibility to accommodate different module designs, different encapsulation materials, different encapsulant-cure cycles and different lamination pressures. With these requirements in mind, design of a research laminator was begun.

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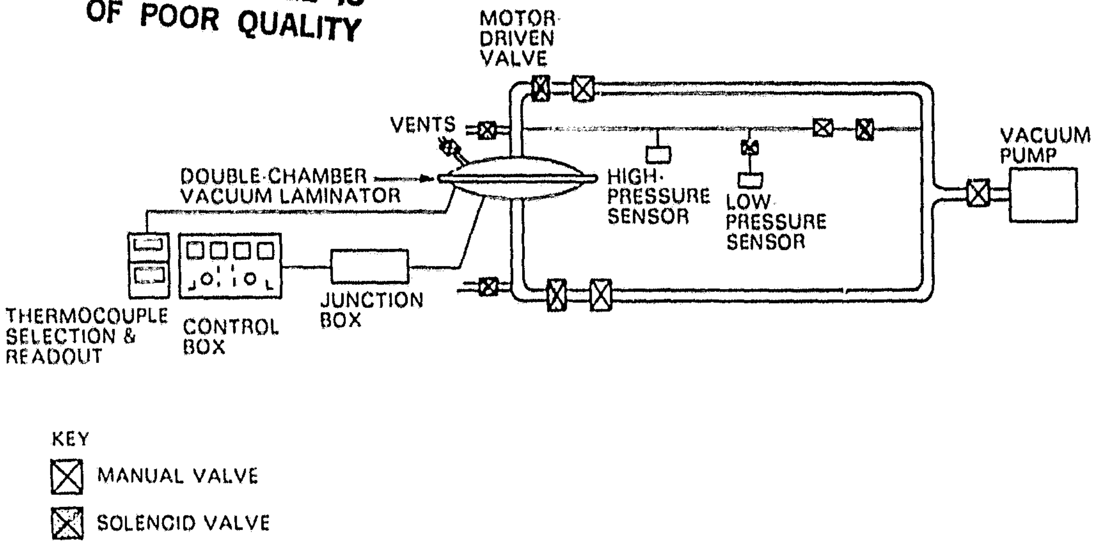


Figure 2. Functional Schematic of Laminator

SECTION II

DESIGN

Design of the laminator can be divided into four decision areas: size, cost, process flexibility and incorporation of new process options. The laminator size was chosen based upon previous structural (Reference 4) and architectural (Reference 5) studies as well as glass processing and installation problems. All of the above considerations point to a maximum feasible glass-superstrate module size of 4 x 8 ft. When a 4 x 8-ft module is examined from a lamination processing point of view, it does not present any greater challenge than a 4 x 4-ft module. Trapped or absorbed gases in the laminant materials will be a maximum distance of 2 feet from an edge in both cases. A 4 x 4-ft module was therefore thought to be an appropriately sized research target.

Based on the chosen module size, some preliminary stress analyses of the laminator plates were made. A simply supported square plate of aluminum was assumed initially. Using standard theory (Reference 6):

$$Y_{max} = \frac{aqb^4}{Et^3} = 0.416 \text{ in.}$$

when

$q = 15$ lb/in.^{2} (atmospheric pressure)

$b = 50$ in. (plate size)

$E = 10 \times 10^6$ lb/in^2 (Young's modulus for aluminum)

$t = 1$ in. (assumed thickness)

$a = 0.0444$ (for square plates).

This is obviously an excessive deflection while laminating brittle materials such as glass and silicon. If a conservative maximum deflection of 0.030 in. is assumed along with the use of steel for increased stiffness, a plate thickness of 1.666 in. was indicated. This plate would weigh about 1200 lb and presents significant machining, handling and support problems.

Two flat steel plates weighing 1200 lb each would be very expensive after fabrication and assembly costs are included. Flat aluminum plates are similarly ruled out because of cost. Because of these considerations, it was decided to use spherical end caps. These are commercially available; they are used in the construction of pressure vessels. Again, some preliminary calculations were made: A 4-ft-square module is 67.88 in. across the diagonal, so it will fit comfortably into a 69-in. circle. If a 100% spherical end cap [a 100% cap's inside diameter (ID) is equal to its spherical radius] with a 3/16-in.-thick wall and a 69-in. ID is used, the center deflection of the dome is about 0.001 in. and the stress is 2800 lb/in.^{2}. Weight of one end cap with a 2-in.-wide flange is only about 250 lb. End caps are fabricated by spinning; their total cost is about $2.40/lb.

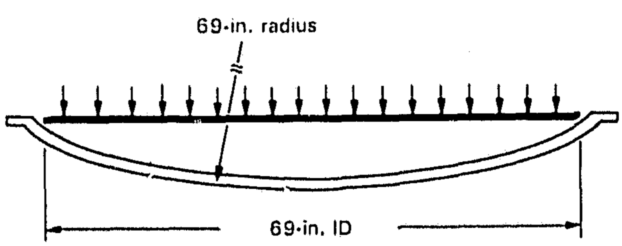
Choice of a hemispherical dome created a problem with support of the lamination platen (Figure 3). When the top chamber is vented to atmosphere, the resultant force on the 69-in.-dia. diaphragm is about 55,000 lb. Designing and fabricating a support structure for this load that would not deflect or conduct heat was a challenge. If the cost consideration is included along with requirements for withstanding heat to 170°C with no outgassing, no standard solution seemed possible. Fortunately, some earlier work (Reference 7) had been done with a layer of sized glass marbles between two flat plates. This combination of support and insulation was to be exploited simply by filling most of the bottom vacuum chamber with marbles.

Once the basic configuration of the chamber was fixed, attention turned to process control. Previous laminators had been controlled by clock-driven cam shafts that actuated a series of microswitches. Changing the timing of one process step often meant resetting the cams for that and all subsequent steps. If two or more functions were to be turned off or on simultaneously, very careful cam adjustment was required. Finally, after the cams had been set, it was necessary to run the timer to check accuracy of elapsed time.

New microprocessor technology was and still is very appealing. However, a survey of the market disclosed prices around $2,000 and necessary accessories costing another $2,000. A lower-cost alternative was sought. A stepping programmer made by Eagle Signal Division of Gulf & Western, which provided 24 steps and operated 10 switches, was selected. Additional features were the inclusion of forward and reverse operation and a tap switch to ensure input signal isolation. This programmer and four adjustable reset timers cost about $650.

Earlier laminators were designed for a single fixed processing sequence, and the solenoid valves controlling the vacuum and venting functions were reduced to a minimum. This made process research difficult, since plumbing changes were needed in most cases. Another problem was the lack of control valves on all lines; during some investigations it would have been helpful to be able to throttle down a vacuum or vent line to reduce the application of sudden stresses to the laminant materials.

One concern in a large laminator is the weight (about 37 lb) of the silicone-rubber diaphragm. This weight presses down on the laminant stack during vacuum pumpdown and could inhibit the escape of air from between the



TOTAL ATMOSPHERIC PRESSURE LOAD = 54,967 lbs
MAXIMUM PROCESS TEMPERATURE = 170°C
VACUUM RANGE OF INTEREST = 0.1 torr to 5 torr
MAXIMUM ALLOWABLE CENTER DEFLECTION = 0.030 in.

Figure 3. Lamination Platen Design Requirements

layers of material. An additional problem is the diaphragm of a large laminator -- how can such a large, hot, limp object be handled during repetitive processing?

Another processing option of interest is the application of partial atmospheric pressure to the laminant stack during curing. Some module designs may be more fragile than others and may not be able to withstand high pressures before the viscosity of the encapsulant has been reduced by heating. Implementation of these new processing options will be discussed in the next section.

SECTION III

FABRICATION

Fabrication of the 4 x 4-ft laminator involved six major subsystems: vacuum chamber, support structure, counterweight and hinge, platen, process controller and temperature and pressure sensing. The spherical end caps were received with a 2-in.-dia central hole as a result of the spin forming operation. This hole was used as a vacuum port, since it was the same size as the mechanical vacuum pump inlet. Two additional 1/2-in. access ports were designed into both the top and bottom chambers. In all cases a pipe coupling of the appropriate size was welded to the chamber wall to allow easy attachment of fittings. Since the top chamber was to be lifted up to load and unload the laminator, the silicone rubber diaphragm was attached to this part. A 100% spherical end cap is fairly shallow (about 9.25 in. from flange plane to top/bottom) compared with its width (69-in. ID). The silicone rubber diaphragm, which cost $700, would be highly stressed if it were accidentally pulled all the way into the upper chamber. A perforated metal diaphragm support (Figure 4) was built into the top chamber as a safety device. The perforated plate was itself tack welded to, and supported by, four concentric rings of perforated metal tack welded to the chamber. A clearance of 1/2 in. was left between the face of the end cap flange and the top of the diaphragm support. This was considered to be sufficient to allow lamination of any projected module designs.

Because the diaphragm was glued (using standard high-temperature RTV silicone adhesive) to the flange of the top chamber, only the bottom surface of the diaphragm needed to be sealed. An O-ring or other standard gasket of 71 in. dia is expensive. Another sealing problem was imprecise fabrication of the flanges. Residual stresses from forming or limitations in the forming process itself resulted in a 1/8-in. gap between the flanges at two or three places around the circumference. A soft seal seemed necessary and sufficient, as the clamping force at full vacuum would be about 250 lb/in. A piece of 1/2-in. OD, 1/4-in. ID surgical tubing was chosen for the seal on the basis of cost and availability. The manufacturers of the surgical tubing were queried about an appropriate adhesive to attach the tubing to silicone rubber. A cyanoacrylate adhesive was recommended. "Crazy Glue" is a member of this family of adhesives; supply and cost presented no problems.

Fabrication of the bottom chamber was much less involved. Since there were access ports in the bottom and marbles were to be used, some protection was needed. A 2-in.-pipe short nipple with a cap was used over the main vacuum port. Holes of 1/4 in. dia were drilled into the pipe nipple and cap before installation. The 1/2-in. ports were for wire access, so 4-in. nipples were used to bring the wires closer to the surface of the marbles.

Once the two chambers were fabricated, a supporting structure was required. Any simple welded angle-iron structure would serve as long as it would support the estimated 2200-lb final weight of the assembled vacuum system. A metal ring with a 56-in. ID and a 2 1/2 x 2 1/2-in. cross section was used as a seat for the lower chamber. A plywood floor was installed near the bottom of the final structure to provide a base for the system plumbing.

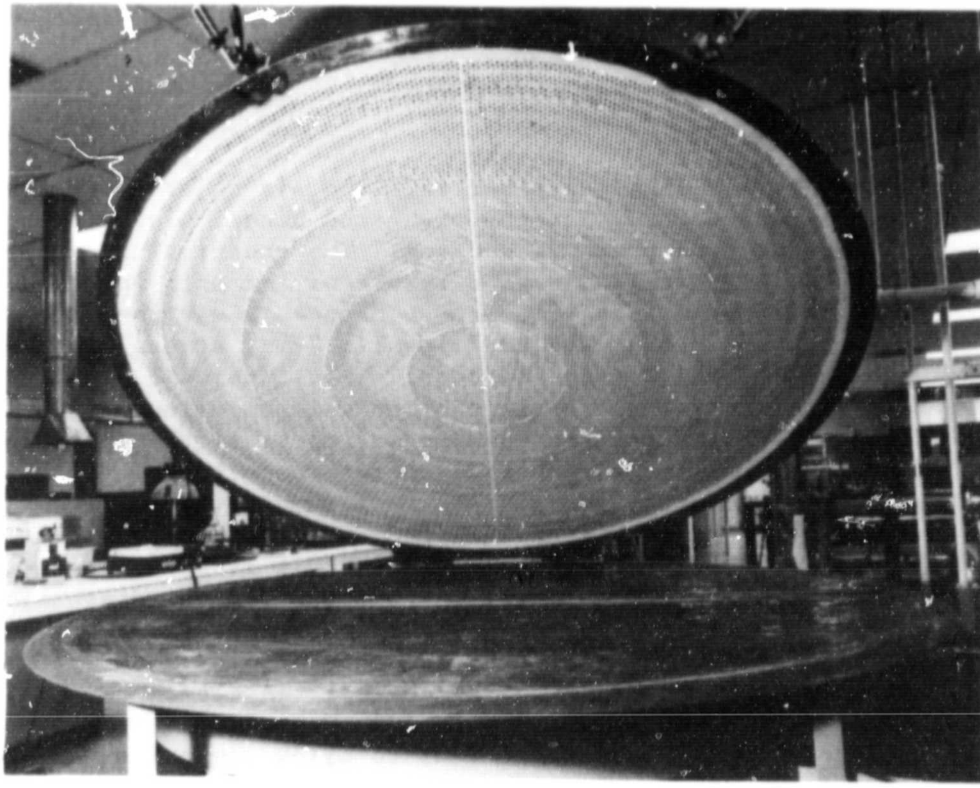


Figure 4. Perforated Metal Diaphragm Support

Raising the upper chamber was a challenge. A small floor-mounted crane able to handle 300 lb is not too expensive; objections to this approach were safety, floor space and slow, awkward operation. The next method considered was a pneumatic cylinder. This was the method used for the earlier 1 x 4-ft laminators. Problems encountered were cylinder cost, control (there are times when the diaphragm sticks) and safety. A 650-lb counterweight was finally chosen. Also needed was a design for a hinge capable of handling 1000 lb. An inexpensive solution was the use of rod and thick-walled tubing. A piece of 1-in.-dia 316 SS rod was used inside a piece of 1 1/2-in. OD by 1-in.-ID thick-walled tubing. The counterweight and hinge were built as one unit (Figure 5). Cold-rolled steel plate 1/2-in. thick was used to construct the counterweight box. This was selected so that the wall thickness would be sufficient for 1/4-20 threads, avoiding the expense of special fittings. After the box was assembled, scrap lead was melted and poured in. The amount of lead used was left a little short so that balancing could be done by adding weight after final assembly.

Once the hardware assembly was complete, plumbing installation was done. Solenoid valves were used to accomplish five functions: (1) vent top chamber; (2) vent bottom chamber; (3) control vacuum line to bottom chamber; (4) protect low-pressure sensor; (5) control small by-pass tube on top chamber vacuum line. The top chamber vacuum line required a 2-in. valve; no such solenoid valve was readily available. A motor-operated 2-in. vacuum valve made by Raymond Control Systems was available from a 1 x 4-in. laminator, so it was used instead. Comments on this decision will be found in Section IV.

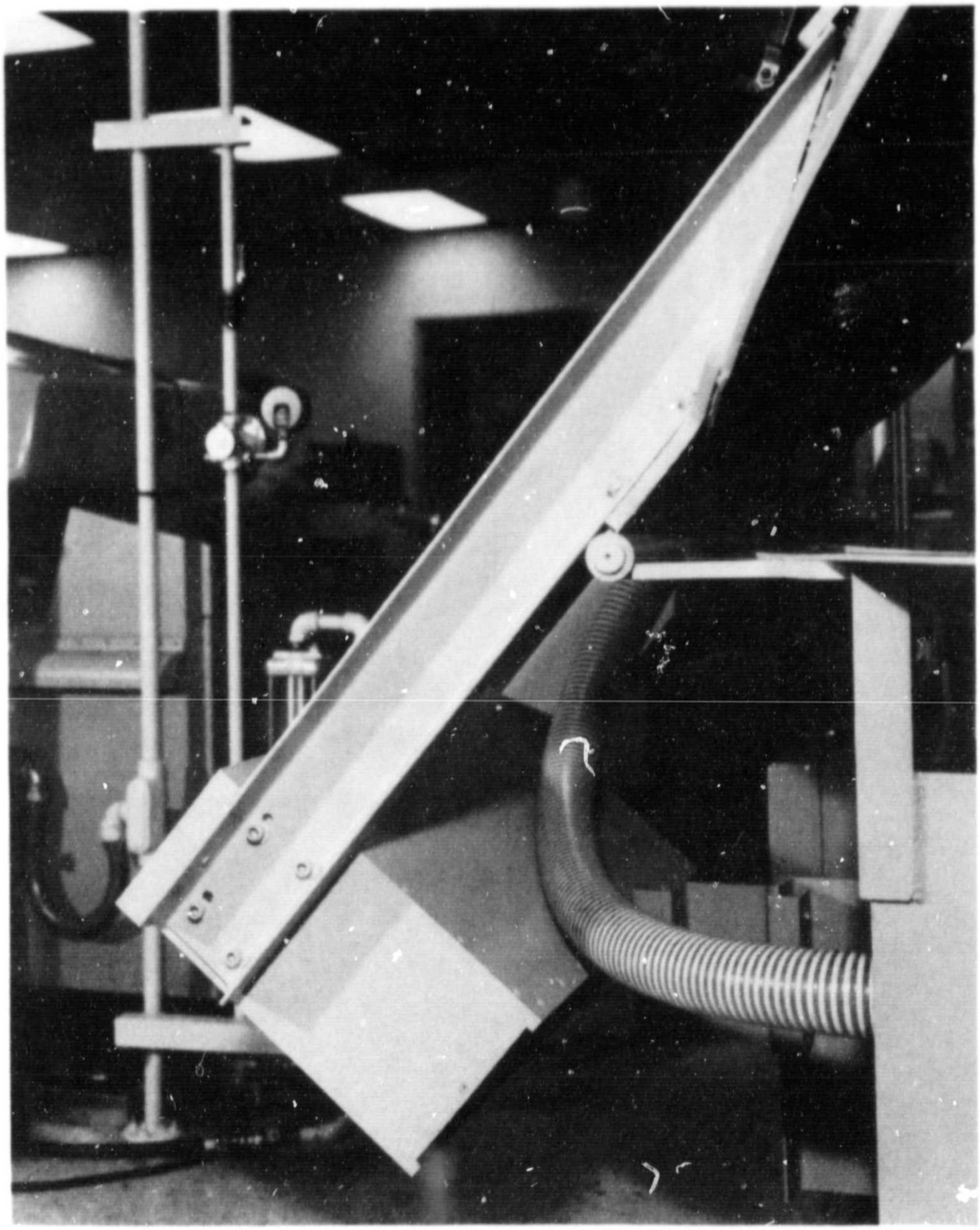


Figure 5. Counterweight and Hinge Assembly

Copper pipe fittings were used for all of the vacuum plumbing. In retrospect, the cost of this decision was considerable. Carefully made-up PVC pipe joints would have been acceptable for the moderate vacuum required (about 2 torr). The high cost of copper fittings and extra labor required to solder all joints was a concession to "the way it's always done." There does not seem to be any adverse safety-code requirement for this type of usage of PVC pipe; however, a brittle failure could occur.

Another plumbing consideration was the attachment of the top chamber vacuum line. Since this chamber pivots on the hinge, a flexible line is required. This line must not create a spring force, nor may it bind. Figure 6 shows that a comfortable configuration for the flexible line was found.

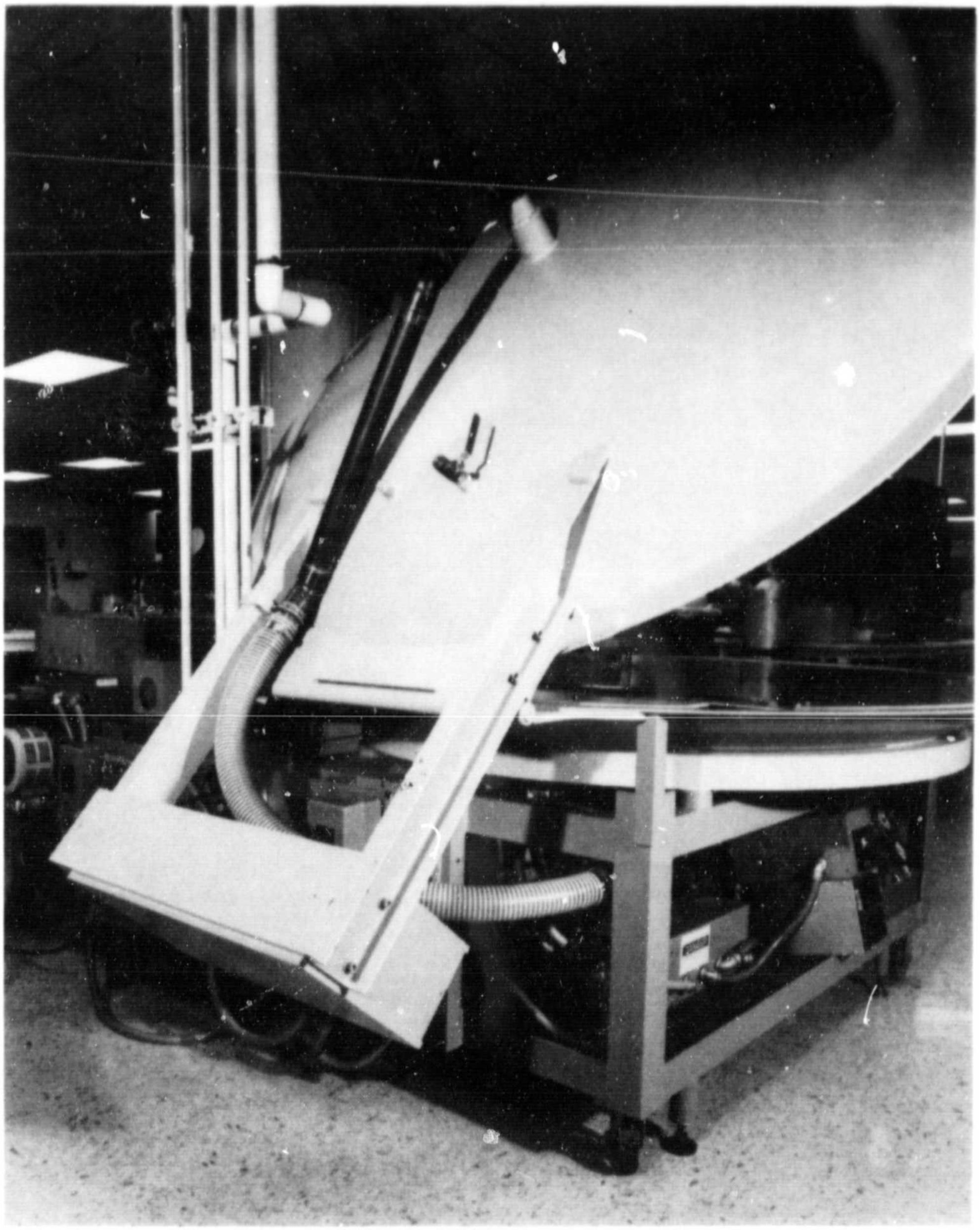


Figure 6. Flexible Vacuum Line Installation

Inasmuch as it was desired to pull a slight vacuum in the top chamber to hold up the diaphragm, a low-pressure sensing unit was needed. The diaphragm weighed 37 pounds; a vacuum producing about 200 pounds was considered reasonable. This was a tradeoff between the diaphragm weight and the strength of the diaphragm support. Unfortunately, 200 pounds is created by a vacuum of only .053 lb/in.^{2} in this large a chamber. Inexpensive vacuum sensors for this pressure level cannot withstand a full 14.7-lb/in.^{2} vacuum. A solenoid valve was installed between the top chamber vacuum line and the low-pressure sensor. Since the sensor was to be used only when the top chamber was near atmospheric pressure, this scheme provided the necessary protection without hindering operations.

Once the basic vacuum system was built, the laminator platen and heating element were installed. The platen was situated in the chamber so that the top of the laminant stack coincided with the plane of the bottom of the diaphragm. This placement avoids problems caused by the diaphragm pulling onto or away from the edge of the laminant, which could cause the encapsulant to flow away from or toward the edge of the laminant. It was also desired that the platen be flat and evenly supported to avoid stresses.

Marbles had been used previously between flat plates. A quick calculation showed that 10.2 ft^3 of marbles would be required to fill the lower chamber. Since the cost would be more than $1000, some alternatives were examined. One possibility was concrete, which was immediately rejected as being too porous. Another possibility was beach pebbles. A small quantity of fine-grained smooth beach pebbles was placed on a hot plate and a beaker was inverted over them. After heating to about 100°C, a noticeable odor was produced along with a quantity of water that condensed on the bottom of the beaker. More searching of the marble market disclosed the availability of E glass marbles, which are used for feedstock in the manufacture of fiberglass. About $300 worth of these marbles were required to produce a roughly level bed of marbles 1/2 in. below the flange plane (coincident with the plane of the bottom of the diaphragm) of the bottom chamber. The 1/2-in. spacing was needed to fit in: (1) a 1/16-in.-thick aluminum sheet; (2) two layers of woven fiberglass; (3) a strip heater; (4) a 1/8-in.-thick aluminum plate; (5) a laminant stack about 3/16-in. thick. After the marbles were in place they were leveled by placing a flat steel plate on top of them and tapping the plate with a rubber mallet. Final levelling was done by applying atmospheric pressure to the steel plate as in a normal lamination cycle. The marbles shifted to reduce point loads and produced a flat surface.

Heating of the laminant could be accomplished in a number of ways. The early laminator was designed to use IR heating. This was later modified to use an electrical strip heater (Reference 7). The change to a strip heater was made to allow fabrication of modules with opaque substrates. Another method, used in a commercially available laminator, uses heated oil. This process is appealing, since an even temperature gradient is easily achieved, but some expensive accessory equipment is required to heat and pump the oil. There are also some additional safety concerns when hot oil is used. Since the earlier electrical strip heater use was successful, a larger version was ordered. The early 1 x 4-ft laminator electrical strip heater was of a special design, and was made with resistive heating wires embedded in a silicone rubber--fiberglass laminant. Wires were used because they did not require production of a foil etching pattern. When the larger 4 x 4-ft electrical strip heater was ordered the fabricator, Tayco Engineering, found that some stock resistive-foil heating elements could be used. The heater was designed to use available single-phase 480 Vac service and draw 10 kW of power. Use of three-phase electrical service had been tried in industry and caused some problems. Two layers of woven fiberglass were placed underneath the heater to provide a soft base. This allowed attachment of control and test thermocouples to the bottom of the heater.

Strip-heater power leads were fed through one of the two bottom chamber access ports to a junction box. The heater control thermocouple and laminant test thermocouples were passes through the other access port.

The next area of concern was the process controller. A wiring diagram of the control box is shown in Figure 7. The significant design decisions during the control box fabrication were: (1) panel layout; (2) access for process modification; (3) wiring layout. As is shown in Figure 8, the front panel contains four timers (also made by Eagle Signal Div.), five control switches, one power switch and two vacuum gauges. Each of the timers is connected to a separate cam-actuated load switch. Unlike the cam-actuated timing system used earlier, this system uses the timers to signal a stepping motor, which advances the controller to the next process step. In order to reduce the chance that spurious signals are received by the stepping motor, control pulses are fed to a tap switch terminal. Since each of the 24 tap switch terminals is only connected during one process step, only the desired control signal should be received. The timers are easily adjusted from the front to select a time interval for a particular step. Sequential selection of different timers with different time intervals allows a wide choice of process step times. Greater accuracy in selecting small time intervals was achieved by buying timers with total ranges of 5, 10, 10 and 30 min. The 5-minute timer has large 15-second divisions and a 5-second interval is easily approximated.

The six remaining controller switches are connected to the following functions: (1) top chamber vent; (2) bottom chamber vent; (3) top chamber vacuum; (4) bottom chamber vacuum; (5) heater; (6) low-pressure sensor. The low-pressure sensor is a diaphragm-type device and operates a single-pole microswitch. A small solenoid-operated bypass tube was installed around the top chamber vacuum valve and is controlled by the low-pressure sensor. This approach allows gradual evacuation of the top chamber. Initial efforts to control the slow, motor-driven 2-in.-dia main valve for the top chamber were ineffective. The pumping rate was much faster than the control response time. With the bypass line installed, control was established. If a slower evacuation rate is desired, a ball valve in the by-pass line is used as a throttle valve.

When a lamination pressure less than 1 atm is desired, another pressure sensor is required. This sensor can be connected in series between the heater control switch and the top chamber vent. The normal top chamber vent command is not used; instead, when the heater goes on, the pressure sensor sees a 1-atm vacuum and opens the top chamber vent. When the vacuum is reduced to the set value (e.g., 5 lb/in.^{2}) the vent is turned off. After the lamination cycle has been completed the normal vent command is given to both the top and bottom chambers.

Changing the process sequence to accommodate research requirements was an important control-box design consideration. Access to the process controller is had by use of a hinged front panel (Figure 9). Each of the 10 load switches on the process controller is controlled by 24 tabs, which may be easily set in either the ON or OFF position. This scheme allows selection of any or all of the 10 switch-controlled functions for any of 24 different process steps. Since a hand must be inserted into the control box to set the control tabs, an interlock switch was installed and the power plug, interlock switch and fuse holder leads were insulated.

The wiring diagram is mentioned above. Routing of the wires in the control box was point-to-point except in two special situations. Wiring

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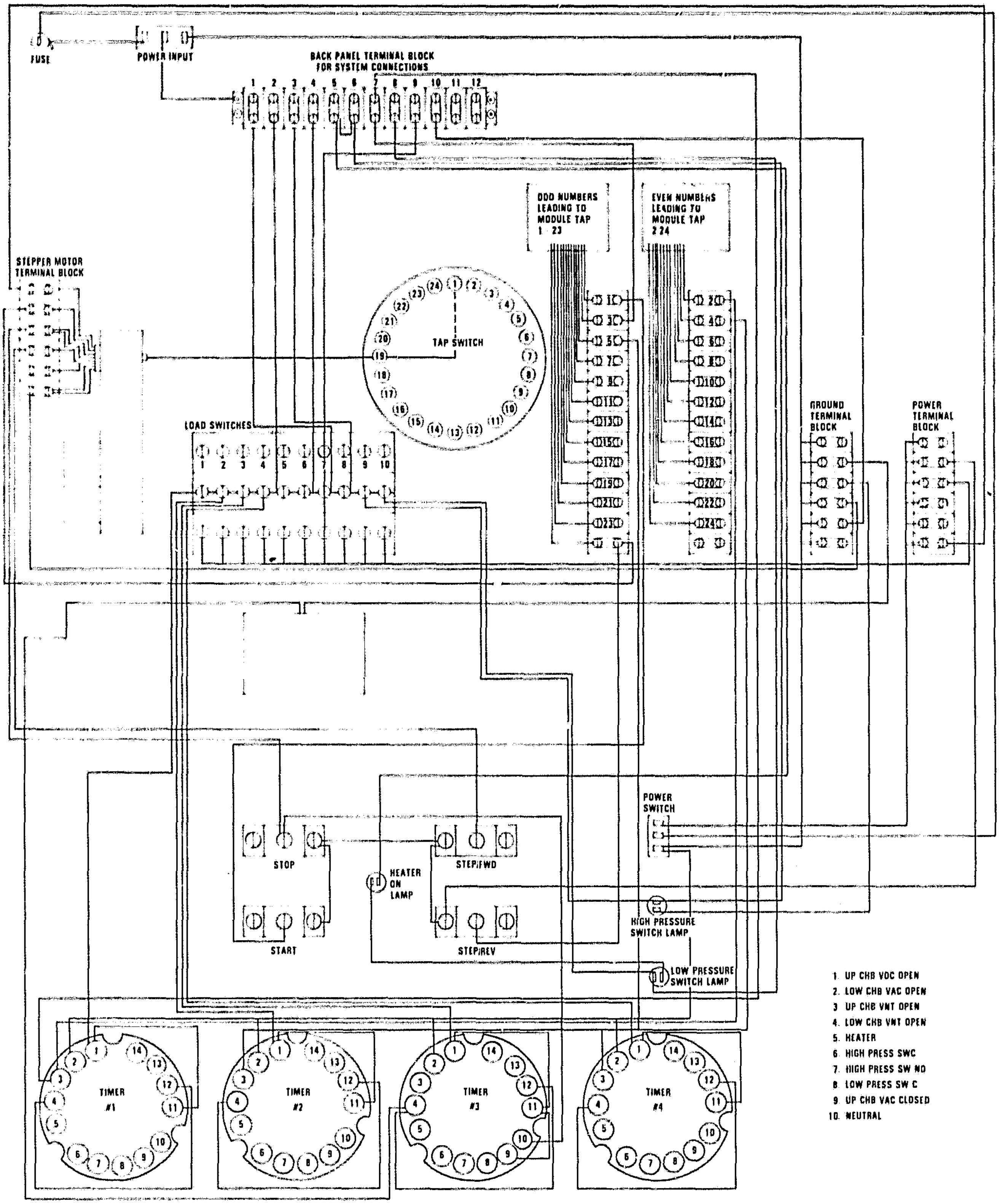

Figure 7. Control Box Wiring Diagram

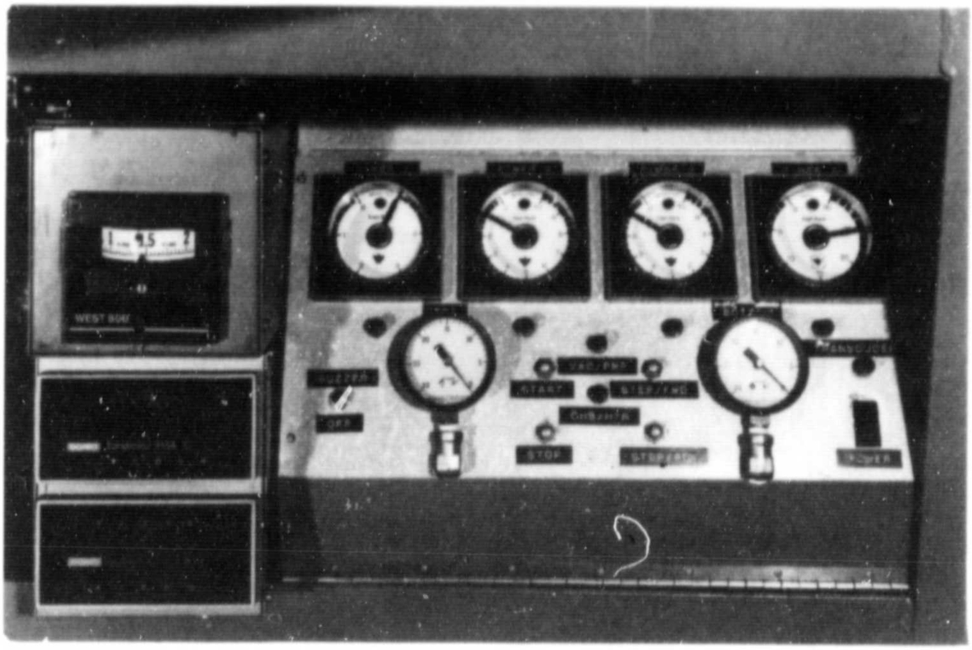

Figure 8. Control Box Front Panel

between the front panel and the remainder of the control box is cabled and routed near the panel hinge to allow easy panel opening. All wires leading to controlled functions are routed to a terminal block mounted on the back panel. A conduit leads from the area near this terminal block to a junction box (Figure 10). The junction box serves as a connection point for all of the electrically operated valves and the temperature controller. Also located in the junction box is a 110-Vac-controlled 480-Vac 30-A power contactor. The contactor receives its control inputs from the temperature controller. Temperature overshoot is prevented by the temperature controller, which starts cycling the heater power at least 10^{o} before the set temperature.

Temperature sensing for the heater uses a thermocouple placed in the center of the bottom of the heater. Five other thermocouples are also located on the bottom of the heater: one in the center and one in each corner. These five thermocouples and five others are routed to a thermocouple switch box. The additional five thermocouples are used to monitor bond-line temperatures during research runs. By pressing the appropriate switches on the thermocouple switch box the process temperatures may be monitored during a run. No bond-line thermocouples may be used when a cosmetically good laminant is desired since the wires create grooves in the surface of the laminant.

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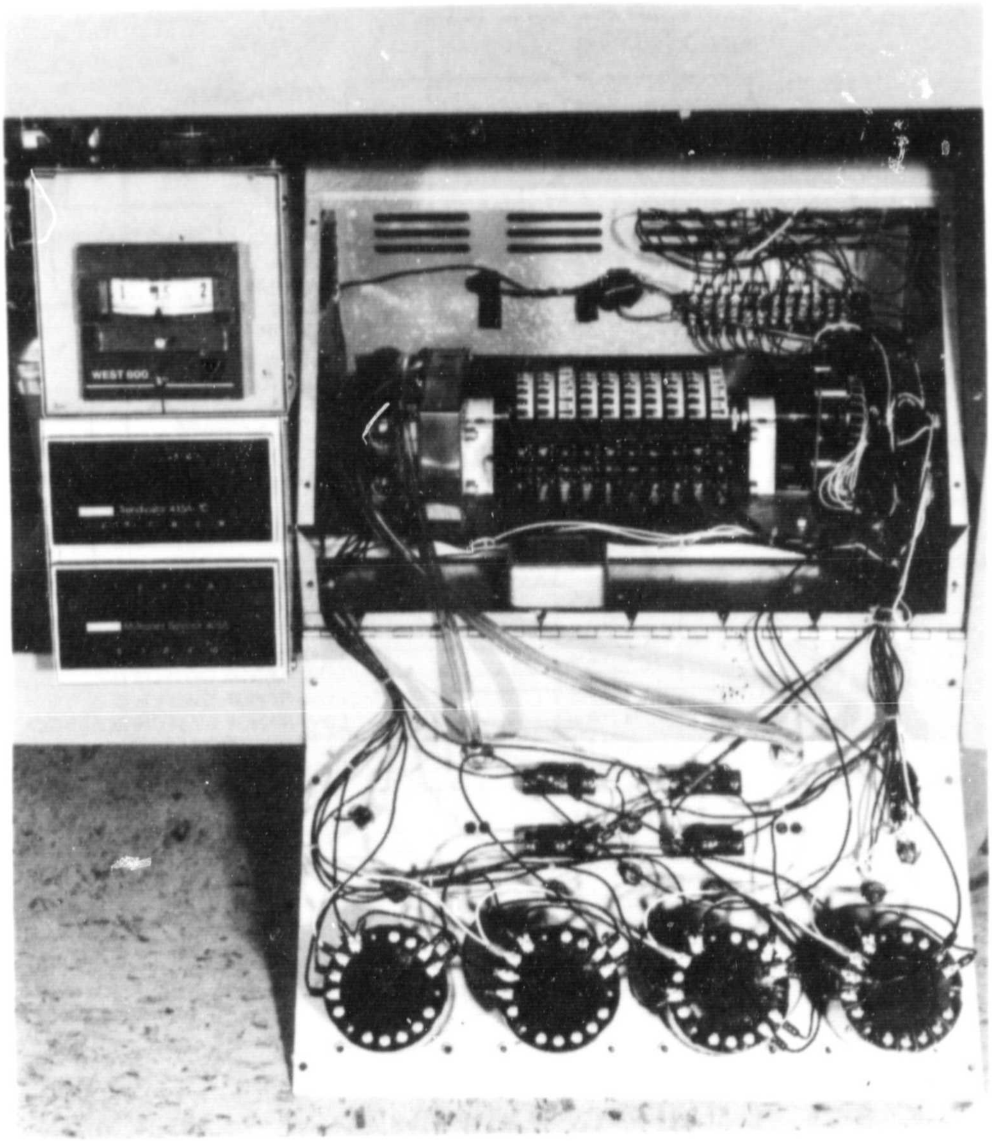

Figure 9. Control Box Interior Access

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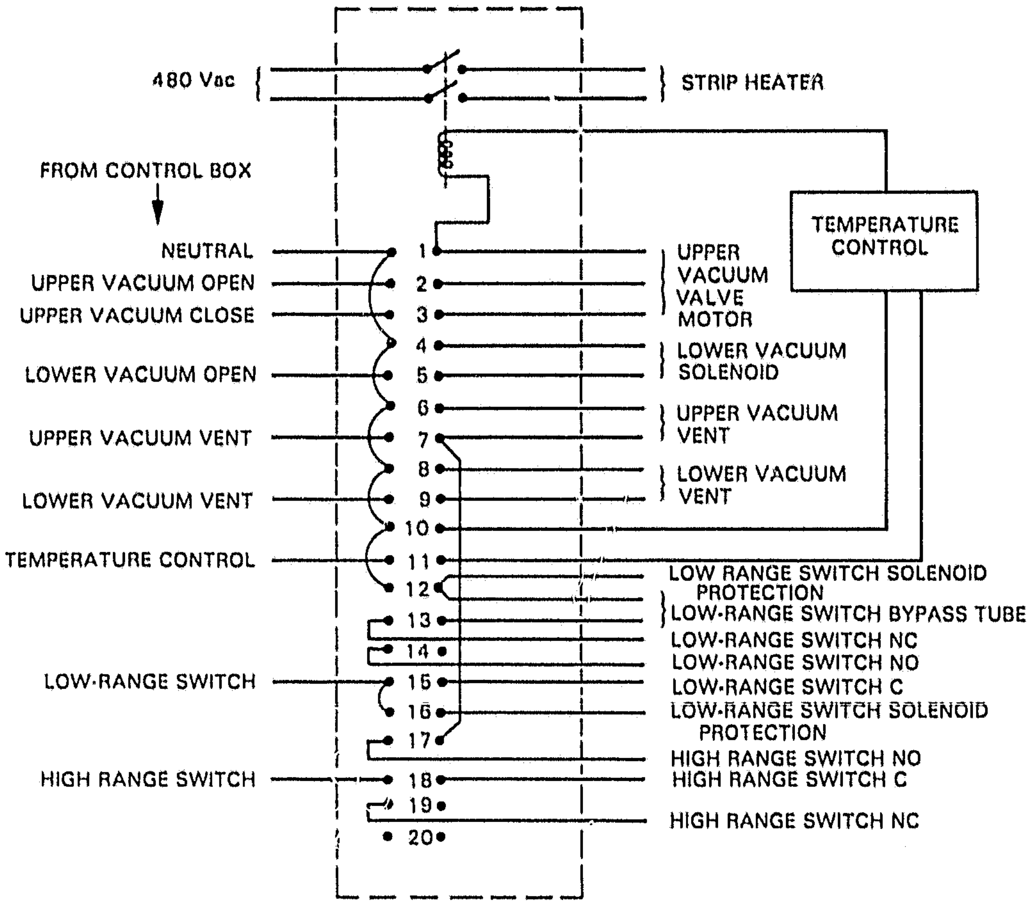

Figure 10. Junction Box Wiring Diagram

SECTION IV

OPERATION

Since large forces would be generated in the operation of the laminator, a stepwise operational testing approach was selected: (1) control system tests; (2) vacuum system tests; (3) lamination tests; (4) trial laminations. Control is achieved through use of simple relay or on-off logic. As such the control system tests posed no problems. Certain desirable system features did create some unexpected results. A warning buzzer was desired to signal the end of a process run. When the buzzer and a latching relay were installed it was discovered that noise generated in the buzzer circuit caused the controller stepping motor to cycle until the buzzer was turned off. Early attempts to fix this problem resulted in the loss of other desirable features. A compromise solution allowed the buzzer to ring while the controller is stepping to the HOME position. Implementing this solution also tied up the No. 3 timer. Obviously a better solution is needed, but demands for the use of the laminator overwhelmed the desire for perfection. Once the control box was functioning acceptably the junction box and temperature controller were checked out.

Testing a large vacuum system for the first time should always be done by the designer. All of the design decisions and compromises come into play at this time. When the valve between the vacuum pump and the laminator was opened a number of details had to be checked. The most important readings were those from the top and bottom chamber vacuum gauges. Since these tracked initially, other items were given more attention. A second look showed that the top chamber had a vacuum of 5 in. of mercury more than the bottom chamber. Since the top vacuum valve is a slow, motor-driven valve, attempts to shut off the system by cycling to the next step were too slow. The silicone rubber diaphragm applied an estimated 12,000 lb of force to the diaphragm support before the support failed. Since the support design load was only 200 lbs, this reflects a very conservative design approach. Fortunately, the diaphragm was not damaged. The misleading vacuum-gauge readings were caused by the top chamber vacuum raising the diaphragm, which acted as a pump, reducing the bottom chamber pressure. The bottom chamber was not being evacuated at all due to a closed throttle valve. A visual check of all valves was added to the procedure sheet. A manual vent valve was also added to the top chamber.

After repairs were completed a second test run was made. No major problems were found. The low-pressure sensor was too sensitive to line fluctuations caused by the large (1500 ℓ/min) vacuum pump. This resulted in a stuttering of the solenoid, so this system was shut off temporarily. Another problem caused by the slow top chamber vacuum valve was disclosed. Since the bottom chamber is filled with marbles, it has a much lower effective volume than the top chamber. This difference had been noted and the bottom chamber valve and vacuum line were of only 3/4-in. dia, not of the 2-in. dia of the top chamber plumbing. While the top chamber valve is opening slowly, the bottom chamber vacuum gauge may show a difference of 10 in. of mercury. This problem did not harm the laminator but it was not a desirable condition before the laminant materials were completely outgassed. Again the procedure sheet was modified: the lamination cycle was started, then, after the top chamber valve was fully opened, the line valve to the vacuum pump was opened.

When the laminator vacuum and control systems were operating smoothly, some lamination and temperature tests were made. Early temperature tests showed a 50°C difference between the center and the corners of the strip heater. While these measurements were being made, two other problems were discovered. The differential heating of the square center of a round plate had been considered. During heating this plate is under a 55,000-lb load. There was a possibility that this load would prevent movement of the plate. Due to lack of time, an empirical resolution of this conflict was chosen. During the first run the plate bowed up in the center by 3/4 in. This was much more deflection than could be tolerated, so a square aluminum plate was substituted for the round steel plate. This solved the temperature difference and bowing problems simultaneously. Since the change was insufficient to have resolved all of the temperature difference, some other measurement problems must also have been solved at the same time.

After lamination the air vented into the top chamber is heated by the diaphragm. If the top vent valve is closed during the cooling period, a vacuum will be formed. This vacuum would be found by using the gas law:

$$P_2 = \frac{P_1 T_2}{T_1} = 9.30 \text{ lb/in}^2 \text{ abs}$$

where

P_1 = 14.7 lb/in.^{2}

T_1 = 463°K (170°C maximum process temperature)

T_2 = 293°K

A vacuum of 5.4 lb/in.^{2} would create a force of 20,192 lb on the diaphragm support, more than enough to cause damage. This problem was solved by keeping the top chamber vent open for at least 30 min after a run.

When the square aluminum plate was substituted for the round steel plate it left segments of the bed of marbles uncovered. These were at first covered with aluminum plates spaced away from the center plate by 1/16-in.-thick strips of epoxy fiberglass. When this proved too difficult to control, the aluminum segments were replaced by epoxy fiberglass segments.

The second problem that showed up during the heating tests was unexpected. When the top chamber is vented to atmosphere there is little force holding the top chamber so that the diaphragm seal will function. This problem was thought to have been solved by the use of five clamps near the front of the laminator. There was no trouble with this approach during the vacuum tests, so none was expected later. Evidently heating causes expansion of the silicone diaphragm and/or warping of the top or bottom spherical end cap so that some force is generated. One lamination test run was aborted after 15 min of heating when the vacuum seal was lost. Addition of four more clamps near the hinge solved this problem.

A process sequence could be established from previous work with the smaller laminator. this process sequence must be entered into the process controller by setting the load switch tabs to an up position. A typical process sequence would be set up as shown below:

Controller Position	Process Function	Controller Tabs Up
1	Start position with low-vacuum sensing switch engaged to pull diaphragm up	10
2	Evacuation of top and bottom, using timer No. 1	1, 5, 7
3	Vent top chamber, enable high vacuum sensing switch to control venting, start heater, using timer No. 2	2, 5, 8, 9
4	Continue heating, turn top vent off, using timer No. 4	4, 5, 9
5	Vent top and bottom, turn off heater, using timer No. 2	2, 6, 8
6-24	Ring buzzer, hold open top vent, step to HOME position, using timer No. 3	3, 8

During the equipment problems and revisions described above some gel test (Reference 5) samples were produced. Since the early temperature difference of 50°C had been noted, it was decided to run the first samples at a reduced temperature (120°C) for a longer time (60 min). When these samples were tested they had a degree of gelation in the 2% to 8% range. An acceptable gelation for the version of ethylene vinyl acetate (EVA) being used is 65%. The 1 x 4-ft laminator typically produces gelation tests around 92% with a 150°C temperature and 25-min cycle.

After a number of test runs had been made a new problem was found: the 4 x 4-ft pieces of fiberglass cloth used as pads and wicks were starting to shred. Fragments of fiberglass were becoming involved in the samples and everything else. When the glass cloth had been cut the cut edges were flamed to fuse them; this resulted in a brittle edge that evidently broke down with repeated use. Repairs were made by coating the fiberglass edges with a series of 3-to-4-in. smears of RTV silicone rubber and re-trimming them. The smears were separated by 1/2-in. gaps to ensure outgassing. So far this seems to have solved the fiberglass-shredding problem.

During the final stages of operational testing some urgently needed module laminations were made. The first 4 x 4-ft module to be laminated contained

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about 200 scrap photovoltaic cells, each of 2.25 in. dia. These cells only covered 2/3 of the module, so other scrap cells and pieces of copper bus bar and interconnects were added. This module was the prototype of a new credit-card module design. A credit-card module will have the cells encapsulated in the laminator and then be adhesively attached to a substrate in a second operation outside of the laminator. In order to run the credit-card module, it was necessary to reprogram the controller and change the temperature controller thermocouple lead. After the extended 60-min cycle the resulting module was gratifying: although the EVA had wept out of the edges of the laminant and caused some difficulty in removing the finished product, there were no bubbles and the EVA seemed to have been cured evenly. A few wrinkles were found in the back sheet, which could have been caused by cooling of the diaphragm while the sticky EVA problem was being handled.

The laminant stack used for the first credit-card run is shown in Figure 11a. A second credit-card module was subsequently laminated. In this instance the laminant stack was changed to that shown in Figure 11b. The results of the second module lamination test were: (1) good encapsulant curing; (2) no bubbles; (3) unusual dimples in the front surface. Subsequent tests showed that a wick of Craneglas or woven fiberglass cloth was needed between the glass plate and the Teflon sheet to prevent air entrapment and subsequent dimples. Additional tests showed that Craneglas alone was a sufficient interface since it did not adhere to the Acrylar film and did not trap air or cause dimples.

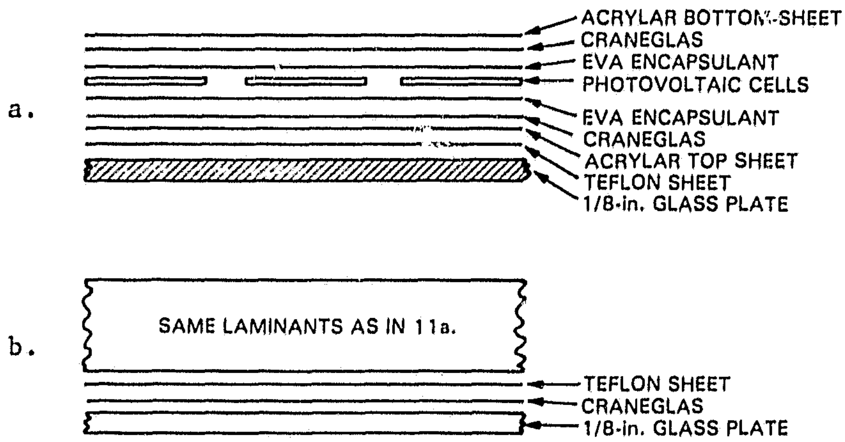

Figure 11. Laminant Stack

SECTION V

FUTURE EFFORTS

Planned future efforts on the 4 x 4-ft-module research laminator fall into three areas: (1) equipment modifications; (2) improved control system; (3) improved heater performance. The most important equipment modification would be a differential vacuum gauge and a proportional valve to equalize pressure between the top and bottom chambers during processing. Other desirable modifications would be a 2-in.-dia solenoid-operated vacuum valve for the top chamber and more test ports in the bottom chamber.

An alternative to the differential vacuum gauge idea was sought. If a solid flat plate is placed between the diaphragm and the present perforated diaphragm support, and a separate vacuum line is led to the plenum thus formed, a vacuum in that plenum will not stress the flat plate or the diaphragm as long as the top and bottom chambers are at equal pressures (e.g., vented to atmosphere). This situation is also workable when both chambers are being pumped down at the same time. The only difficult time is when the top chamber is vented and the bottom is not. This requires a crossover valve between the diaphragm plenum and the remainder of the top chamber. A three-way solenoid valve between the vacuum pump, diaphragm plenum and top chamber would be safe and appropriate.

Contemplated control system modifications center on the process controller. If the process controller had been purchased with 20 load switches some desired process research functions would have been simpler. However, the process controller would have been larger, which aggravates another problem. The process controller is a tight fit in the control box chosen to fit into the available space under the laminator. Since the interference is in the long dimension, it restricts access to the controller terminal boards for the motor and tap switch and new connections, which are often desired to the tap switch, are difficult to make.

Use of an electrical strip heater has worked well; however, there is always the question of temperature uniformity over such a large surface. Since uniformity can be affected in the present system by the degree of thermal coupling of the surfaces, running extensive thermal profiles with a group of thermocouples does not resolve the question. Even though heated oil requires expensive auxiliary equipment, it does have appeal if the encapsulants require close temperature control.

A boost-and-buck power-control system was used on the earlier 1 x 4-ft laminator. After some experimentation with slow and fast temperature rise process cycles on the smaller laminator it was decided that this feature was not needed for the 4 x 4-ft laminator. Provisions are easily made on the power panel for addition of this feature if experimental interest warrants the expense of a large autotransformer.

SECTION VI

CONCLUSIONS

Successful lamination of 4 x 4-ft photovoltaic modules using a double-chamber vacuum laminator has been demonstrated. A low-capital-equipment cost laminator can be constructed from generally available industrial materials.

Potential problems with wrinkling or dimpling of the back sheet can generally be avoided by using a porous interleaf material such as Craneglas or woven fiberglass.

Use of marbles for thermal isolation is feasible in large vacuum systems. An industrial stepping programmer can be used as an inexpensive, flexible process controller if mated with adjustable reset timers.

Useful lamination process modifications are available by incorporation of vacuum sensors in the process control system.

A research laminator can give useful insights into economic, process and operational problems if these areas are considered during the initial design.

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